STRUCTURAL GLASS FACADES: A UNIQUE BUILDING TECHNOLOGY

by

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Epigraph

To Lifelong Learning

Dedication

To my bride, Victoria Mercedes, with all my heart.

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One cannot help but burden others when doing as I have done under the circumstances in which I have done it. I am indebted to the following people that inhabit vast areas of my being.

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My parents, Bob and Toni, enjoyed their 60th wedding anniversary this year; “enjoyed”, and that is truly the magic and beauty of their relationship; they have enjoyed every year of the 60. It is truly a gift to have parents that teach you that nothing is beyond you, that challenges are opportunities; parents that love, support and encourage you no matter what the circumstances. I thank them for this gift with all my heart. Thanks Mom and Pop.

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Finally; I have had a life full of teachers, and I have done my very best to learn from them all. Now I want to thank you all.

Mic Patterson   30 March 2008

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Abstract

This thesis formulates a hypothesis that the rate of diffusion of innovative building technology, in this case structural glass façade technology, can be facilitated in a manner to accelerate growth, and a strategy is developed for accomplishing this. In the process, structural glass façade technology is defined and described, and significant aspects categorized. A web-based resource is developed as a source for information, learning programs, design guides and tools. Reference information is included with respect to all aspects of the technology including glass materials, glass-fixing systems, and structural systems as required to develop a comprehensive façade concept. A Microsoft Windows based analytical design tool has also been developed to facilitate conceptual development of appropriate façade solutions by aspiring adopters of the technology. The tool provides for the development of comparative solutions from a selection of structure type options.

Introduction

An Advanced Glass Façade Technology has Developed and Matured Over the Past Three Decades.

The building skin is a vitally important architectural consideration. No other building system combines as significant an impact to both a building's performance and aesthetic. The use of glass as a component of the building envelope has been increasing since its initial introduction as a building material, accelerating in the twentieth century owing to the development of high-rise steel framing systems and curtain wall cladding techniques. Little has changed in the core technology of glass curtain walls and façades since their initial development. Much has changed, however, in the building arts in the past decade alone in terms of aesthetic and performance drivers, as well as in available structural systems and materials.

In response to these market forces, new glass facade types have emerged in spot applications over the past two decades. These new façade designs play off the primary attribute of glass, its transparency, and increasingly off the structural properties of glass and the integration of glass components into the structural system. As a body, a case can be made that the completed works represent a new façade technology. Characteristics of this technology include; highly crafted and exposed structural systems with long-spanning capacity, integration of structure and form, simultaneous dematerialization and celebration of structure, complex geometries, extensive use of tensile elements, specialized materials and processes, an integration of structure and cladding system, and a complex array of design variables ranging from facade transparency to thermal performance and bomb blast considerations.

The push by leading architects for transparency in the building envelope has historically been the primary driver in the development of the new façade types. The façade structures have developed in parallel with the development and application of frameless or point-fixed glazing systems. While any type of glazing system can be supported by the new façade structures, the point-fixed systems are the most used. Structural system designs with minimized component profiles were desired to further enhance the transparency of the façade. This led to structure designs making extensive use of tensile structural elements in the form of rod or cable materials. A structural element designed only to accommodate tension loads can be reduced significantly in diameter over a similar element that must accommodate both tension and compression loads.

These new façade types have evolved primarily in long-span applications of approximately 20 ft (6m) and over, and can perhaps be best categorized by the various structural systems employed as support. While these facade structure types are derived from the broad arena of structural form, they have become differentiated in their application as facades. Identifiable classes of cable trusses and cable nets are examples of such structure types. This thesis proposes that these façade structure types represent the core of a new façade technology. An component of this thesis will be to identify and classify this body of façade structure types.

Advanced Façade Technology is Poised for Wider Application.

This emergent façade technology has been evolving for over thirty years, with considerably varied application in the commercial building marketplace. Public sector works include airports, courthouses, convention centers, civic centers, and museums. Private sector work includes corporate headquarter buildings, hotels, retail and mixed-use centers, churches, institutes and other privately funded public buildings.

While applications have been limited to a small niche market in the overall construction industry, many innovative designs have been introduced over the years, with many more creative imitations and variations springing from those. As a result, this technology has matured over the years and is no longer largely comprised of experimental structures. It has been tried and tested in a considerable diversity of built form; structural systems have been adapted to façade applications; specifications and methods have been developed, tested and disseminated; practitioners have built hundreds of highly innovative façade structures in a variety of applications; development costs have been absorbed. An infrastructure of material suppliers, fabricators and erectors has developed in response to increasing project opportunities. These factors have combined to make the technology more competitive. Thus, this body of façade types represents a mature building technology positioned for broader application in the marketplace.

Growing Interest in the Use of Advanced Façade Designs

At the same time, owing to the high profile and success of recent projects featuring advanced façade designs, increasing numbers of architects are interested in incorporating this technology into their building designs. The new façade designs are becoming increasingly valued by the design community for both their varied aesthetic and the ability to provide a controlled transparency ranging from very high to modulated in response to environmental considerations. Growing interest and a maturing technology promises significant growth in the small niche market for advanced façade technology. There exists the potential for a partial conversion in the larger curtain wall market, whereby the advanced technology replaces conventional curtain wall in an increasing number of applications.

Barriers to Implementation

As with any emergent building technology, implementation requires an important element of education to take place in the building community. Implementers must develop their design techniques, then identify qualified fabricators and inform them as to the particular considerations of material and process in demanding architectural application. Similarly, installers must be informed of appropriate means and methods, the tools and techniques required to assure an efficient erection process.

Perhaps most important is to inform the design community regarding the new technology. There is a burgeoning interest among the design community in these new façade technologies, but a widespread lack of technical familiarity with them. While many of the larger architectural offices have experimented with these new façade forms, a great many more small and midsize firms would like to utilize them in their designs but are not comfortable with their capability to do so. A few specialty-consulting firms are available to facilitate this work, but project budgets frequently exclude their participation. Lack of familiarity by the design community can quite effectively limit the growth of new technology.

Hypothesis

The hypothesis presented here is that strategies can be developed to accelerate the diffusion of new and innovative technology into a broader market. More specifically, this thesis proposes to develop a comprehensive methodology incorporating design resources, guidelines, tools and learning programs to facilitate the implementation of structural glass façade technology. Central to this strategy is informing the building community regarding new and innovative technology, and providing the architect with a simplified methodology to facilitate the development of appropriate conceptual designs without the requirement of a paid specialty consultant. In a broader context, this thesis explores the implementation of innovative technology, more particularly building technology, and most particularly structural glass facades as a prime example of innovative building technology. In the process, the intent is to define, categorize and describe this technology and the materials and processes of which it is comprised, thereby perhaps adding to the rich vocabulary of this building form.

Design and Reference Tool

Building designers need information, delivery strategies, and tools to facilitate the incorporation of advanced façade technology in their designs. Knowledge of the fundamental considerations of material and system options, grid module, component sizing, spanning capacity, span/depth ratio, deflection criteria, finish options and relative costs is a prerequisite to the effective deployment of the technology in any specific design application.

The structural systems employed in the new façade technology are somewhat more complex than conventional framing systems. Form determination with these structures is largely driven by considerations of performance and less by arbitrary determinants of style. The integration of structure and form characteristic of this technology make it imperative that the designer have some feel for the behavior and attributes of the various structural systems and the glazing systems they support. Very useful to the system designer would be a conceptual design resource that would facilitate the development of comparative solutions in response to a specific façade application. These solutions would be derived from the current body of structural glass façade technology.

The program is envisioned ultimately as a web-based resource providing information, case studies, technical reports, design guidelines and tools, for all aspects of structural glass façade technology; glass, glass systems, structure systems and related systems and components. such as a providing The tool will be useful to architecture and engineering students as well as practitioners.

The primary focus of this thesis will be the definition of a resource embodying a comprehensive implementation methodology for structural glass façade technology. The process is the priority, and will be mapped out as a whole system. Pieces of the system will be prototyped as an attempt to demonstrate the conceptual viability of the program. Analytical tools are part of this; a simplified structural analysis tool for example, to determine preliminary structure attributes such as truss system depth, grid, member sizing, deflections and reaction loads in response to user-defined inputs such as span, spacing, and design loads. Equally important however, is reference information with respect to such diverse aspects of the technology as glass and glass-fixing systems, and project delivery strategies, all as required to support the efficient development of an appropriate façade concept. Such resources will enable the designer to develop a structural façade concept with the confidence that the design can be engineered and detailed without significant modification, and that realistic budgets can be developed along with the design.

Literature Search

While many publications deal with structural systems, and many others deal with building skins, few if any deal specifically with the long-span glass façade technology referred to herein. Nor is there a defined classification of the structural systems employed in these applications. The best source of information on this technology can be derived from case studies on the completed works to date.

All known forms of long-span façade structure types will be identified based upon a search of the available literature and an informal survey of the built environment.

Design tools will also be researched in an attempt to identify prior work that may have relevance to the effort described herein.

Classification of System Types

Long-span façade structure types identified in the search will be classified according to parameters to be determined as part of this thesis exercise. Broad categories are anticipated to be 1-way and 2-way spanning systems, and closed (no pre-tension forces to boundary structure required for initial stability) and open (pre-tension forces to boundary structure required for initial stability) structural systems. Further structure types will include; simple trusses, cable trusses, flat cable nets, anticlastic cable nets, space frames, grid shells, and glass fin structures.

FaçadeDesigner: A Design Methodology for Long-span Structural Glass Facades

The intent is to develop a resource for use by the façade designer to facilitate the development of an appropriate structural design from a choice of structural system types. The methodology will start with development of the glazing grid, the prerequisite for the design of an appropriate supporting structural system. Considerations of the glazing grid, largely driven by attributes of glass type, fabrication, handling and installation, will be provided as reference material.

Comparative attributes of the various structure types are developed and charted. Evaluation criteria includes design, manufacturing, and installation complexity, spanning capacity, transparency, interface system flexibility, glazing system types accommodated, adaptability of form, and cost. A component of this methodology is a prototype tool for analyzing select structure types identified from the classification process. The intent has been to create simple, automated methodologies for determining span, interval spacing of primary structural members, design loads and allowable deflection, system depth, member stresses and sizes, and reaction loads.

Chapter 1 - Context

1.1 Structural Glass Façades Defined

"Structural glass facades" and "structural glass façade technology" are terms used in this thesis to describe a relatively recent class of building technology comprising a component of the building envelope. The use of façade here is synonymous with building skin. Structural glass facades integrate structure and cladding, and are used in long-span applications (spans greater than approximately 20 feet (7 meters)) where heightened transparency and a dematerialization of structure are often predominant design objectives. The structural systems are exposed, and generally refined as a consequence. The design pursuit of enhanced transparency in these façade systems has resulted in the development of increasingly refined tension-based structural systems, where bending and compression elements are minimized or eliminated altogether. In fact, it is a premise of this thesis that this class of building technology can be most effectively categorized by the structural systems that have developed to support these facades (see Chapter 6).

The various structural systems can support any of the glass system types, which will also be identified, classified and discussed herein. While the technology can be classified by the various structural systems employed, it was the advent of point-fixed (frameless) glazing[1] systems that provided the germinating force propelling the early development, and while associated with a cost premium, point-fixed glazing systems remain the most commonly

[1] Glazing is an industry term used almost interchangeably with glass, such as in "glass system" and "glazing system." However, glass is only the most common glazing material, and the term can refer to any form of thin translucent material, so one may encounter the term "glass-glazing." A "glazier" is a construction professional specializing in anything from residential windows to high-rise curtain walls.

used in structural glass facades. Point-fixed glazing systems are mechanically bolted or clamped to supporting structure rather than continuously supported along two or four edges as are conventional glazing systems.

However, while high transparency, dematerialization of structure, and point-fixed glazing systems have come to characterize structural glass facades, the technology is not limited to their use. Other glazing systems have been developed and frequently used in response to objectives beyond mere transparency. Structural systems also have been used to express exposed structure in a manner that celebrates them rather than attempting to make them disappear. In fact, the current state of the technology can support a wide range of design drivers ranging from controlled transparency to cost.

It is a contention of this thesis that structural glass façade technology is mature and robust, and ready for broader infiltration into the building marketplace. There is, however, no consistent nomenclature in general use describing this technology. Sweets Catalog, the largest product catalogue in the construction marketplace, includes a section 08970 “Structural Glass Curtain Walls” that includes brochures by glazing subcontractors featuring project examples of what are herein referred to as structural glass facades. The use of the term curtain wall in describing these works is generally confusing and inappropriate. While curtain walls are indeed frequently a part of the building envelope, especially in high-rise construction projects, and often incorporate the use of glass as a cladding element, they are a distinctly different product from structural glass facades. The difference between them is discussed later in Chapter 2.

Another source of potential confusion is the term “structural glass.” This term is unfortunately sometimes used in reference to point-fixed glazing systems, and also in referencing glass used in actual structural applications, such as a beam or column element. The term could as easily refer to tempered glass. In contrast, the use of the word “structure” in structural glass facades as used herein refers to the structural system acting as the spanning element supporting the façade. “Structural glazing,” on the other hand, refers to glass that is fixed to supporting structure with a structural adhesive material in the absence of any mechanical capture of the glass pane. Compagno (1995, p.16) comments that a more appropriate term would be “bonded glazing”, as the supporting frame is the same as a conventionally captured curtain wall system. Similarly, there is no generally accepted categorization or naming of many of the glass and structure system types that comprise structural glass façade technology.

It is conceivable that opaque panel materials other than glass could be used as a primary cladding element on the façade structure systems. It is similarly conceivable that transparent or translucent plastic materials could be used. The former condition would effectively remove the resulting façade from the class described herein. The latter condition represents a special case so infrequently encountered as to be of no particular consequence to this naming strategy.

The structural systems used in support of structural glass facades are discussed generally in Chapter 2, and rigorously identified and categorized in Chapter 6. It is interesting that the majority of structural glass facades inhabit the top of the pyramid when it comes to complexity and cost; the reasons for which are discussed later in this thesis. The intent here is to describe the fundamental elements of this technology in a clear and simple form, and in a manner that may provide for better understanding and result in wider application by the building community; simpler, more efficient and economical solutions that begin to fill out the base of the pyramid. To facilitate this simplification, the technology is viewed from the limited application of essentially vertical, mostly planar façade structures as a partial element of the building skin, and in fact this does represent the majority of existing application. However, structural glass façade technology is capable of a remarkable diversity of form. All of the basic structural systems can be used in sloped and overhead applications. More significantly, many of the systems can be used to form complete building enclosures of complex, irregular geometry. The structural systems can be mixed in combinations that open up new possibilities of form and performance, or blended to form hybrid structural systems.

An excellent example of this is the Berlin Central Station train shed designed by von Gerkan Marg and Partners (GMP) architects with Schlaich Bergermann and Partners engineers.

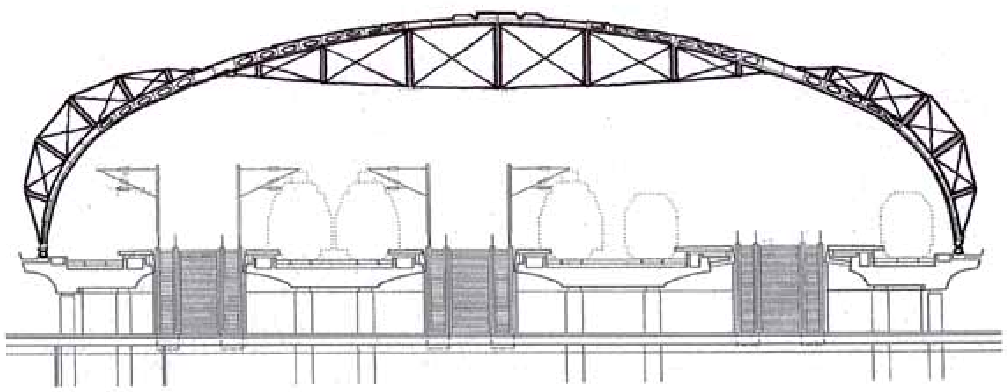

Figure 1.1 Berlin Central Train Station; section at cable truss (Schlaich & Gugeler 2005, p.1)

Figure 1.2 Berlin Central Station; construction photo (BBC News 2006).

The vaulted enclosure spans six tracks, curves slightly in plan following the curvature of the tracks, and the section gradually reduces toward each end as the vaults move away from the central station. Flat, multi-centered arched cable trusses are set on 13-meter (43 feet) centers, and cable-stiffened grid shells span between the trusses. (Schlaich & Gugeler 2005, p.3)

That the technology can embrace such enormous complexity in geometry and form has been of the utmost interest to the small group of highly innovative practitioners that have developed it and pioneered its use. There will always be a tip of the pyramid to this technology, the cutting edge in long-span glass facades represented by highly custom, innovative designs that push the envelope of the technology beyond the current state of the art. The intent here is to explore the potential for harvesting the spin-off from these predecessor structures, repackaging it in a simplified, efficient, more accessible form with broader potential market application, and transferring the resulting technology to a new group of users.

1.2 Historical Context

Structural glass façade technology is not new, having emerged from a variety of highly innovative experimental structures over the past three decades or more. With roots in Northern Europe, the technology can be traced back to a select few seminal projects and among a handful of pioneering architects and engineers. From a broader perspective however, structural glass façade technology can be seen as a prominent branch on the evolutionary glass tree, commencing with humankind’s early development of glass as a material and most especially, the later development of glass as an architectural material.

1.2.1 Glass as Material

"Glass is arguably the most remarkable material ever discovered by man," states Michael Wigginton (1996, p.6) in his great book *Glass in Architecture*.[2] An estimated 4,000 years ago, probably at the site of an ancient pottery kiln in the eastern Mediterranean, some curious soul stopped to wonder at the unusual properties of an inadvertent mix of sand and ash that had been exposed to the kiln's heat, and ignited a love affair between man and material, glass in this instance, that has been going strong ever since. Amato (1997, p.31) references the old story attributed to Pliny (1st century AD), of the Phoenician sailors trading in soda cooking on the beach one day and using blocks of soda (natron; an ash derived from plant material) to support their cooking pots. The combination of sand, ash and heat produced a primitive, translucent glass material. While one can never know the exact circumstances of this imagining, one can assume the high probability of a discovery born of some similar accident, and the earliest evidence of glass artifacts can be documented from this time.

It was nearly another two thousand years before the technique of glass blowing was discovered in the 1st century BC on the Syro-Palestinian coast, laying the foundation for the diffusion of glass technology throughout the Roman world. Wigginton (1996, p.12) observes that by the time of the Roman Empire, the composition of glass had been refined to a mix quite similar to the slightly green-tinted soda lime glass used today in the manufacture of flat glass: 69% silica, 17% soda, 11% lime and magnesia, and 3% alumina, iron oxide and manganese oxide. However, it was not until the turn of the 18th and into the early 19th century that exacting recipes for the chemical mix were developed empirically by early material scientists. Glass as material is explored more fully in Chapter 2.

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[2] This book is highly recommended to anyone interested in architectural glass or the use of glass in architecture. The first chapter of this thesis draws heavily from Wigginton's comprehensive, insightful and inspiring writings.

1.2.2 Architectural Use of Glass

It is difficult today to imagine a world of architecture without glass. Envision the built environment of any other major urban city of the world, and imagine all of the glass instantly disappeared; the naked skeletons of towers poking into the sky surrounded by perforated buildings and exposed storefronts. Or rather, imagine all else gone and envision the glass landscape uninterrupted by steel or concrete; it is remarkable the magnitude of glass material that comprises the urban construct.[3]

The use of glass in architecture has grown steadily since its first application as window glass, dating back to approximately the 1st century AD. Its properties of color, translucency, and transparency are so uncommon that mystical properties were often associated with it by the various cultures using it. Early glass making processes were closely guarded secrets by the ruling governments. Glass was traded as a prized material among kings and emperors of the lands. The wealthy classes long ago developed an appetite for glass that has pushed producers to make larger and better quality products over the centuries and continuing to this day. Over the years, the taste for glass spread throughout the population as glass in window applications became a commodity item in Northern Europe in the late 18th and into the 19th centuries. Today, most people value floor-to-ceiling glass if they can get it, at least a window if they cannot.

1.2.3 Glass as Window

The emergence of glass in window applications is attributed to the Romans in the Roman Imperial period. Window glass was first used in isolated applications, such as in the public baths to reduce air drafts. Early window glass was translucent, as the techniques for

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[3] This musing was inspired by a similar remark made by a moderator at the Engineered Transparency Conference held in September 2007 at Columbia University. The author took little note of these remarks at the time, and thus did not note the speaker's name.

producing transparent glass products were yet to develop. Glass at this point was not about transparency or view; it was most likely used for security and insulation from the exterior environment and for natural lighting. Then, around 100 AD in Alexandria, some early empirical materials experimenter tried the addition of manganese oxide to the melt, and transparent glass was discovered. Important buildings in Rome were soon adorned with cast glass windows, as were the villas of the wealthy in Herculaneum and Pompeii. (Fleming 1999).

In spite of the poor optical quality, the roots of future architectural glass production methods were developed during this period. Rudimentary glass blowing and casting processes were both available by the 1st Century AD and both could be used to produce glass that was relatively flat and translucent, although size was very limited and thickness in both processes was difficult to control. It was not until approximately the 11th century that Germanic and Venetian craftsmen refined two processes for producing sheet glass, both involving glass blowing techniques. One involved blowing a glass cylinder and swinging it vertically to form a pod up to 3 m long and 45 cm in diameter. Then, while still hot, the ends were cut off the pods, the cylinder cut lengthwise and laid flat. A second process involved opening a blown glass ball opposite the blow pipe and spinning it. This process was to become common in western Europe, and Crown glass as it was called was prized for certain optical properties, although size remained very limited. (Wigginton 1996, p.13)

It is interesting to note that the push for transparency and increasing sheet size in glass appears to date from the beginning of its use as an architectural material. References to the various glass processes and comparisons between them often refer to the relative limitations of size and optical imperfections.

Wigginton (1996, p.14) identifies the first true glass architecture as Northern European Gothic. Utilizing structural elements of arches, vaults and flying buttresses, the builders of the great cathedrals of the period were able to construct stone frames, highly expressive structures, with large openings to the outside to admit light. The local climate conditions never would have allowed for this if the openings had exposed the interior spaces to the raw elements. A robust glass technology was available to fill this need in most dramatic fashion. Glass was available in many colors, but only in small pieces. The window-makers developed a structural system comprised of leaded bars that were used to tie the mosaic of glass pieces into a single membrane of glass and lead capable of spanning the frequently quite large openings. These large stained-glass windows represent an early precursor to structural glass facades. In a similar manner, the morphology of the structural masonry frames with glass membrane infill built around Paris from the 12^{th} through the 14^{th} centuries, herald the new architecture to emerge in Chicago in the late 19^{th} century in the work of Louis Sullivan and others, where large glass sheets are used as infill to the new multi-story steel framing systems.

Figure 1.3 Chartres Cathedral, France, 1194-1260. (Beck 2008)

Figure 1.4 Carson Pirie Scott Building, Chicago 1898, Louis Sullivan architect. (Billmoy 2003)

Figure 1.5 Chartres Cathedral, south ambulatory from west. (Johnson Architectural Images 2007)

This first glass architecture was not concerned with transparency. The windows were not designed for view, often located high on the cathedral walls. Rather they were an exploration of light, the luminous properties of colored glass, and to communicate the stories and messages of the church to a largely illiterate congregation. (Wigginton 2006, p.14)

Glass production and the secular use of glass increased steadily throughout the Italian Renaissance. By the 18^{th} century, window glass had become a commodity item in Northern Europe. Double-hung windows were also developed in England during this period. The use of glass in architecture branched to the development of fenestration as an elevation design technique, and alternately to the development of the conservatory. It was this later branch which was to have such a huge influence on the future use of glass in architecture, and the branch to ultimately yield structural glass façade technology.

1.2.4 Glass as Building Skin

Structural glass façade technology clearly has its roots in the great iron and glass conservatories of the 19th century. This century witnessed the unfolding of the industrial age, and the introduction of the age of metal into architecture with such dramatic examples as The Palm House at Bicton Gardens, The Palm House at Kew Gardens by Richard Turner and Decimus Burton, and Joseph Paxton's Crystal Palace. A profound aspect of the great conservatory structures in Europe and England is the dramatic departure from masonry architecture, where heavy masonry walls act as load bearing structure, instead adopting structural iron framing systems allowing for far greater design freedom. The weather barrier was provided merely by a non-structural cladding material laid over and supported by the framing system; a building skin. Glass as building skin was made possible by the age of steel that emerged from the industrial revolution. Cast and wrought iron replaced the lead bars of the Gothic cathedral windows, allowing for the construction of complete enclosure framing systems comprised of slender metal components. Glass was simply laid over and attached to the frame. Suddenly, building enclosures could be transparent, clad entirely in glass. This development set the stage for the Modernists of the 20th century, and the advent of high-rise towers sheathed in glass.

In the early half of the 19th century the conservatory structures flowered under the influence of such designer-gardener-builders as JC Loudon and Joseph Paxton. The conservatories were impressive as a performance-based architecture responding to the demanding requirements of the exotic botanical species they housed, entirely free of the prevailing conventional masonry architectural style of the period. With little in the way of prior art, these pioneers in this new building form proceeded intuitively with the development of the structural systems. They developed slender wrought iron bars and methods to connect them. The structures were so minimal that literature of the time describes the structures as deflecting in slight breezes until the glass was affixed to the fame. The glass was actually being used as a structural element of the enclosure as a stressed skin. These innovators were far ahead of their time in using glass as a structural element, even before the advent of glass-strengthening techniques. (Wigginton 1996, pp.34-37)

While the building form represented by the conservatory structures quickly transcended its early botanical applications to become an important public structure type, perhaps as best represented by the Crystal Palace, there was no real integration of this building form with the conventional architecture of the time. (There are certain relevant exceptions, primarily involving the glass roofs of train halls and shopping arcades such as Pennsylvania Station, New York, 1905-10, McKim, Mead and White, and the Galleria Vittorio Emmanuele II, Milan, 1865-7, Giuseppe Mengone, but these represent unique building forms themselves that typically interface rather than integrate, with the adjacent architecture.) The great conservatories were all free-standing, autonomous buildings. Certainly they inspired, as they continue to inspire new generations of designers even today. Equally certain they fueled a continuing increase in the desire for and use of glass in architecture. (Wigginton 1996, pp.47-48)

Meanwhile, in the great cities of Europe and America, density and land values were creating pressure to build upwards, pushing the limits of the predominantly masonry building practices of the time. By the end of the 19^{th} century, a Chicago engineer named William Jenney had devised a method of steel framing and thus gave birth to the technology of high-rise buildings. Exterior walls became functionally different in a quite significant way; as with the earlier iron framing systems used in the conservatory structures, they were no longer load bearing, carrying only their own weight over a single story span. They need no longer be masonry (although masonry remained the predominant wall material for years to come); in fact masonry was an inappropriate material for most of these new applications because it was unnecessarily heavy. (AAMA n.d.)

1.2.5 The Advent of the Curtain Wall

This use of glass as a predominant element of the building facade exploded in the 20th century fueled by Modernism, especially post-war Modernism, and the development of steel frame structures and curtain wall cladding systems. After some initial stunning architectural innovations like the Bauhaus Building in Dessau by Gropius in 1926, the Seagram Building in New York by Mies van der Rohe in 1954, and the Lever House by SOM in 1952, this ultimately led to a plethora of cheap, sterile, and poor performing glass clad towers populating, some would say polluting, the skylines of the world's major cities; what Wigginton (1996, p.96) refers to as, "a sort of 'International Style' without the style." Regardless, it significantly boosted the glass industry.

Flat glass for architectural applications is produced today through the float process. Invented by Alastair Pilkington (no relation to Pilkington the glass producing company) in the 1950's, the process was commercially viable by the early 1960's. The float process provides the convenience of making glass horizontally, similarly to the older casting processes. The bottom side of the cast glass sheet suffered from poor surface quality that could only be remedied by expensive grinding and polishing. The float process solved this problem by floating the liquid glass on a bed of molten tin. The resulting high quality product is flat, smooth and transparent. The float process provided the fabrication technology required for the next boom in the use of glass in architecture, replacing the drawn glass process of the time.

Glass, as discussed above, was becoming increasingly available and economical. The new steel-framing technology opened the door to the dramatic and extensive use of glass in building skins. But designers were struggling with solutions to replace the masonry practices dominant at the time. In the early 20th century, aluminum was becoming available in larger quantities and lower prices. By the 1920's it was beginning to see significant use in architecture. Visionary designers produced a relatively small number of landmark buildings over the first half of the century utilizing these new materials and processes, paving the way for the paradigm shift that was to come in the 1950's, when the modern curtain wall industry was born.

Booming post-war economies in America and Western Europe resulted in an explosion of high-rise curtain walled structures. Unfortunately, many of these lacked both the design sensitivity and the quality of the earlier work. The technology was quite effectively hijacked by the commercial developer, who found in it a low cost solution for maximizing leaseable square footage in a given building footprint. The result was a plethora of rather sterile looking, water leaking, and energy hogging glass towers redefining the skylines of the world's great cities. (Wigginton 1996, pp. 95-96)

1.2.6 Curtain Wall verses Structural Glass Facades

While closely related, there are differences between curtain walls and structural glass facades. Curtain walls typically span only from floor to floor, the primary spanning member being an aluminum extrusion. Curtain walls are separate from the building framing system, but attached to and supported by it. Aluminum extrusions are typically used to construct a frame that secures some type of panel material, ranging from glass to composite metal panels and stone. The panel structure may be expressed, or completely covered on both the inside and outside of the building. Curtain walls most frequently employ a dry gasket strategy to provide the primary weather seal.

Structural glass façade technology embraces a design objective of high transparency and expressed structure, and incorporates some type of glass as the cladding material. The facades are used in longer spanning applications where an aluminum extrusion as the primary spanning member becomes impractical or impossible. A variety of structural options are available to accommodate the spanning conditions, as described in Chapter 2. The structure is exposed, and thus becomes a dominant element of the façade design. Great attention is typically placed upon the detailing and craftsmanship of the supporting structure. There has been a consistent evolution towards a dematerialization of the facades. This resulted in the increasing use of tension elements in the structural systems, leading to the use of pure tension based systems like cable nets. Frameless glass systems, often called point-fixed or point-supported systems, are quite often used for the same reason. Framed panel or stick type systems utilizing aluminum extrusions are also used quite effectively in structural glass facades, but they are integrated in design with the structural systems that support them, and are substantially different than curtain wall systems.

Another big difference is in the strategy employed to provide the weather seal. Contemporary curtain wall systems employ complex extrusion designs that provide a rainscreen and a supposedly pressure-equalized cavity, or cavities, to control water penetration and air infiltration. The design is intended to allow pressure differences to equalize within the extrusion cavities so that even if water penetrates the rainscreen it will drain out of the system and not penetrate to the inside. Consistent with a minimalist approach, the weather seal typical of the glazing systems used on structural glass façades is a slender joint of silicone, field applied between adjacent glass panels; as with the structural systems, nothing is hidden. Today's silicone sealants are high performance materials providing an effective, reliable, and durable weather seal.

1.2.7 The Glass Market Today

Architectural glass today is certainly a commodity item. Used throughout most of its history with at least some premium, glass today is often used because it is the cheapest cladding option for certain applications. Prominent architects such as Steven Holl have complained about being effectively forced to use glass in certain instances due to budgetary considerations.[4] According to the Freedonia Group, an industry research organization, global demand for flat glass will rise 5.2 percent annually through 2010. The dominant construction market will grow the fastest, driven by greater use of value-added glazing products and by architectural trends favoring more natural lighting.

Pilkington, one of the oldest and four largest global glass producers pegs the flat glass market for 2006 at 44 million metric tons with a value of approximately USD 23 billion. Approximately 70 percent of this is used in architectural applications, with the majority of the balance used in automotive, furniture, and interior applications. Demand over the past two decades has outstripped GDP. Europe, China and North America account for 75 percent of global demand. The fastest growth in demand is occurring in developing countries in Asia, especially China and India. Just four global producers are responsible for 66 percent of the world’s flat glass output; NSG Group (Pilkington, British), Asahi (Japanese), Saint-Gobain (French), and Guardian (USA). The industry was running at about 90 percent capacity in 2006, largely influenced by demand from China, a trend expected to continue for some years to come. Over the long term, the overall market has been growing at about 4 to 5 percent per year, and similar growth is expected to continue at least through 2010. (Pilkington 2007)

Economic growth is the principle factor driving demand in growth for architectural glass products. Other factors influencing demand include legislation, regulation, and general concern over such issues as safety, acoustic and energy performance. These other factors can both negatively and positively affect demand. Legislative mandates for energy performance in buildings, for example, can potentially result in the reduced use of glass as it is replaced by materials and wall systems with better thermal behavior. This is not

[4] From comments made by Holl during a lecture at the Engineered Transparency Conference, November 2007, Columbia University.

necessarily the case, however. Northern Europe, where energy prices have been historically much higher than in North America, began instituting legislative mandates over 20 years ago. Rather than restrict the use of glass, this action fueled a burst of technological development that yielded such innovations as dual-skin and building system integrated (intelligent) glass facades, with quite the opposite result; Germany's major cities are populated with new buildings featuring the most advanced clear glass facades in the world. As a consequence, Germany and northern Europe have the strongest demand for value-added glass products; glass that is post-processed by some combination of insulating, laminating, strengthening, coating, fritting, and the like, to improve some aspect or aspects of performance. (Pilkington 2007)

Burdened with artificially low energy costs (not reflecting the true cost to the environment, the cost of oil-dependency, and other factors), North America has been slow to adapt to the changing conditions that are now bringing rapid climate change and oil prices surpassing USD 100 per barrel. Recent programs such as LEED, a set of evaluation criteria for rating the energy efficiency in buildings, are gradually being adopted, and some governmental organizations are beginning to mandate some level of LEED certification, although the lack of legislated performance requirements has resulted in slow adoption of the system by the general building industry. However, as in Germany, despite the issues created by increasing performance demands, designers continue to specify increasing amounts of glass in buildings. And as in Germany, the demand for value-added products to address the issues referred to above is increasing. In fact, the global demand for value-added products is growing faster than the base market for flat glass, an important measure of the increasing sophistication of architectural glass facades in general (Pilkington 2007).

1.3 Market Forces and the Evolution of Structural Glass Facades

1.3.1 Early Development

To a notable extent, growth in the architectural glass market has been driven by a chain of high profile applications with widespread impact, especially starting with the great windows of the Gothic cathedrals in Europe followed by the transition to a widespread secular use of glass in buildings and such milestones as Hardwick Hall, 1590-7 by Robert Smythson and the new wing at Hampton Court, 1689-96 by Sir Christopher Wren. Many if not most of these milestone projects were made possible or even inspired by advances in glass making technology, but it is ultimately the architectural manifestations that inspire broader adoption and use. This is nowhere more obvious than in the great burst of glass conservatories in 19th century Europe and England that so influenced architecture and set the bar for decades to come in glass structures. Wigginton (1996, pp.36-37) comments that the burgeoning glass design movement was international, with designers and patrons traversing Europe to keep an eye on the competition. Rohault de Fleury started the Jardin des Plantes project in Paris in 1833, and traveled to England to research the state of the art there. Joseph Paxton, on the other hand, visited the Fleury's project accompanies by his employer, the Duke of Devonshire, three years before producing the Great Chatsworth Conservatory. These projects in turn were the source of inspiration and technological infrastructure necessary for the realization of the Crystal Palace in 1849.

These conservatory structures along with related structures they inspired, such as some of the great train halls, represent a contextual technology-based building form, an industrial architecture born of the technological innovations of the industrial age of the 19^{th} century. This architecture directly inspired and informed the Modern Movement starting in the last decade of the 19^{th} century that led to the International Style of architecture. The developers and practitioners of this style, Walter Gropius, Mies van der Rohe, Peter Behrens, adopted glass as a primary architectural material and began to master its integration into the new Style. They explored the various properties of glass; transparency, translucency, and reflection as none before them, and architecture became increasingly focused on the manipulation of light, shadow, reflection and view.

Figure 1.6 The Gage Building, 1898 Holabird and Roche with Louis Sullivan (Sullivan n.d.).

Other technological innovations of the industrial age were equally important to the new Style, among them the evolution of cast and wrought-iron structures leading into the early multi-story steel structures realized in the decades around the turn of the 20th century in Chicago, such buildings as; The Gage Building, 1898 by Holabird and Roche and Louis Sullivan, the Carson Pirie Scott Store, 1899-1904 by Louis Sullivan, and the Reliance Building, 1894, by DH Burnham and Company.

Figure 1.7 Carson Pirie Scott building, Chicago, Louis Sullivan architect, 1903 (Library of Congress 1903).

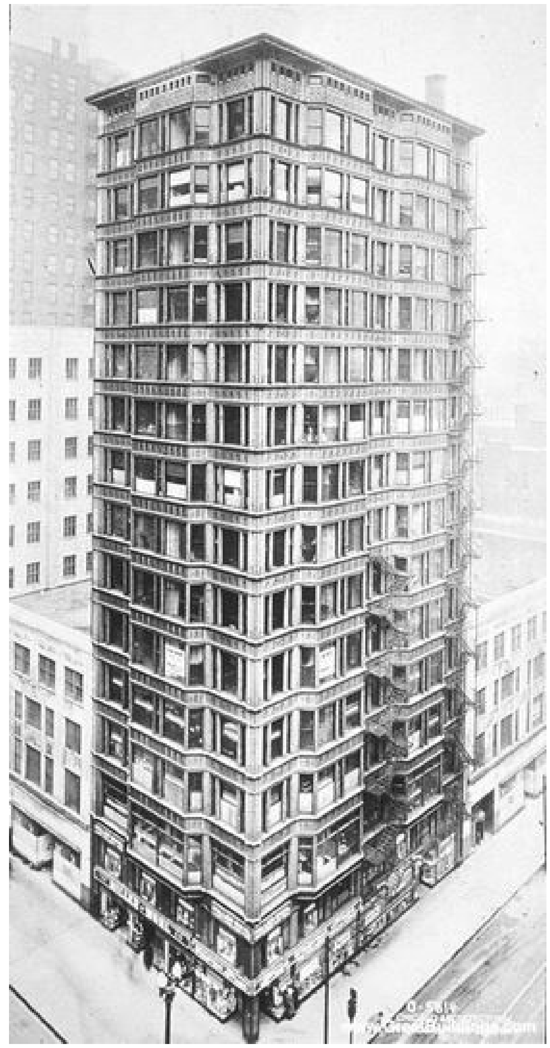

Figure 1.8 Reliance Building, Chicago, 1894 (Library of Congress 1890).

Throughout, interest in the design community repeatedly cycled back to the theme of enhanced transparency and light-drenched architectural spaces. The sources of inspiration were not always completed works. Many brilliant concepts by Loudon and Paxton went unrealized, but powerfully influenced what was to come.

Figure 1.9 Maquesse Glass Skyscraper, Mies van der Rohe, 1922 (Glass skyscraper n.d.).

In the same manner, Mies van der Rohe's visionary Model of the Glass Skyscraper Project, 1922, laid bare the potential for an entire new architecture of high-rise steel and glass structures, although the glass technology necessary to realize the vision would not be available for another half century. Along the way came the development of the curtain wall as a high-rise cladding system and such milestones as the Seagram Building, New York, 1954-8, and 860 Lake Shore Drive, Chicago, 1948-51, both by Mies van der Rohe, and the Lever House, New York, 1951-2, by Skidmore Owings and Merrill. The age of the glass and steel tower had arrived.

Figure 1.10 860-880 Lakeshore Drive, Mies van der Rohe, 1951 (City of Chicago 1951).

Figure 1.11 The Seagram Building, Mies van der Rohe and Philip Johnson, 1954 (Seagram Building n.d.).

Figure 1.12 Lever House, Gordon Bunshaft SOM, 1951 (Shankbone 2007).

The diffusion of glass into the building arts was not confined to the urban or commercial sector. Mies van der Rohe’s Farnsworth House, 1951, coming 100 years after Paxton’s Crystal Palace, became a symbol of another kind, an icon of Modernism, and the embodiment of the diffusion of architectural transparency to the level of the individual residence. In the same timeframe, the Case Study House Program sponsored by John Entenza’s Arts & Architecture magazine, which started in 1945 and ran through the early 1960’s, served to popularize large glass areas in residential architecture in a manner that the more controversial Farnsworth House perhaps failed to do. Residential housing tracts began appearing across America comprised of single-family “ranch” style houses, invariably sporting a newly popular feature, the “picture window.” Residential floor-to-ceiling glass and the concept of blurring the boundary between inside and out dates to this period.

1.3.2 Emergence of Structural Glass Façade Technology

With the French invention of the process for heat-strengthening glass in the late 1920's, all of the material elements were in place for the initial emergence of structural glass facades; steel framing techniques and tempered glass. Yet the exploitation of these materials was several decades to come. By the 1950's the French had also conceived the long-span frameless glass façade. The Hahn system used at the Maison de la Radio in Paris in 1953 used large glass plates 2-stories high, and is one of the very early examples of a suspended glass façade, with the glass clamped and hung from the top edge, and stiffened laterally by the use of glass fins set perpendicular to the façade at the glass joints. (Wigginton 1996, p.102) This concept quickly diffused into the marketplace, resulting in many similar facades being constructed during the 1960's.

A viable prospect for staking out the progenitor of the immediate line of structural glass façade technology is the Willis Faber & Dumas Building, Ipswich, England, 1973-5, Foster Associates. Wigginton (1996, p.110) cites the landmark glass façade of this building as completing a "particularly thematic journey in glass architecture," referring to Mies van der Rohe's 1922 Office Tower concept model referred to above as the start of that thematic journey. The end of one journey can be the start of another, and such a case can be made here. Although not the first glass wall completed by Foster, this project for various reasons has become an icon inspiring future structural glass façade innovation.

Sweeping walls of glass with little or no apparent means of support are so common place now as to attract little attention. Such was not the case as little as 30 years ago. Unlike the Glass Office Tower, the façade for the Willis Faber & Dumas is not about transparency, but reflection, at least during the daytime. The glass is coated with a bronze solar control coating, presenting a solid, uninterrupted reflective exterior face. (The weather seal is provided by a minimal field applied silicone joint.) From inside the wall is almost entirely transparent, and at night with the interior lit, the glass wall virtually disappears. This is one of the early suspended glass walls, with glass fins providing lateral support. As with the Hahn system some 15 years earlier, the glass for the Willis Faber & Dumas façade is hung from above, only instead of a single sheet, six sheets are linked together in a chain from top to bottom, in this respect a truer "curtain" wall than the technology commonly referenced by that term. The façade is 12 meters (39ft) high, and follows an irregular curve in plan. In addition to Foster, Martin Francis played a role as glazing consultant in the realization of this façade, and Pilkington advanced the design by providing the suspended glazing system at a competitive price. The Pilkington system uses a "patch plate" to accommodate the fixing of the glass. From this general timeframe forward, mechanical "point-fixed" glass systems become a driving force in the evolution of structural glass façade technology. (Wigginton 1996, pp.110-115)

Figure 1.13 Willis Faber & Dumas Building, Ipswich; Foster and Associates, 1972 (Cambridge 2000 Gallery 2005).

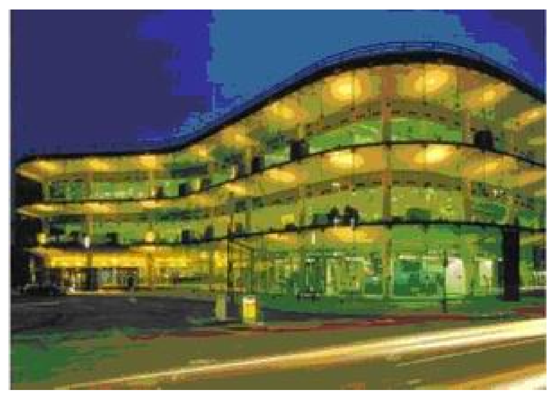

Figure 1.14 Willis Faber & Dumas night image, (Craven n.d.).

1.3.3 Transparency and Beyond

Architecture is intrinsically bound up in the play of light, form and space. Glass is the unique material that opens the interior spaces of architecture to this play of light. It is difficult to imagine contemporary architecture without glass. The three most significant visual properties of glass are transparency, translucency and reflectance. These properties dominate the reason glass is used as well as the manner of its use.

Materials that are optically transparent can be seen through. They are clear. Air can be transparent, as can water. Few solids are transparent; certain plastics and glass. Glass is such a unique material that arguments persist over its fundamental properties; is it a liquid or a solid? The super-cool term "supercooled liquid" persists as a description of glass. Wigginton (1996, p.62) reasonably refers to glass as a transparent amorphous solid. The myth that medieval window glass shows signs of thickening at the bottom because of material flow have been debunked, the thickening recognized as characteristic of the glass-making processes of the time. Wigginton is in agreement with Gibbs (1996), but in describing the physics and thermodynamics of glass, Gibbs concludes that the answer to whether glass is a liquid or solid is not so clear, and that different views can be justified from the standpoint of molecular dynamics and thermodynamics. Still, the differences are largely semantic, and in the absence of other reasonable determinants glass is defined by its perception as a solid. Glass is the closest thing man has to the "force fields" of science fiction lore. Air and water cannot provide security and separation from the elements as can glass. Transparency is the most profound property of glass, and was regarded as a mystical property in its early history as a manmade material.

Structural glass facades are often referred to and marketed as "high-transparency" structures. It has been the pursuit of transparency in these long-span façade structures that has driven the evolution of structural glass façade technology. The various techniques discussed herein to dematerialize the structural systems supporting the facades are an attempt to enhance the fundamental transparency of glass itself. Peter Rice (1994, p.107), the engineer for the Les Serres at La Villette commented it was the hope of the design team, "…that the transparency of the main material would lead to a feeling of 'non-materiality' and, although separated from the structure, the public would feel a sense of communication through the transparent skin." One of the more common building types to make use of high-transparency structures is civic architecture; civic centers, courthouses and other governmental structures where the transparency takes on another connotation, a double-entendre. A quick Google of the word "transparency" will reveal that most hits involve civic or organization reference to open communications, visible processes, especially of governance, as a reflection of accountability and citizen participation.

After three decades of the pursuit of transparency and the many spectacular projects that have resulted from this pursuit, evidence suggests the dialog is gradually beginning to shift to one of "beyond transparency." At a conference held at Columbia University in September of 2007 entitled "Engineered Transparency" dedicated to the technology of glass and glass architecture, architect Steven Holl, a featured speaker at the event proclaimed his disinterest in transparency. Holl spread his arms wide to represent a scale with opacity on one end and transparency on the other, and indicated with a gesture the roughly three quarters of the scale he was interested in, starting at the opacity end. Over a year earlier, in April of 2006, The *Architect's Newspaper* published an article titled 'Beyond Transparency' *(Guiney 2006)*. The article featured the Toledo Museum of Art Glass Pavilion, among other projects. This very same project was the most prominently featured at the Engineered Transparency conference, with the architect, Kazuyo Sejima of SANNA delivering the keynote address.

Transparency is the property that has pushed glass to its prominent position as an architectural material, and structural glass façade technology along with it. It will always be the most profound attribute of glass, and will find continued use as such. However, another property of glass and the potential it holds for architecture are of growing interest to the design community. it is controlled transparency and translucency that represent the fertile future ground for glass and glass façade evolution.

Opacity is the opposite of transparency; no light passes through an opaque material. Glass can be made opaque. Spandrel glass is opaque glass often used in curtain wall systems over areas where clear glass, or vision glass as it is sometimes referred to, is undesirable, as in the area between floors in a high-rise structure. Most commonly, a ceramic frit material is applied to the glass and fused to the surface in a tempering oven. Is use in this manner provides a continuous and consistent glass surface, which points out another noteworthy attribute of glass; the surface quality is largely impermeable, durable and relatively easy to maintain.

Between transparency and opacity lies the broad spectrum of translucency, the declared domain of interest for Steven Holls, among others. Translucent materials allow light to pass through, but diffuse the light by some means in the process. Translucent materials cannot be seen through as transparent materials can, do to the diffusion of parallel light rays that provide optical clarity. While no image is transmitted, the amount of diffused transmitted light can be even more than that transmitted by a transparent material. Transparent and translucent materials are rated by the percentage of light they allow to pass through, a property called transmittance discussed in the following Chapter. Various techniques can produce translucency in glass, among them; melt chemistry that produces clouded, milky glass; sandblasting or coating of one or both surfaces of a glass pane; or the use of translucent plastic laminates in the making of laminated glass products. The quality of light and degree of translucency vary quite significantly among these different processes.

Figure 1.15 Nelson-Atkins Museum of Art, Kansas City, Steven Holl Architects, completed 2007 (Ryan 2007).

Translucency in a material is not necessarily obvious. A creamy white translucent glass may appear white and quite opaque when viewed from a reflecting surface with the light source on the same side as the viewer. But when the same glass is viewed with the external light source extinguished and an internal light source in its place, the material appears to glow. Holl used this property of glass to dramatic affect in his recently completed Bloch Building for the Nelson-Atkins Museum in Kansas City. Five translucent glass blocks, which Holl calls lenses, are built from 6,000 panels of sandblasted glass, and illuminated from the inside by florescent lamps such that the structures glow through the Missouri night. (Christy 2008)

As with the transparency discussion above, the control and adaptability of these properties in glass materials is the direction of the future. Electrochromic and Photochromic glass materials are capable of changing their property of transparency or translucency in response to changing light levels or the flip of a switch. These so-called "smart" materials hold the future promise of significantly improved thermal performance as components of the building skin.

It was not until the later half of the 20th century that the pursuit for transparency emerged in the form of long-span façade designs fully integrated into building architecture.

1.3.4 High Profile Applications

The evolution of structural glass façade technology can be viewed in a series of high-profile applications. A few of the most significant of these follow.

Willis Faber & Dumas Building

Ipswich, England; Foster Architects, designed 1971-2, completed 1975.

See Figure 1.13 and Figure 1.14 above.

This project, discussed earlier and mentioned throughout this thesis is significant in many respects. It is one of the very early examples of a frameless, suspended glass fin supported façade system. It represents the productive partnership between industry and architecture with the first application of a new product technology provided by Pilkington, a leading glass producer. It popularized this façade type leading to a proliferation of applications. It represents a viable candidate for defining the birth-point of structural glass façade technology as articulated in this thesis. Wigginton (1996, pp.110-115) provides a good case study of this project.

Figure 1.16 Garden Grove Church; Johnson/Burgee architects (Nardella 2007).

Garden Grove Community Church

Garden Grove, California; Johnson/Burgee Architects, designed 1977-8. constructed 1978-80.

Popularly known as the Crystal Cathedral, this building obviously finds its roots in the great iron and glass conservatory structures of mid 19th century Europe. Predating the development of the lighter tensile structures to emerge over the next decade in façade applications, the design here makes use of a space frame structural system. The structure is clad entirely in reflective glass using a panel system where the single-glazing was silicone-sealed into and aluminum frame under factory-controlled conditions. Panel systems are discussed in the following

Chapter. This system includes operable panels that provide natural ventilation to this quite large enclosure. (Wigginton 1996, pp132-137)

Figure 1.17 Cable trusses of Les Serres, Paris; Adrien Fainsilber with RFR (author's image).

Glass Walls (Les Serres)

Parc de la Villette, Paris; Architect Adrien Fainsilber with Rice Francis Ritchie (RFR), designed 1983, constructed 1984-6.

This was a seminal project for structural glass façade technology incorporating many innovations and pointing out the direction for future work. This project is covered in wonderful detail in Rice and Dutton's book Structural Glass (1995), and highlights the remarkable contributions of RFR to structural glass façade technology.

The Pyramids at the Louvre

Paris; Pei Partnership architects with RFR, designed 1983-5. constructed 1986-8.

Figure 1.18 Louvre Pyramid by night, Paris; Pei Partnership architects (Goran 2007).

Building on what was learned with Les Serres, Peter Rice and RFR once again led the pursuit of transparency. The structure is one of the first to make use of a “super clear” virtually colorless glass further discussed in the following Chapter as low-iron glass. The structure is clad with a fully perimeter supported structurally glazed system, where the glass is fixed through the use of a structural silicone adhesive alone. The Pyramid served as a great popularizer of the emerging new technology of structural glass facades. Wigginton provides a case study of this project also (1996, pp. 126-131).

Figure 1.19 Banque Populaire de l'Ouest; Decq and Cornette architects, 1990 (DuPont 2002).

Banque Populaire de l’Ouest

Rennes, France; Odile Decq and Benoit Cornette architects, completed 1990.

Rice and Dutton (1995, p.116) comment that this project, “…furthers the research conducted into suspended glazing and the idea of transparency…" The project is also one of the first to explore the concept of dual-skin facades with large thermally treated cavities. The structure is exterior to the glazing system and quite complex in design. The structure is both double and single glazed with point-fixed glass supported from cast stainless spider-type fittings.

Figure 1.20 Cable net at the Kimpinski Hotel, Munich; Murphy/Jahn architect with Schlaich Bergermann engineers (photo courtesy of Schlaich Bergermann).

Kempiski Hotel

Munich; Murphy/Jahn architect with Schlaich Bergermann Partners, completed 1993.

This is widely recognized as the first cable net façade, conceived by engineer Jorg Schlaich of Schlaich Bergermann Partners, a leading engineering firm in the development of structural glass facades. Another bold and seminal structure, the cable net is simply comprised of prestressed cables in a planar configuration. The glass is clamped to the net and butt-glazed with silicone to provide the weather seal. The structures enclose opposing sides of the Hotel lobby. (Holgate 1997)

Figure 1.21 Channel 4 Headquarters, Richard Rogers Partnership, 1994, (Boake 2007).

Channel 4 Headquarters

London; Richard Rogers Partnership architect, completed 1994.

This building features a remarkable curved suspended glass membrane supported by a complex cable structure. The glass is point-fixed using an articulated H-shaped cast fitting designed to accommodate the façade movements. (Rice & Dutton 1995, pp.136-137)

This is just a small sampling of a few early milestone projects and not a rigorous overview of the many fascinating applications that populate the technology of structural glass facades.

1.3.5 Accelerating Demand and the Infusion of Innovative Technology

The leading edge of glass technology has always been associated with a significant cost premium, and there have consistently been clients willing to pay the price. Indeed, an ostentatious display of glass has been associated with wealth from the days of the luxurious Roman villas in Pompeii. A later example is the new wing at Hampton Court by Sir Christopher Wren c. 1690. A new cast plate glass had just become available featuring higher surface quality and larger sizes, but at a cost nearly 23 times that of the conventional crown glass of the time. (Wigginton 1996, p.28) Regardless of the cost, it was used by Wren at the Hampton Court as a symbol of status. However, the cost did restrict the use of the larger panes to a smaller feature area of the building, a common practice today with the application of structural glass facades where larger budgets are confined to lobby and public area facades.

Another example is suspended glass facades, first developed by the French in the mid 20th century, and only made possible by their earlier invention of heat-strengthening processes for glass. The Hahn system referred to earlier was used in the 1950's by Henri Bernard in the Maison de la Radio in Paris. This led to a number of systems introduced by both industry producers and designers, and a number of built façade structures in the 1960's and 1970's that established suspended, fin-supported glass walls as a viable façade technology. Fin-supported glass facades thus initiated the evolution of structural glass façade technology as characterized in this thesis, and are to this day perhaps the most commonly found type of high-transparency façade.

The success of glass technology can be attributed at least in part to the persistence of a client base willing to pay a premium for innovative designs using the very latest the technology has to offer. The newest structural glass façade technology employs cable net supporting structures. A review of the high-profile applications, as exemplified by recent buildings completed in New York City, the Time Warner building at Columbus Circle by SOM, the Freedom Tower and 7 World Trade Center with David Childs, SOM, and glass specialist designer James Carpenter, reveals this premium technology integrated as feature elements in the most public areas of the architecture.

As these high-profile projects are completed they typically generate some significant media coverage, both in local and professional media sources. The growing interest in and demand for cable net structures is typically reflected in one of the many articles to feature the cable net wall at the Time Warner Center in Manhattan (Kenter 2007, p.2), "Sylvie Boulanger, executive director, Quebec Region of the Canadian Institute of Steel Construction, says presentations on the technology usually have Canadian architects and engineers champing at the bit to get started."

> *"You can't order a kit from Canadian Tire," says Boulanger. "They are highly personalized to the project. Many architects are very excited by these structures, engineers are warming up to them, manufacturers are starting to adapt their pricing and specialty erectors are emerging. It will just take a slight cultural shift before we see such projects built here."*

The examples above exhibit a common trend. The luxury of window glass by the Romans became a commodity item in 18th century Europe. Christopher Wren's premium glass had a maximum dimension of approximately 30 inches; today's commodity float glass is commonly produced at 130 inches. Fin-supported glass walls introduced in the mid 20th century have become commonplace in the architecture of today. These products were introduced to the market as cutting-edge technology and were embraced in limited applications at a premium cost. They all subsequently matured as applications increased and costs dropped. The same can be expected to happen to varying extents with all the structural glass façade types, including cable nets. There will always be innovative custom designs incorporating these various technologies that will come at a premium cost, but the basic technology in a simplified form will become more competitive in cost and come into wider use in the building arts.

Wren, Bernard, Childs and Carpenter are what Everett Rogers (2003), the author of a theory on the diffusion of innovation in culture, would call "early adopters." Early adopters in this instance are wealthy clients; individuals, enterprises or institutions, seeking the status of innovation and high technology as part of their building program. They typically seek out other early adopters, design innovators known for their work with the emergent technology. These early adopters are a very small percentage of the larger design community, as their clients are a similarly small percentage of the property development community. As can be seen, the early adopters and their projects tend to be very high-profile, very visible to the rest of the construction industry, and even the general public. There is another tier of designers and developers below them inspired by emerging innovations and aspiring to use the new technology. These Roger's refers to as "secondary adopters," the tier below them as "tertiary adopters," and so on.

Diffusion of innovation theory recognizes that propagation through the adopter tiers can be facilitated, but suggests that the respective levels are unlikely to respond until the tier above has adopted. People tend to imitate their influences and thus adopt from them. There are many factors impacting adoption, these depending upon the nature of the innovation, which range from food to fashion to building materials; virtually all aspects of culture. The history of glass demonstrates that the primary factors influencing the diffusion of innovation were accessibility and cost. Cost is often a predominant factor in the adoption of high technology, be it cell phones, HDTV, or building materials. Cost has been a significant barrier to the wider adoption of photovoltaic technology, for example, and its impact on the progress of glass technology from time to time is well documented (Wigginton 1996).

Accessibility of the technology is a broader factor that affects the primary parties involved in the implementation of the technology differently, these parties being the producer, the designer, the installer, and the owner/developer. Production requires access to the required techniques and formulas, know-how that provides for the making of the materials; trade secrets. These secrets have been jealously guarded since the beginning of glass-making. Early Venetian glassmakers were threatened with death if they were to leave the guilds in which they worked (Amato 1997, p.35) Today the international patent system is the inheritor of this concern, and while protecting the investment of the innovator, can affectively slow the diffusion of the innovation. In a certain respect, the producer is the top tier early adopter. Even if a designer or end user had envisioned the suspended glass wall earlier, they were prevented from adopting such technology until the French invented the process to heat-strengthen glass in 1928 (Wigginton 1996, p.55). The fact that the first suspended glass wall was not constructed until the 1950's evidences the tendency for materials innovations to drive design innovation, albeit with some lag time on occasion. Pilkington, one of the oldest glass producers and one of the four largest, together responsible for 66% of global glass production (Pilkington 2007), became an early adopter of suspended glass wall technology by developing their own system and offering it to the marketplace. The Pilkington suspended glass system was one of the first commercial products available to the building community for glass-fin supported facades. The fact that a major glass producer was offering such a system complete with warranty had a major impact on the use of such systems.

The use of point-fixed glazing systems in the North American market has been limited by the lack of a domestic fabricator.[5] Until very recently there was not a single glass fabricator providing a product warrantee for point-fixed applications. Glass for point-fixed applications was and is available with warrantee from European sources, with Pilkington providing an industry leading 12-year warranty. Saint Gobain, the French glass producer, will provide a similar product and warranty. It was not until 2005 that Viracon, the largest glass fabricator in the US (unlike Pilkington and Saint Gobain, Viracon is not a glass producer, but provides such fabrication services as laminating, insulating and coating), began offering a competitive product. Any project requiring point-fixed glass from a quality producer providing an industry standard warranty before that time required the importation of glass from offshore sources. The obvious cost impact and scheduling logistics certainly slowed adoption to some extent.

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[5] The use of point-fixed glazing systems in the North American market has been slowed by several factors, not the least of which is the litigious nature of US society, especially the domestic construction industry, and the resulting risk aversion of building developers and even design professionals with respect to new or innovative technology. One need only visit Europe or the developed or developing urban areas of Asia to witness the widespread diffusion of point-fixed glazing systems and structural glass façade technology in these areas with an underdeveloped legal profession. The acceptance of this technology is happening gradually in the US as increasing application emerge in high-profile applications, such as the recently completed 7 World Trade cable net wall discussed elsewhere herein.

Once the product is available the next tier implementer is brought into play; the façade designer or architect. Having the material is not enough. The designer must have the information and tools that inform the design process. The know-how must be learned or discovered. The tools must be acquired or developed and the technique of their use learned. Alexander Graham Bell was the first to discover and experiment with space frame lattice structures at the turn of the 19^{th} century, but it was not for another 60 years that the tools necessary for implementation of the structures in the building arts were developed in the form of computer-driven finite element structural analysis software, a byproduct of the NASA aerospace program.

This was the power of Pilkington's system; not only did it make the required materials available for implementation; the product was accompanied by deep technical support and product documentation that greatly facilitated the design and installation process.

The designer's work with respect to structural glass facades is most often comprised of schematic design followed by some level of design development. As with the Palm House at Kew Gardens, the final design, detailing, engineering and production design is accomplished by a contractor skilled in such work. With the Kew Gardens structure it was Decimus Burton acting as architect, but engineer Richard Turner acting as what today would be termed the design/builder. (Wigginton 1996, pp. 34-37)

The potential exists to positively influence the diffusion of structural glass façade technology into the broader marketplace by increasing the inclusion of the technology in the design output of the building designers. It is the hypotheses of this thesis document that this can be accomplished by providing resources and tools to the architect that facilitate the conceptual design of structural glass facades.

1.3.6 Practitioners

The following entities comprise the players on the field of structural glass facades.

1.3.6.1 Architects

Design architects are generally responsible for proposing the use of structural glass façade technology, and to the extent successful in securing their inclusion in the design, responsible for the conceptual design of the façade.

1.3.6.2 Engineers

An engineer must be involved to provide engineer-of-record services. This is very rarely the building engineer, most of whom have little or no familiarity with the specialty of structural glass facades. This service is typically provided either by a specialty consultant, or more often, by a design/builder.

1.3.6.3 Design Consultants

Specialty consulting firms do exist with expertise in structural glass facades, although their number is relatively small. Schlaich Bergermann Partners, Werner Sobek Engineering and Design, and Dewhurst MacFarland and Partners are prominent among them.

1.3.6.4 Design/Builders

Most structural glass facades completed in North America have been completed by design/builders that specialize in the technology. This practice is relatively uncommon in Europe. The design/builders pick up where the architect leaves off and provide final design and detailing under the architect’s direction, in addition to final engineering, fabrication and installation services as required. Design/builders include Novum Structures, Gartner and Seele.

Given the long development of the technology in Europe before emerging in the North American market, it is not surprising that the prominent consulting and design/build entities are all European, most with offices in the US. The design/build firms are small and specialized. It is likely that the larger curtain wall companies will adopt the specialty technology at some point. Permasteelisa, the international curtain wall firm has accomplished this through the purchase of Garner. Enclos Corp, the leading US curtain waller, has similarly acquired the capability through the purchase of Advanced Structures Incorporated, a specialty design build firm that pioneered the introduction of structural glass façade technology in North America.

1.4 Structural Glass Facades as Emergent Technology

As has been pointed out earlier, structural glass façades are not new, but the technology is emergent by virtue of accelerating interest and use by the building industry. The technology is increasingly visible and differentiated from conventional glass use in architecture, which is primarily comprised of storefront, window wall and curtain wall systems. The market growth in structural glass façade technology parallels but outpaces the general increased use of glass in architecture.

1.4.1 A Unique and Maturing Technology

The roots of structural glass façade technology extend well back into the 19th century, with first instances of the immediate technology dating back well over three decades. Adoption of the technology has been gradual, however, and restricted to a relatively small portion of the design community. Nonetheless, consideration of the body of completed projects comprising this class of building form reveals a remarkable diversity of design in a variety of applications numbering in the hundreds.

In a common development pattern, seminal projects such as the Hahn suspended fin-glass system or the cable net wall at the Kempinski Hotel spawn imitations; imitations in the most positive sense, each building on the prior work, and each contributing to the maturation of the technology in various ways.

A novel design or use of material in one instance, becomes commonplace after repeated use over time. The basic morphologies, materials and processes that comprise the technology are well tested and of known performance validated from use.

Concurrently, a proliferation of highly visible structural glass facades in the built environment has resulted in the dissipation of perceived risk among the building community and the public, and an increasing acceptance of the innovative technology. As a result, interest in utilizing structural glass façade technology is increasing among architects and their owner-developer clients. The next tier of adopters is primed. Structural glass façade technology is poised for significant potential growth, but barriers remain.

1.4.2 Conventional Technology under Pressure

The architectural glazing market is under pressure. Pressure brings change.

The demands on building systems have increased in many respects over the past several decades. Nowhere are these demands greater than with the building skin. Architects are demanding more design control and more diverse aesthetic possibilities out of the available cladding options. At the same time, as energy costs rise and rapid climate change emerges as a looming threat, developers, architects, and increasingly, government and regulatory agencies are mandating improved thermal performance in building facades.

Little has changed in the fundamentals of curtain wall and storefront system design since their post-war development in the 1950’s and 1960’s. Some performance attributes relative to water penetration and air infiltration are better understood now, and certain modifications based on the rainscreen principle, pressure-equalization, and thermal conduction, have been made on the systems, and unitized systems have enhanced quality and lowered field costs, but the basic technology is unchanged. Limitations in basic curtain wall technology have resulted in new system developments such as dual-skin facades, some examples of which involve structural glass façade technology.

Of course, the performance pressures on the building skin apply to structural glass facades as well, but the technology is more flexible and adaptive than conventional curtain wall. This flexibility provides the potential for the technology to respond to a wide range of aesthetic and performance issues. Because of this, there is the possibility that some adaptation or manifestation of structural glass façade technology will emerge that better address the increasing pressures of the marketplace. This opens up the potential for a partial market conversion whereby a new or hybrid technology will replace some percentage of the conventional curtain wall or storefront market. Such a partial conversion did occur with fin-glass walls in the storefront market, and while still a specialty item with a premium cost, the number of product suppliers and installers has increased, the cost has dropped, and market share continues to grow.

1.4.3 Development Costs Absorbed

Innovative building technology typically comes at a premium cost, and such is the case with structural glass facades, which represent more of a solution technology then a product. Designs are often highly custom, and both design and engineering a matter of some specialty not provided by the mainstream industry. While the use of new and untested materials is rather rare, the adoption of unfamiliar materials from other industries is occasionally involved (as in the adoption of high-strength tension rod technology borrowed from the yachting industry and used initially on the Glass Walls and the Pyramid at the Louvre structures discussed previously).

As any builder knows, there is risk in doing anything he has not done before, and when the doing involves something that no one has ever done before, the risk escalates a rough order of magnitude. The best way to mitigate this risk is to incorporate a rigorous and comprehensive mockup and testing program as part of the project execution. This was precisely the strategy employed by Paxton, the designer-gardener-builder, in the execution of the Crystal Palace. Fabricated components were test-assembled to assure fit-up in the filed. Iron was a relatively new material, and no reliable means of calculating component capacity existed at the time. Lacking sophisticated testing equipment, iron assemblies were field-tested by regiments of soldiers marching in cadence over a stepped testing fixture supported by the iron assemblies prior to installation in the structure. The successful completion of this nearly 1 million square foot structure in a mere 6 months time had much to do with the adoption of these strategies.

Nonetheless, such measures add time and cost to project execution. These measures, however, become increasingly unnecessary as the behavior of the structures and capacity of materials are proven out over a series of completed projects. Innovators and early adopters of the structural glass façade technology have now born much of the development costs. The UBS Tower in Chicago features a cable net enclosure at the ground level public area of the building, the first such structure to be designed in the US (Sarkisian et. al. 2007). Concern among the design and developer teams regarding the use of such new and unfamiliar technology prompted them to require full-scale mockup testing by the design/build contractor. The test was useful in demonstrating predictable deflection behavior to the large group gathered to witness the test at a curtain wall testing facility in Florida, and to validating the water penetration and air infiltration performance of the wall. Such tests can, however, add considerably to the cost of a project.

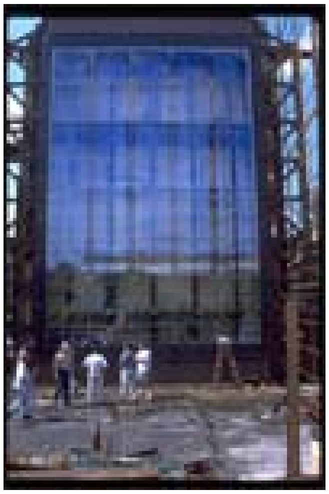

Figure 1.22 USB Tower cable net façade; a full scale mockup prepared for testing (ASIDI).

New or unfamiliar fabrication and installation processes present a similar problem. Vendors and contractors unfamiliar with a building system, material or design will typically add a sizeable contingency to the cost of the job, often as high as 10 to 20 percent or more. Acquiring equipment and expertise will also cause a contractor to add cost to a project. Cable net structures require pre-tensioning of the cables during installation. The magnitude of pre-tension force can require hydraulic equipment to facilitate the process, and there is some technique involved that will be unfamiliar to most installation contractors. But once the equipment and technique are acquired, they can be applied to future projects with little or no significant cost premium.

Figure 1.23 UBS Tower cable net facade; testing underway (ASIDI).

Figure 1.24 USB Tower cable net facade; water penetration test in progress (ASIDI).

It is characteristic of any product cycle that costs will drop as the product matures. This is the case with structural glass facades. The technology will continue to have application in highly custom designs, and such designs will typically come with a cost premium. The value of imitation reveals itself here; repeated applications of a common morphology, such as that used on the UBS Tower, will result in falling cost. While new aspects continue to emerge at the top of the product cycle, the core technology of structural glass facades has matured to the point that a broader diffusion into the marketplace has a distinct potential.

1.4.4 Materials and Services Infrastructure

Mies van der Rohe's Glass Tower was envisioned and modeled in 1922, long before the analytical techniques, materials, or fabrication and installation methods were available to realize that vision. In order for an innovative building technology to diffuse into the marketplace, an infrastructure of designers, engineers, material suppliers and fabricators, and installation contractors must be available to support the work.

The materials involved in structural glass facades, the glass, steel fabrications, rod and cable rigging systems, machined and cast components and assemblies, are all readily available to the building community in a competitive market. There are numerous examples of their use in structural glass facades. Fabricators having worked on past projects understand the unique considerations of exposed structural systems and finishes. Erection contractors familiar with the installation of the various structural system types employed in support of structural glass facades are increasingly available, as are specialty contractors providing complete design/build services. The infrastructure is in place to handle significant growth in this market sector.

A good example is the glass fixing component typically called a “spider” fitting; a stainless steel casting used to fix the corners of four adjacent glass panels to a supporting structure. Pilkington was the first to offer this component as part of their suspended glass product. Most such components were custom designed and fabricated for individual projects. Fifteen years ago, the designer had a choice between using the Pilkington product, or custom designing and producing a fitting. Now there are at least a dozen companies worldwide offering off-the-shelf glass-fixing components of amazing variety.

1.4.5 The Project Constituents

The core constituents involved in a structural glass façade project are the owner/developer, architect, building engineer, and perhaps a façade consultant and/or a specialty consultant dealing solely with the structural glass façade. Owner/developers have been exposed to the work of the innovators and early adopters, and are increasingly interested and amenable to considering the use of structural glass façade technology, generally within some budgetary context. The building engineer is important in managing the interface between the structural glass façade and the perimeter support provided by the building structure.

Today, the primary driver of the diffusion of this technology into the broader marketplace is the design work coming out of the architect's offices. The innovators and early adopters typically introduce their client, the owner/developer, to the technology and convince them of incorporating some aspect into a building design. This group of innovators and early adopters is relatively small; the body of completed works is largely from the same small group of practitioners. This group is comprised largely of architectural offices with deep resources including façade designers, industrial designers and even engineers on staff. Such firms as Foster Associates, Renzo Piano Building Workshop, SOM, Murphy Jahn Architects, have the resources internal to the firm to generate highly sophisticated structural glass façade designs.

The most effective way to diffuse the technology into the marketplace is to enable another tier of adopter, arguably secondary adopters. Many structural glass façade projects have featured prominently in the media over recent years, spawning much interest in the design community. There are many architects interested in using the technology and confronting their lack of familiarity with it. Many of these architects do not have access to the resources characteristic of the early adopter group.

The early adopters often employ the services of a specialty consultant, one of a handful of firms specializing in structural glass façade technology. These firms are most frequently called on to provide conceptual and schematic design services, and some level of design development. The cost of these consultants, however, represents a barrier to the diffusion of the technology; projects budgets tend to be tighter with the potential secondary adopters and the cost of the specialty consultant can be prohibitive.

1.4.6 The Opportunity for Growth

The potential for growth is apparent from the previous discussion. The opportunity lies in the convergence of growing demand and a mature technology capable of delivery of increasingly competitive products to a growing marketplace.

The opportunity for catalyzing this growth lies in enabling a tier of secondary adopters. The key to accomplishing this is to first establish an appropriate project delivery method that minimizes the requirements laid upon the architect; a strategy that the architect can embrace. Any delivery strategy however, will require some level of expertise on the part of the architect. Once the strategy is understood and accepted by the architect, they must then be provided with the information, tools and resources necessary to implement the strategy; a form of technology transfer.

It is likely that the designs produced from such a strategy will be simpler, less costly, and more widely appropriate both functionally and economically to a diversity of commercial building types, but this is exactly what is needed to diffuse the technology into the building marketplace.

This also highlights the opportunity for educators in architecture to impact the built environment by developing and disseminating technology, tools, technique, and other resources regarding the building skin, an increasingly important building system in modern architecture. Nothing so profoundly impacts both the aesthetic and functional performance of a building as does the building skin.

1.4.7 The Threat to Growth

Threats to the diffusion of the technology are many and significant.

1.4.7.1 Security Concerns

Primary applications for structural glass facades include many public structures such as airports, courthouses, hotel lobbies, office building lobbies, and the public areas of various other government buildings. There was much speculation within the design community in the days following the destruction of the World Trade Center, when many such projects were put on temporary hold, that the days of long-span glass facades were over. This proved to be wrong, and in fact quite the opposite happened. Still, the concern is legitimate in the face of repeated terrorist attacks. The industry has responded to this threat by developing glass systems resistant to extreme loading conditions, including impact and blast loads. It appears that the highly flexible behavior characteristic of structural glass facades may represent a distinct advantage in these circumstances.

1.4.7.2 The Economy

Like most industries, growth can be dramatically impacted by general economic conditions. The commercial construction industry has been on a long run of positive growth. A negative change in the overall economy could impact the construction industry and slow, halt or even reverse the growth of any technology. Structural glass façade technology could be especially susceptible to such an occurrence, as the premium technologies are generally the first to be cut and replaced with cheaper, more conventional solutions.

Oil prices blowing by USD 100 per barrel poses a distinct threat to the global economy. Yet this same phenomenon will bring much needed pressure to bear on the performance of buildings and building systems, building skins chief among them. This demand for greater efficiency and performance has the potential to create a significant new opportunities for structural glass façade technology.

1.4.7.3 Thermal Performance

The thermal performance of all-glass facades had improved considerably over the past two decades. New glass fabrication and coating techniques coupled with improved framing systems have provided these improvements, and the work continues with electrochromic and photochromic glazing (see Chapter 2) and new coating systems, as well as new façade designs such as the dual-skin systems. The primary objectives are to admit abundant natural light while controlling glare, control heat gain and loss, and provide ample ventilation. As much as the systems have improved, there are cheaper and more effective ways to meet the second two objectives. Rising energy costs will place increasing performance demands on the building skin, but there is great subjective value among both the public and the design community in an expansive use of glass. There is a general reluctance to return to the days of small windows punched in heavy, opaque walls. In every threat lies opportunity, and the great opportunity here is to develop façade building technology capable of energy production, moving as quickly as possible to a neutral state of zero averaged net energy consumption, and onward to the point the façade systems become net energy producers.

1.4.7.4 Technology Stall

Finally, secondary adopters must be enabled. If this fails to happen the market for the technology could stall or even shrink, coupled with other threats described above. This happened with space frame technology. Space frames peaked in popularity in the 1980's without the technology ever reaching its potential as a building form. A primary cause for this was a complete lack of tools and resources that would allow the architect to effectively design with this unique structure type. The services of a specialist were typically required for design through installation. Partially as a result, the market for the technology stagnated and market diffusion never occurred. Structural glass façade technology is much more robust, and there is good reason to believe that it will persist as a significant building form, but it could easily be relegated to a tiny specialty niche market if a new tier of adopters cannot be enabled.

Chapter 2 - Materials, Processes, and Systems

2.1 Overview

There is a dynamic and vital interplay between the material scientists, producers, and the building designers that use the materials in inventive ways. Sometimes design practice evolves in a manner that begins to push the limits of available materials and processes, presenting an opportunity for industry to respond to an emerging need. In this manner design may drive the development of new materials technology. Often however, new materials and processes emerge that only later find application in architecture, potentially changing design practice and building form in the process. Sometimes there is a considerable lag between the emergence of new materials and processes before they are embraced in the building arts. As discussed in Chapter 1, engineer William Jenny discovered the solution to high-rise steel framed structures by the late 19^{th} century, but in spite of the new opportunity for architectural freedom presented by this development, designers still clung to heavy looking masonry as the wall material. It was another 50 years before the curtain wall cladding techniques made possible by Jenny’s discovery came into widespread use.

There are many examples of this phenomenon in the history of building, and many causes, entrenched interests and restrictive codes chief among them. Long before this, however, such visionary architects as Louis Sullivan, Willis Polk, Walter Gropius, and Mies van der Rohe had commenced their pioneering efforts that showed the way to following generations of designers. Good designers understand the importance of a design methodology rooted in a deep understanding and exploration of materials and processes, providing a foundation that will both inform and inspire the design.

Following are the materials, processes and building systems that comprise the technology of structural glass facades. Many of these are rich enough in content to deserve significantly more comprehensive treatment, but such is beyond the scope and focus of this thesis. Instead, the priority is on highlighting the most relevant considerations required to facilitate the implementation of structural glass façade technology. What is presented here is an overview of the most popular materials and systems. Chapter 6, in a more systematic and rigorous manner, identifies and categorizes structure types, glass, and glass system types, and discusses the primary attributes of each type.

2.2 Structural Support Systems

Façade technology is complex, glass facades even more so, with long-span glass facades topping the challenge. Appropriate designs are as unique to the particular requirements of any architectural project as is the ultimate form of the building. The designer must balance myriad variables to develop an optimum solution to the façade design.

Central to the application of the technology is the development of a supporting structure. An interesting diversity of structure types has evolved in these façade applications, with each of the types possessing varying attributes that may impact their appropriateness to a specific application. A cable net may provide optimum transparency in a given application, but a steel truss system will likely prove to be more flexible in accommodating other design considerations that might be addressed with such elements as shade systems, louvers, canopies, screens, or light-shelves, features that can be integrated into the design of and supported by the truss elements with relative ease.

The following describes generic types of structural support systems, sometimes referred to as “backer-structures” in the industry, which are used in structural glass facades.

2.2.1 Structures and Strategies for Transparency

As discussed in Chapter 1, the pursuit of transparency has been a primary driver of structural glass façade technology from its inception. Deriving from this pursuit is intent to dematerialize the structural systems supporting the facades. The primary strategy in achieving this dematerialization involves the use of tension elements. Interestingly, this is consistent with a strategy of efficiency and sustainability; doing more with less material. The following steps (Melaragno 1981, p.58) were initially recommended as a means to improve the economical efficiency of a truss, a technique here suggested for application to truss systems and the pursuit of transparency:

- Minimize the length of compression members.
- Minimize the number of compression members, even if the number of tension members must be increased.
- Increase the depth of the truss as much as is practical to reduce the axial forces.
- Explore the possibility of using more than one material in the truss, one for compression and another for tension.

A structural system designed such that certain elements receive only axial tension forces allows for those elements to be significantly reduced in section area from elements designed to accommodate compression loads. A 100 millimeter diameter tube or pipe element can potentially become a 10mm rod or smaller, significantly reducing the element profile. The primary reason for this is that buckling disappears as a phenomenon. Small sections, especially of high modulus materials, are remarkably strong in tension; thus the effectiveness of steel cable.[6] The overall aesthetic affect can be quite dramatic.

Figure 2.1 Tension rod rigging terminations (Sta-Lok 2008).

The tensile elements themselves are most frequently comprised of strand or rod materials, often in stainless steel, although occasionally galvanized and/or painted mild steel materials are used. End fittings can be quite sophisticated in design, intended to present a minimal profile and leave no exposed threads while still accommodating the requirements of assembly and tensioning. These are generally high tolerance machined components with a quality finish. High strength alloy steels can be used for rod materials to further reduce their profile. Cables are, as a rule, more economical than rods, sometimes dramatically so. Cables are capable of bending within a specified radius with no loss of structural capacity, and can thus be used as longer elements intermittently clamped but requiring only two end fittings. Bent rods are most often impractical, so rods must be provided as discrete linear elements of greater quantity, each requiring two end fittings. The additional quantity of end fittings drives up both the fabrication and assembly costs in most applications. Nonetheless, this method is sometimes used as an aesthetic preference. Both cable and rod fittings are currently available from a number of suppliers providing a wide variety of system types and aesthetics. Refer to the section on rods and cables below.

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[6] For the classic demonstration of the relative difference between tensile and compressive forces, one need but try and pull a pencil apart and after quickly giving up, attempt to compress it by pushing its ends together.

2.2.2 Strongbacks and Glass Fins

Strongbacks are the simplest form of support for a glass façade, but are only useful in relatively short spans. They can be comprised of simple steel or aluminum open or closed sections with provisions for the attachment of the glazing system. Rectangular tubes are often used, and provide a useful flat surface for the attachment of veneer glazing systems. Round pipe or tube sections see frequent application, with integral weldments to accommodate glazing system attachment. Extruded aluminum sections can be quite complex, and designed to facilitate the attachment of an integrated glazing system. They are commonly used in curtain wall systems where the floor-to-floor span is in the 3 to 4 meter range. Aluminum is more expensive than steel, however, and possess only one third the strength of steel. Thus, in structural applications with spans over 6 to 8 meters, steel is generally the material of choice.

Strongback sections can also be built up of multiple standard steel sections, such as two tubes or pipes joined by continuous, or more likely discontinuous web plates welded between the two sections. This strategy can effectively increase the spanning capacity and efficiency of the Strongback.

The relevance of the strongback is as a supporting component in a façade system intended to provide uniform glazing over varied spanning conditions. Some designs might use a conventional curtain wall system in typical areas and a structural glass system on an exposed long-span structure, presenting a design challenge at the interface. Other designs call for a uniform glazing condition throughout. In such a case, a short span, medium span, and long-span solution may be required. The strongback provides the solution for the short spanning condition.

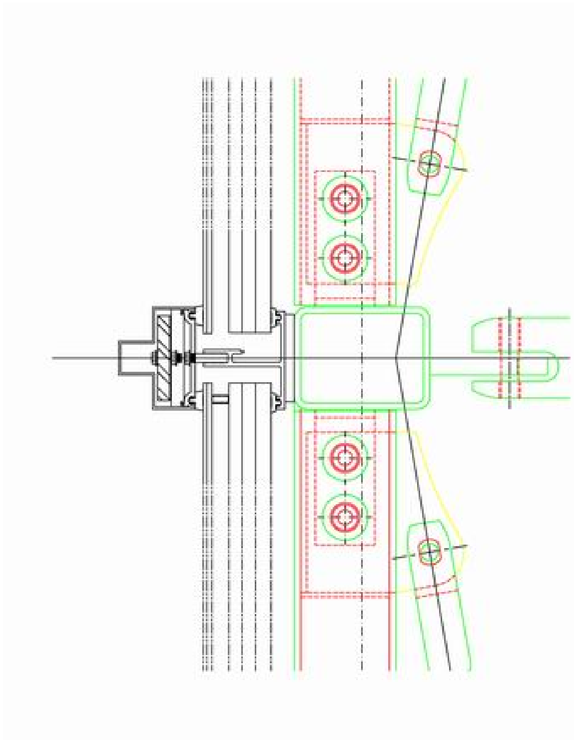


Figure 2.2 A veneer type system in section view is continuously supported by either a simple strongback or the outher chord of a truss (ASIDI).

A simple example is a long-spanning truss with a square or rectangular outer chord, presenting a flat face for the attachment of a veneer glazing system. If the same or similar square or rectangular section is used for the strongback, the glazing system can be applied seamlessly across the varied spanning conditions.

Closed or open section structural members are often used as simple strongbacks, as with a rectangular section steel tube spanning between floor decks. The strongback can be modified to accommodate the attachment of any type of glazing system. With a square or rectangular section, a glazing system can be continuously supported at the face of the strongback.

2.2.3 Space Frames and Space Trusses

The terms space frame and space truss are used interchangeably in the industry. Space frames are three-dimensional, multiple layer truss systems, often constructed with prefabricated components; nodes and struts, that can be assembled with bolted connections in the field. They are 3-dimensional truss networks capable of 2 and even 3-way spanning depending upon geometry and configuration. They are seldom used in vertical façade applications because of the frame depth encroaching on the interior space, and the particularly dominant aesthetic which some designers object to. They do provide a uniform grid to high tolerance that can be convenient for attaching a glazing system.

Various geometries are possible, most taking advantage of triangulation to achieve very stiff and efficient structures on a span to weight basis. Space frames can be form-active structures when configured as a vault, dome or pyramid, but they are always geometry-active, taking maximum advantage from strength of geometry. (See Figure 6.3)

2.2.4 Simple Trusses and Truss Systems

Figure 2.3 Simple trusses set at each vertical grid module (ASIDI).

Planar trusses of various types and configurations can be used to support glass facades. The most common application is a single truss design used as a vertical element with the depth of the truss perpendicular to the glass plane. The trusses are positioned at some regular interval, most commonly a gridline of the building or some uniform subdivision thereof. The truss spacing must be carefully determined as a function of the glass grid. The individual trusses comprise a truss system, the structural system supporting a structural glass façade (Melaragno 1981, p.60). A truss system can include more than one truss type. Primary trusses for example, may be separated by one or more cable trusses to increase the system transparency (see Figure 2.4). The truss systems often incorporate a minimal tensile lateral system, bracing the spreaders of the cable trusses as well as the primary truss elements against lateral buckling. Alternatively, lighter trusses may span horizontally between widely spaced primary vertical trusses, providing lateral support and attachment for the glazing system.

Figure 2.4 Simple trusses alternate with vertical cable trusses (ASIDI).

An effective strategy as discussed earlier is to employ a square or rectangular tube as the outer chord of the truss (Figure 2.2). The same section can then be utilized as a horizontal purlin element spanning between the trusses at the glazing grid. A bolted connection can be detailed along the truss chord to accommodate the attachment of the purlins. fig The resulting truss system provides a high tolerance exterior grid of flat steel matching the glazing grid. The steel grid can then accommodate the attachment of a simple, non-structural veneer glazing system, providing a high level of functional integration of the structural and glazing systems with favorable economy.

Figure 2.5 A horizontal bolts into a vertical simple truss (ATS).

While most frequently vertical in elevation and linear in plan, façade truss systems can be sloped inward or outward, and follow a curved geometry in plan. Truss elements can also be manipulated to provide a faceted glazing plane (see Figure 2.6).

Truss systems can incorporate other structural elements, as with the steel purlin discussed above. Glass fins, cables, other truss types, and conceivably even cable nets can be incorporated as elements within a façade truss system.

The application of trusses as part of a glass façade system brings other considerations; the glazing plane and grid will dictate certain geometric parameters of the truss system, deflection criteria must be considered, limitations in the design of boundary supports may eliminate certain system types, the intended glass system must be evaluated in terms of the supporting structural system (these issues are discussed further in Chapter 7). However, aesthetic considerations are always in play, and are often the primary design driver. Long-span façades make use of exposed structural systems. The emphasis has been on elegant structural system designs, highly crafted system components, and a general dematerialization of the structure in an effort to enhance overall system transparency.

Figure 2.6 Spertus Institute, Chicago; faceted glass façade, Krueck Sexton Architects, 2007 (Built Chicago 2008).

Figure 2.7 Simple truss system with internal tension rod bracing and rectangular exterior chord (ASIDI).

Figure 2.7 shows a simple truss system with tension rod bracing and a horizontal purlin mirroring the exterior glazing grid can provide relatively high transparency with considerable economy over more complex truss systems. Virtually any glass system can be adapted to this truss system.

Geometric configurations of simple truss types include variations of Pratt, Warren, and Lenticular trusses. Various truss types are represented in Figure 2.8. Truss design is a function of the structural considerations of span, loading, pitch, spacing and materials. A deflection criterion for truss systems making predominant use of simple truss elements is typically in the range of L/175 (T Dehghanyar 2008, pers. comm., 12 March).

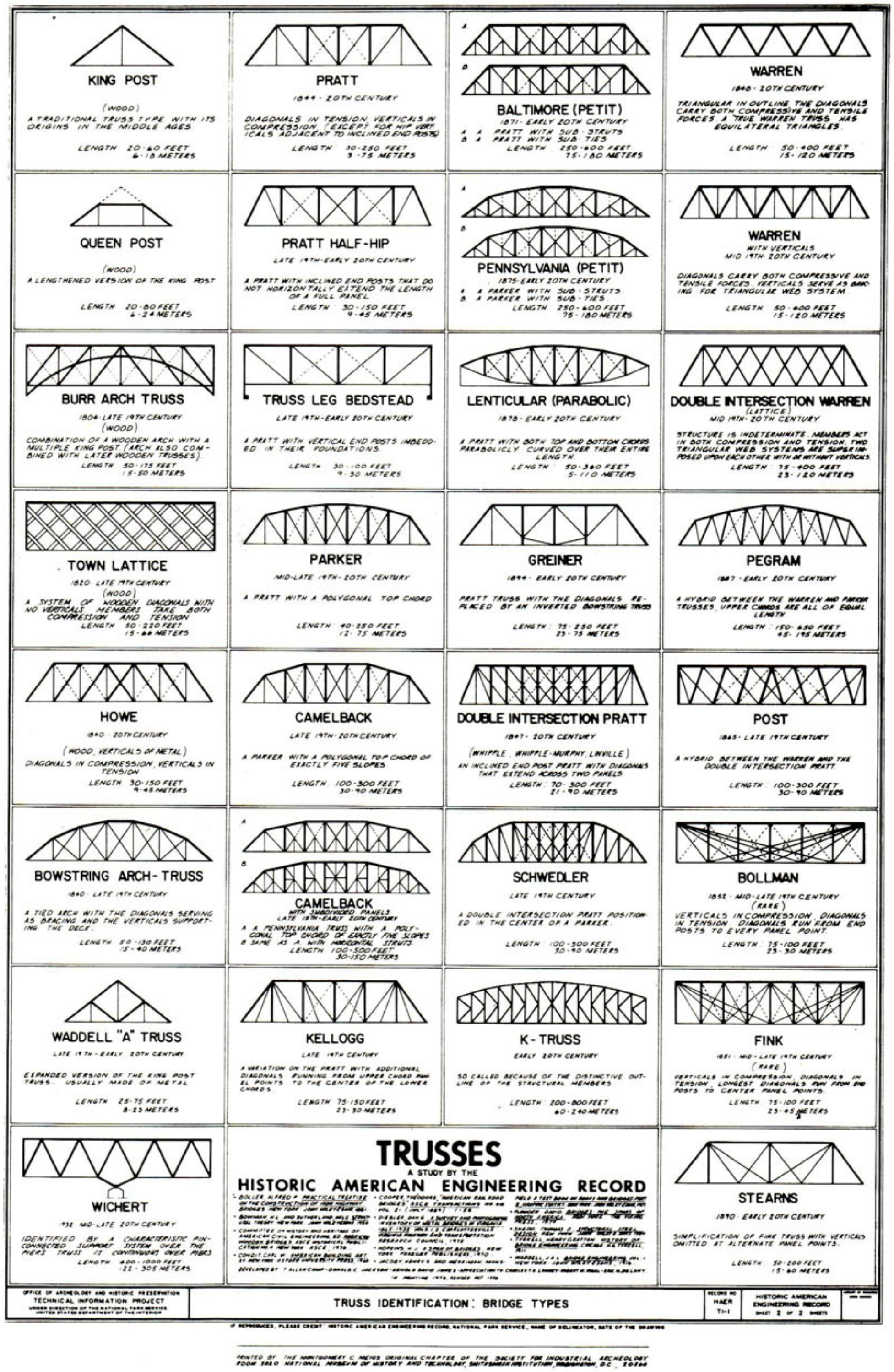


Figure 2.8 Truss identification: bridge types (Historic American Engineering Record 1976)

2.2.5 Guyed Struts and Mast Trusses

Guyed struts or mast trusses use tension elements to stabilize a central compression element (mast), usually a tube or pipe section. The cables attach at the mast ends and incrementally at the ends of “spreaders” struts of varied length attached at intervals along the length of the pipe. The spreaders get longer toward the longitudinal center of the mast, thus forming a cable arch between the mast ends. Two, three or four of these cable arches can be radially spaced about the mast, acting to increase the buckling capacity of the mast and allowing for the use of a smaller mast section.

Figure 2.9 A planar mast truss with point-fixed glass during installation (ASIDI).

A planar mast truss formed by two of these cable arches 180 degrees opposed can be used as a primary truss element in a structural glass façade. The glass plane can be located in the plane of the masts, placing one of the cable arches on the inside and one on the outside. Alternately, the spreaders on one side can be extended out to form a plane parallel to but offset from the mast plane, thus enclosing the entire truss system within the façade envelope. In this configuration, a “dead load” cable is typically employed to support the dead load of the glass. The cable would be located at the top of the glass plane on a cantilevered outrigger and drop vertically behind the glass plane connecting to the extended spreaders at their ends.

Monolithic glass panes are being attached to the spreaders of the mast trusses in Figure 2.9. A vertical dead-load cable supports the spreader struts just behind the glazing plane. In this case, horizontal glass will be installed at the top of the trusses back to the building roof.

A large cavity double-skin façade could be easily accommodated by this truss system, with glass planes at both ends of the spreaders, or at the mast plane and either end of the spreaders.

2.2.6 Gridshell

Shell structures have long been recognized for the superior efficiency deriving from their shape. Thin shell structures in reinforced concrete have been used in many long-span structural applications. While the design, engineering and construction of these form-active structures remains challenging, they are highly efficient structures. The strength of the shell derives from the double-curved (synclastic or anticlastic) surface geometry.

Figure 2.10 Mannheim Mulithalle, Germany; grid shell by Frie Otto with Burro Happold, 1975 (Griel 2006)

.Gridshells are a subset of shell structures. Rather than being monocoque shells, they are comprised of a grid of discreet structural members forming squares, triangles or parallelograms that define the shell geometry. Unique shapes can be developed with grid shells that benefit from the combination of shell and arch action. This structure type was pioneered by Frei Otto in the 1940's, and used in the construction of the Mannheim Multihalle in Germany constructed in 1975. (Paoli 2007, p.12)

Engineering firm Schlaich Bergermann & Partners, working with various architects, have designed a number of glazed enclosures using gridshell structural support, and have pioneered a gridshell technique based on the kitchen sieve (Schlaich & Schober 1994, p.1-27).

The systems employ a network of in-plane cables to provide stability and shear resistance to the minimal shell grid. These designs represent the state of the art in structural glass facades as full building enclosures of complex geometry, and beyond the focus of this thesis. Nonetheless, gridshells are a viable structure type for application in façade structures, as some simple examples here attest. This structure form remains rather under-explored in this application, and there may be some interesting potential in future work.

Schlaich Bergermann were also involved in the New Milan Trade Fair gridshell canopy designed by Massimiliano Fuksas completed in 2005 (Figure 2.11).

Figure 2.11 Gridshell glass canopy (New Trade Fair in Milan n.d.)

2.2.7 Tensegrity

What became known as tensegrity structures were first identified and explored by Kenneth Snelson in 1948. Snelson introduced Buckminster Fuller to his findings, and in the mid 1960's Fuller coined the term "tensegrity" (Coplans 1967) as a portmanteau of 'tensional integrity'. A true tensegrity is a balanced construct of complimentary forces, with continuous tension elements and discontinuous compression elements. Fuller defines tensegrity as compression elements that do not touch, but exist as "small islands [of compression] in a sea of tension" (Fuller 1962 cited in Robbin 1996, p.25). A tensegrity tower sculpture built by Snelson (1968) is shown in Figure 2.12.

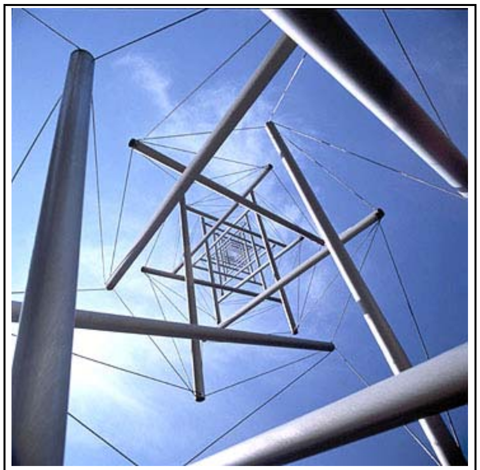


Figure 2.12 Needle Tower, 1968 by Kenneth Snelson.

Fuller later went on to develop tensegrity dome concepts, and in 1964 patented his "aspension dome" system. While not pure tensegrity structures (they are open systems), Robbin (1996) argues that they can fairly be classified as tensegrity structures. Moreover, as used by David Geiger to develop a tensile roof structure system that was used, among other applications, to build the Seoul Olympic Gymnastics Arena in 1986, they represent the first architectural application of tensegrity structures. The fabric clad structure weighed in at just 2 psf (9.8 kg/m²). (Tuchman & Ho-Chul 1986)

Matthys Levy of engineering firm Weidlinger and Associates developed a similar dome that was used on the Georgia Dome, a sketch and images of which are shown below.

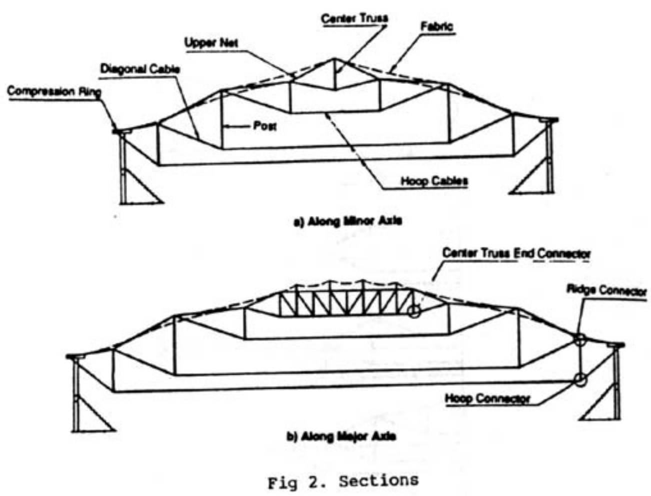


Figure 2.13 Sections of Georgia Dome (Castro & Levy 1992).

Figure 2.14 Interior and exterior of Georgia Dome (ballparks.com n.d.).

Unfortunately, these stadium roof structures are not appropriate for façade applications, but other variations of tensegrity geometry could well be developed for such applications.

2.2.8 Cable Trusses

Figure 2.15 The spreader is the only compression element in this cable truss system (ASIDI).

Pursuing the truss development guidelines established earlier, the next step is to remove the big compression member, the mast, from the truss element described immediately preceding. This leaves the spreader struts as the sole compression elements in this truss type. However, this has been accomplished at a price; the remaining truss is no longer stable, and cannot even stand on its own, much less carry any load. The solution is to tension the truss against an upper and lower boundary structure. This represents a fundamental change in truss behavior from those preceding. Cable trusses must be prestressed, or externally stabilized, to function as load-bearing structural elements. This type of truss, and truss systems comprised of this truss type, can be referred to as open systems. The preceding truss types were internally stabilized, or closed systems; stability was provided as a function of truss geometry, requiring no interaction from the boundary structure to provide intrinsic truss stability.

Figure 2.16 Cable trusses span between tubular steel infrastructure (ASIDI).

There are several important nuances in designing with open systems. Appropriate prestress forces required to stabilize the truss and control deflections under design loading conditions must be determined as part of the system design. These prestress forces must be balanced against the reaction loads that will be transferred to the boundary structure. The more deflections are limited, the higher the system prestress that will be required, and the higher the resulting reaction loading transferred to the boundary structure. An appropriate deflection criterion with these systems might be L/140 or more (T Dehghanyar 2008, pers. comm., 12 March). Perhaps the predominant consideration in the design of an open truss system is assuring that the boundary structure is designed to handle the reaction loads, and that the affect is factored into the budget early in the design process. It is important to note that the loads generated from the prestress requirements are not intermittent loads like wind or seismic loads, but continuous loads like dead loads.

The next challenge is to assure that the correct prestress forces are in fact achieved in the field during installation of the truss system. Long-span systems can require prestress forces achievable only with hydraulic jacking systems, and must include connection detailing carefully developed to support the field pre-tensioning of the system. Prestress forces can range widely depending upon variables of span, design loading, and geometry, but each configuration of open system geometry will have an optimum prestress value, beyond which no worthwhile improvement in performance results (Schierle 1968).

What is gained is a significantly enhanced transparency to the façade system. While many cable truss geometries are conceivable, lenticular and inverted geometries with horizontal compression struts are most common. A spider or other fitting type can be positioned at the end of the extended spreader struts to fix the glass. More conventional panelized glazing systems can also be accommodated. Cable trusses can also be positioned horizontally between vertical mast trusses in a hierarchical scheme.

2.2.9 Cable Supported Structures

This structure type represents the most recent developments in structural glass façade technology, and the current apogee of structural minimalism.

2.2.9.1 Cable Hung

The next step in the move towards dematerialization of these truss systems is to delete the spacer or spreader struts, the last of the remaining compression elements in the cable truss discussed above, thus yielding a new category of open system structure that is cable based instead of truss based. All that remains from the former cable truss category are the cable elements, which can be tensioned vertically against top and bottom boundary structure. If adequate prestress forces can be achieved, the cables can be used to support glass. Dual function clamping components that clamp first to the cables can then be used to clamp edges or corners of adjacent glass panes on the glazing grid (fig.4). The glass plane can be straight or curved in plan. A narrow glazing grid will result in a higher density of cable elements, thus lowering the prestress requirements for each individual cable. Nonetheless, high prestress forces will be required to control deflections. Deflection criterion of L/45 or L/50 is commonly used (T Dehghanyar 2008, pers. comm. 12 March), producing a highly flexible system with significant deflections under wind load.

2.2.9.2 Cable Net

Figure 2.17 UBS Tower,Chicago; flat cable net, Lohan Caprille Goetsch Architects (ASIDI).

The addition of horizontal cables to the system described above yields a cable net, an open system capable of 2-way spanning behavior. Adding the horizontal cables to a straight plan geometry of vertical cables produces a flat cable net structure, with an orthogonal cable grid defined by the relative spacing of vertical and horizontal cables. The addition of the horizontal cables makes controlling system deflections easier, assuming an effective spanning distance, resulting in lessened prestress requirements in the cable elements. Simple flat cable nets as described here have been constructed with spans of 50 meters or more. One cable net of more complex, faceted geometry and using a hierarchy of cable sizes has been constructed in China that spans nearly 100 meters.

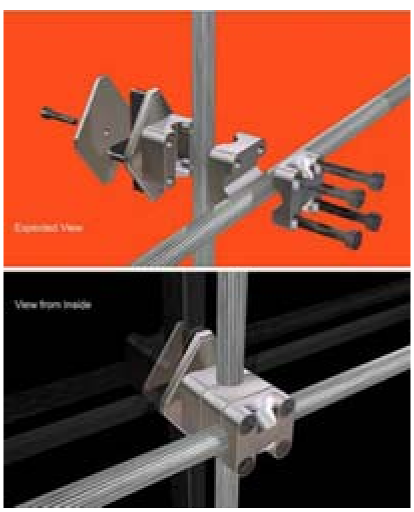


Figure 2.18 A typical cable net clamp (AISD).

Cable nets top the transparency chart. Figure 2.18 shows a four-part cast stainless component that clamps the cables of a flat 2-way flat cable net and clamps the glass to the net.

2.2.9.3 Double Curved Cable Nets

The addition of horizontal cables to the system of vertical cables aligned to a curve in plan, as described in Cable Supported Structures above, produces another kind of cable net. If the horizontal cables are aligned to a curve in elevation opposing curvature of the vertical cables in plan, the horizontal and vertical cables can be tensioned against each other to form a double-curved (anticlastic) surface with unique properties (fig.5). The opposing curvature provides stability to the cable net that a flat net does not have, significantly limiting deflections under wind load and thus requiring lower prestress forces in the cables. Lost, however, is the facility of the orthogonal grid; the double curved net produces a variety of trapezoidal shapes that greatly complicate the requirements of the glazing system. Depending upon system geometry the corners of some trapezoids may not even lay on the same plane, resulting in the possibility that glass panels could require cold-forming during installation to conform to net geometry, thereby inducing warping loads to the glass panels. These potential affects can be mitigated through careful design of the net geometry.

Figure 2.19 Sea-Tac Airport, Seattle; double curved cable net, Fentress Bradburn Architects 2005 (ASIDI).

Insulated glass units are point-fixed to this double-curved cable net structure at Sea-Tac International Airport in Seattle shown in Figure 2.19. Cable net structures have been used to support both clamped and drilled point-fixed glazing systems, as well as panelized systems.

Cable net structures are remarkably minimal; cables, clamping elements and glass fixing components comprise the entire structural system, and are easily the most transparent of the façade structure system types. However, this material advantage is at least partially offset by the necessary strengthening of the supporting boundary steel.

Kieran Kelley-Sneed, a former professional engineer with ASI Advanced Structures Incorporated, the design/builder of the cable net wall at the Time Warner Center in Manhattan is quoted in a publication (Kenter, 2007);

> *Kelly-Sneed says that the cost of cable net technology increases with the size of the surface to be covered, so cost comparisons with more traditional walls are difficult. "You pay more for a lot of transparency," he says. "For a 40-foot span, a cable net system would probably cost about one-and-a-half to two times as much as one built with heavy steel trusses."*

The highly flexible behavior of the cable truss and cable net systems suggests that they may present performance advantages under extreme loading conditions, although research has yet to verify this hypothesis.

2.2.10 Glass Fin-supported Facades

Figure 2.20 Glass fins are set perpendicular to the glass plane to resist lateral loads (ASIDI).

These structures represent the earliest form of all-glass building, and what today have been referred to as high-transparency structures. They represent a special case of structural glass façade technology; a stand alone structural glass system for use in facades, requiring no metallic supporting structure beyond hardware and splice plates. The glass fin set perpendicular to the glass membrane provides lateral support to resist wind loading, but essentially acts in the same manner as a strongback structural member as defined above. Glass fin facades are hard to surpass when it comes to transparency, and are still quite popular, although their use is often rejected in favor of newer structural system technology such as cable nets. Ironically, the various structural systems that have evolved in the support of structural glass facades, while certainly providing an aesthetic differentiation, do not in most cases provide higher transparency. After all, it is hard to beat an all-glass structure for transparency.

Figure 2.21 Splice plates at the fin sections act to tie point-fixed glass to fins (ASIDI).

Glass fin facades have a broad spanning range from approximately 20 feet (6 meters) or less, to over 100 feet (30 meters). They are most economically effective at the lower spans where the fins do not require splicing. The glass fins are tempered, and their height is therefore limited by the maximum length of material a producer can get out of the tempering oven. Fin glass facades are often seen with a partial length fin cantilevered out of the floor and/or roof as a means to provide a longer spanning condition without the need for a full length fin. As the spans increase, the fins get deeper, the glass thicker, and ultimately laminated fins are a requirement. When a single fin cannot be long enough to support the span, the fins must be spliced. This is accomplished with a series of holes drilled in the mating ends, and metal cover plates spanning across the fin ends to accommodate the transfer of loads. Neoprene sheets are sandwiched between the plates and the glass surface. Various fixings can be used to attach the glass cladding to the fins.

2.3 Steel

The following sections explore various material and process aspects of steel and steel components.

2.3.1 Steel Fabrication

Steel fabrications in exposed structural façade systems are frequently specified per standards developed by the American Institute of Steel Construction (AISC) for the fabrication of Architecturally Exposed Structural Steel (AESS). This standard provides for the specification of such important considerations as surface finish of the steel and the finishing of welds. Welds can be specified as ground smooth, and even polished if circumstances warrant. Such care with the fabricated steel will lead to equivalent concerns with the finish of these materials. High performance two and three-part aliphatic urethane coatings are available in a range of standard and metallic colors that provide excellent results, both with respect to performance and appearance. The procedure typically involves initial substrate preparation of cleaning and surface blasting followed by a zinc-rich prime coat prior to application of finish coats.

2.3.2 Castings

Figure 2.22 Center Pompidou, Paris; Rodgers and Piano architects, cast gerberettes on the production floor (Vincent n.d.).

Casting is an old process with a long tradition in the building arts. Cast iron was the material that provided the structural basis for the great iron and glass conservatory structures of the 19th century, so central to the story of glass in architecture. Cast components have been used extensively by contemporary European architects. Renzo Piano and Richard Rogers, with considerable help from engineer Peter Rice and the local casting industry, made great use of castings in the gerberettes and other components of the Centre Pompidou.

The casting process provides great flexibility in the design of components, as evidenced by the great diversity of parts produced for the various projects by the designers referred to above. It is also a relatively inexpensive process, and does not require mass quantities of a component be produced to achieve those economies.

Problems with cast components that were part of a space truss system used in the construction of the Javits Convention Center in New York City in the early 1980's resulted in massive delays in completion of the structure. This much publicized problem resulted in a bad name for castings in the construction industry in the US, and there was great resistance to their use over the next two decades. Castings have been reintroduced to the US marketplace only fairly recently through the technology of structural glass facades. Spider fittings, cable net clamps, and other components of custom façade designs are commonly cast of stainless steel or ductile iron. Often, however, these components are imported into the US from Europe or, increasingly, Asia, as the casting industry is limited domestically, especially with respect to familiarity with the requirements for architectural castings, perhaps as a side effect of the Javits problem.

Investment casting is an excellent process for producing elegant components of relatively small quantity. There are issues however. Component designs must be developed with an awareness of the strengths and limitations of the process. There are only a limited range of materials appropriate for casting, and these possess varying properties that must be closely matched to application requirements. Also, cracks and voids can be problematic with castings, and precautions must be taken that appropriate quality assurance measures are in place, often involving both destructive testing, and non destructive testing utilizing radiographic, magnetic-particle, and/or die-penetrant techniques.

2.3.2.1 Stainless Alloys

There are several choices in stainless alloys for casting, including ASTM A316 material that is frequently used for machined components and rods because of its excellent corrosion resistance. Higher strength materials are available, but the other properties, such as corrosion resistance and workability must also be evaluated. Some alloys will require passivating after casting, a process that removes surface impurities that can lead to staining of the material. The castings will also need to be surface finished by bead-blasting, polishing, or some similar process to produce a uniform appearance over the surface of the component.

2.3.2.2 Ductile Iron

The history of casting with ductile iron dates back over 2,000 years. Although most castings used in structural glass facades are stainless steel, ductile iron is a good choice for larger components. Ductile iron is not a single material, but a family of materials with a remarkable range of properties. The Ductile Iron Society is an excellent resource for the designer or engineer, providing information on all aspects of the material and process, as well as casting producers.

Composition and mechanical properties of Austempered Ductile Iron (ADI), one form of ductile iron with interesting properties, follow. (Keough 1998)

A typical iron composition (and control range) that can be used is shown below:

Carbon*	3.7%	+/- 0.2%
Silicon*	2.5%	+/- 0.2%
Manganese	0.28%	+/- 0.03%
Copper	as required	+/- 0.05% up to 0.8% maximum
Nickel	as required	+/- 0.10% up to 2.0% maximum
Molybdenum	only if required	+/- 0.03% up to 0.25% maximum

Mechanical Properties

ADI is a group of materials whose mechanical properties can be varied over a wide range by a suitable choice of heat treatment. **Figure 4.6** illustrates the strong correlation between austempering temperature and tensile properties. A high austempering temperature, 750F (400C), produces ADI with high ductility, a yield strength in the range of 500 MPa (72 ksi) with good fatigue and impact strength. These grades of ADI also respond well to the surface strain transformation previously discussed which greatly increases their bending fatigue strength. A lower transformation temperature, 500F (260C), results in ADI with very high yield strength (1400 MPa (200 MPa)), high hardness, excellent wear resistance and contact fatigue strength. This high strength ADI has lower fatigue strength as-austempered but it can be greatly improved with the proper rolling or grinding regimen. Thus, through relatively simple control of the austempering conditions ADI can be given a range of properties unequaled by any other material.

2.3.3 Tensile Components: Cable and Rod Rigging Systems

The seminal projects of Les Serres at Lavallette, and the Pyramid at the Louvre, inspired a new market for cable and rod rigging systems as a major component of structural glass façade technology. Strand and wire rope technology has a long history of use in architecture, including suspended bridges and buildings, and in building elevators, and in the assembly of buildings with the cranes and hoists used in construction. But these seminal projects took this technology not only to a new niche market, but to a new level of refinement as an element of the exposed structural systems that comprise the core technology structural glass facades.

2.3.3.1 Cables

Cables come as strand or wire rope. Modern cable technology was first developed in Germany in the 1830's by German mining engineer Wilhelm Albert. Wire rope evolved from hemp rope-making, and the first ropes were wire twisted around a rope core. John A. Roebling later manufactured wire rope in America, the material becoming intrinsic to the building of his suspension bridges. He made many innovative contributions to the manufacturing process and construction of wire rope among them the ability to make cables on site (GG Schierle 2007, pers. comm., 22 Nov.)

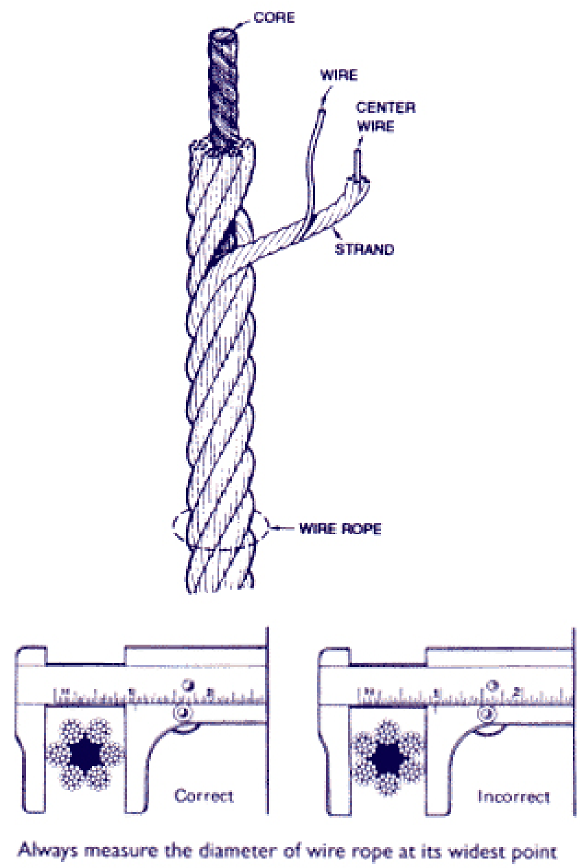
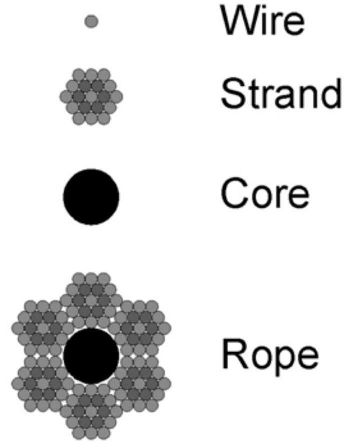


Figure 2.23 Wire rope diagram (Saftey Sling 2005).

Individual wires are fist twisted into strand. Strand can be used in place of rope, but has different properties and is stiffer (E~22,000 ksi), less flexible than rope (E~16,000 ksi). The flexibility of rope is important in applications where the wire must be bent around a tight radius or repeatedly wound and unwound around a drum as with elevator cables. Wire rope is made by twisting strands around a steel core. There are various techniques in constructing the rope involving the manner in which the wires and strands are twisted, called the lay. When specifying wire rope the lay must be designated, along with material type, the number of wires in a strand, and the number of strands in a rope.

Table 2-1 Wire rope construction (Wire Rope 2008).

6	Number of strands that make up the rope
19	Number of wires that make up each strand
FC	Fiber core
RH	Right hand lay
OL	Ordinary lay
FSWR	Flexible steel wire rope



The rope shown above is designated: 6x19 FC RH OL FSWR. Each of the designations in this example has multiple alternatives, making for many possible combinations.

End terminations are fittings of various types swaged to the end of the strand or wire rope. Many standard fittings are provided as options by wire rope fabricators, although these may not meet the aesthetic standards of a design. Because the exposed structures used with structural glass facades and the emphasis on craftsmanship and design detailing, end fittings are sometimes custom designed. An increasing diversity of cable termination fittings is available from the many small manufacturing firms producing glass-fixing components.

2.3.3.2 Rods

Table 2-2 Hayden Planetarium, New York; Polshek Partnership architect, glass fixing by TriPyramid Structures (TriPyramid 2005).

Design innovations are often the result from the borrowing of a developed material or process from a related or unrelated industry, and applying the old technology to a new problem. High-strength tension rods were developed for use on racing yachts. Tim Eliason had founded Navtec, a company providing rigging systems to the yachting industry, and had played a key role in the development of rod rigging systems. He got the opportunity to transfer some of the technology when invited to participate on the Pyramid at the Louvre. Subsequently, Eliason started TriPyramid Structures to pursue opportunities for cable and rod rigging systems in the building arts. TriPyramid has been one of the leading innovators in the evolution of structural glass facades, producing some of the finest design and fabrication work the technology has produced.

The end terminations for rods present a different problem than that presented by cables, which can be swaged or soldered, techniques that will not work at all on rods. Rods can be threaded at the ends to receive threaded end fittings. Alternately, threaded fittings can be placed on to the rod, and the end of the rod upset by a process called cold-heading, whereby the rod end is compressed in a hydraulic press so that it mushrooms. The end fitting is thus affixed to the rod.

The design of these connections is a subtle art. There are a number of factors to balance, including the intent to conceal the threads in the installed work. The fittings must have enough tolerance build in to the design to accommodate field conditions of the installed work, and to provide the function of tensioning the rod itself within the work. The rod assembly essentially acts as its own turnbuckle.

Rods do present an elegant solution as a tension component, but they are not appropriate in all applications. As discussed earlier in this Chapter, rods can be difficult to store, handle and install without damaging the finish, most often a brushed stainless steel. Rods are generally limited to straight segments, unlike cables which can be wound through a structure as appropriate, minimizing the number of end terminations, which can result in considerable savings.

2.4 Glass

Chapter 1 focused on the historical context of glass and its use in architecture. Here the focus will be on the composition and properties of various glass types. Glass is an ancient material with unique properties and diverse applications. Glass comes in many forms as a function of chemistry and process. The basic ingredient however, is silica, or sand, one of the most common and inexpensive materials on the planet. The two largest users of glass are the construction and automotive industries, and here glass material takes a more specific form.

2.4.1 Glass as Architectural Material

Soda-lime glass is the most common form of glass, and the material used in the modern day float process by which architectural flat glass is produced. The various material properties of glass; transparency, durability, resistance to corrosion and high temperatures, coupled with the huge production capacity of the industry and relative low cost, render it a uniquely appropriate material for application in architecture. The glass used in structural glass facades, while varying substantially among projects, is almost always annealed flat product yielding from the float glass process, subject to modification through some form of secondary processing adding value in some manner. Secondary processes include various combinations of heat-treating, laminating, fritting and coating, among others as discussed following. Flat glass can also be bent for an interesting architectural affect.

2.4.1.1 Float Glass

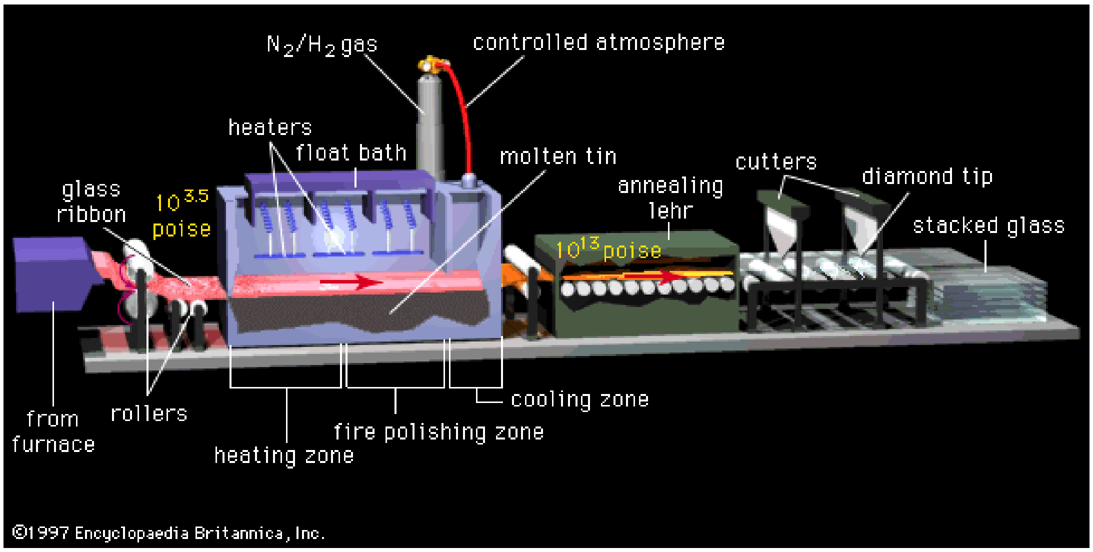


Figure 2.24 Float glass process diagram (Encyclopedia Britannica n.d.).

Figure 2.25 Pilkington float glass plant in Moscow, completed 2006 (Bovis n.d.).

2.4.1.2 Physical Properties

Table 2-3 Properties of Soda-Lime-Silica Float Glass (Pilkington 2008).

Properties of Soda-Lime-Silica Float Glass			
Modulus of Rupture (MOR), (in-service glass surface tensile stress at fracture, not the scored and cut glass edge) for 60-Second Load Duration on weathered glass.			
Typical Mean MOR (50% Probability of breakage)	6,000 psi	(41 MPa)	Annealed
	12,000 psi	(83 MPa)	Heat-Strengthened
	24,000 psi	(165 MPa)	Fully Tempered
Typical Design Stress for 0.8% Probability of breakage	2,800 psi	(19 MPa)	Annealed
	5,600 psi	(39 MPa)	Heat-Strengthened
	11,200 psi	(77 MPa)	Fully Tempered
Modulus of Elasticity (Young's)	10.4×10^6 psi	(72 GPa)	
Modulus of Rigidity (Shear)	4.3×10^6 psi	(30 GPa)	
Bulk Modulus	6.2×10^6 psi	(43 GPa)	
Poisson's Ratio	0.23		
Density	158 lb/ft³	(2530 kg/m³)	
Coefficient of Thermal Stress	50 psi/°F	(0.62 MPa/°C)	
Thermal Conductivity at 75°F	6.5 Btu.in/hr.°F.ft²	(0.937 W.m/m².°C)	
Specific Heat at 75° F	0.21 Btu/lb_m.°F	(0.88 kJ/kg.°C)	
Coefficient of Linear Expansion (75-575°F)	4.6×10^{-6} in/in.°F (8.3×10^{-6} mm/mm.°C) e.g. 200" of glass heated 100 °F expands by 0.090" (5.1 m of glass heated 56 .°C expands by 2.3 mm)		
Hardness (Moh's Scale)	5-6		
Softening Point (ASTM C 338)	1319°F	(715°C)	
Annealing Point (ASTM C336)	1018°F	(548°C)	
Strain Point (ASTM C 336)	952°F	(511°C)	
Index of Refraction:	(0.5893 μm, Sodium D Line)		1.523
	(1 μm)		1.511
	(2 μm)		1.499
Emissivity (Hemispherical) at 75°F	0.84		
Stress-Optical Coefficient	Stress (psi) = 2.18 x Retardation (μm) / thickness (in)		

Table 2-4 Raw materials used in typical float glass (Pilkington 2008, p.2).

Raw Materials used in Typical Float Glass					
Sand	Soda Ash	Limestone	Dolomite	Salt Cake	Cullet
SiO_2	Na_2CO_3	$CaCO_3$	$MgCa(CO_3)_2$	Na_2SO_4	(recycled glass)

Table 2-5 Chemical analysis of a typical clear float glass (Pilkington 2008, p.2).

Chemical Analysis of a Typical Clear Float Glass							
SiO_2	Na_2O	CaO	MgO	Al_2O_3	K_2O	SO_3	Fe_2O_3
Silica	Soda	Calcium Oxide	Magnesium Oxide	Alumina	Potassium Oxide		Iron Oxide*
72.6%	13.9%	8.4%	3.9%	1.1%	0.6%	0.2%	0.11%

* Iron Oxide aids the melting process and produces the green tint seen at the cut edge of a glass plate.

Table 2-6 Glass weights (Anver 2008 modified).

Weight of Glass				
	thickness		**weight**	
fraction inch	**decimal inch**	**mm**	**lbs/ft²**	**kg/m²**
1/8	0.125	3.0	1.62	17.43
5/32	0.156	4.0	2.02	21.73
3/16	0.1875	5.0	2.43	26.14
1/4	0.25	6.0	3.24	34.86
5/16	0.3125	7.9	4.06	43.68
3/8	0.375	10.0	4.87	52.39
1/2	0.5	12.0	6.49	69.82
5/8	0.625	16.0	8.11	87.25
3/4	0.75	19.0	9.73	104.68
7/8	0.875	22.2	11.35	122.10
1.0	1.0	25.4	12.98	139.64

Weight (in lbs.) is determined by the following formula:
Weight equals (Thickness) multiplied by (0.0129765) multiplied by (1000)
Where thickness is in the decimal form of inches.
Ex: .250 * 0.0129765 * 1000 = 3.24 lb / ft²

2.4.1.3 Tinted Glass

> *"Tinted glass is produced by the addition of small (typically less than 1%) amounts of other metal oxides. These small amounts do not change the basic physical properties of the glass, other than the color and solar/optical transmission/reflection" (Pilkington 2008, p.2).*

The light transmission properties of glass, and thus color, can be changed within limits by the alteration of the glass chemistry. Iron oxide, cobalt oxide, selenium and other chemicals can be used in very small quantities to modify the transmission properties. The performance objective in using tinted glass is to minimize infrared transmission with minimum reduction in the visible light spectrum. Green glass exhibits excellent properties in this regard.

2.4.1.4 Low-Iron Glass

Low-iron glass is used extensively in structural glass facades. The low iron-oxide content of the melt produces a glass without the slight greenish tint that characterizes conventional clear glass, and provides a noticeably more transparent product. A cost premium in the range of 10 to 20% over clear glass is typical. The material is available under the industry trade names of Diamont by Saint Gobain, UltraWhite by Guardian, Optiwhite by Pilkington, and Starphire by PPG.

2.4.1.5 Monolithic

Monolithic glass refers to a glass panel comprised of a single sheet of glass. The glass can be tinted, coated and otherwise processed, but used as a single sheet. Monolithic glass is frequently used in structural glass facades, as it provides for a distinctly smaller silicone joint that enhances the overall effect of the façade transparency. The side effect of this strategy is poor thermal performance, and for this reason insulated glass panels are often used, particularly in temperate climates where cold winters can present thermal challenges to enclosures with large areas of glazing.

2.4.1.6 Laminated Glass

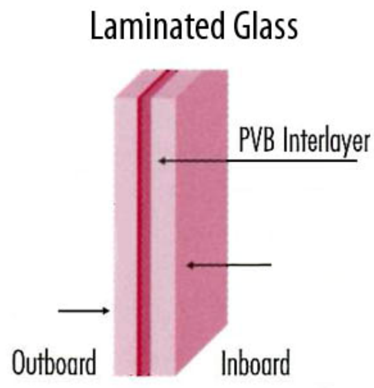


Figure 2.26 Diagram of laminated glass (Viracon 2006).

Laminated glass consists of two or more pieces of glass bonded together by a piece of plastic/vinyl called polyvinyl butyral (PVB.) A minimum interlayer thickness of .030 (.76mm) meets the requirements of ANSI Z97.1 or CPSC 16 CFR 1201 safety glazing standards. (Viracon 2008) Laminated glass can utilize tinted glass, high-performance coatings, silk-screened patterns and pigmented interlayers together or alone.

The gluing or laminating of sheets of glass in layers evolved as a strategy for strengthening the resulting panel and providing additional safety by eliminating the risk of injury from sharp glass shards resulting from the breaking of monolithic glass; if one sheet breaks the broken sheet will be held in place by the interlayer material. The process was invented and developed by the French scientist Edouard Benedictus, who patented his new safety glass under the name "Triplex" in 1910. (DuPont 1995)

Polyvinyl butyral (PVB) is the most common interlayer material. It is available in rolled sheet form in various thicknesses. The thickness of the laminate, or interlayer, is usually a function of the thickness of the glass pieces being laminated. In the glass grids used in structural glass facades requiring pane thickness generally in the ¼ inch (6mm) to ½ inch (12mm) range, 1/16 inch (1.5mm) thick PVC would be used. Overall thickness of the fabricated 2-ply panel would then be 9/16 inch (13.5mm). The process involves compressing the glass/PVB/glass sandwich and heating it in an autoclave. The translucent PVB becomes a clear, tough material adhering to the glass surfaces and binding the two pieces of glass firmly together. If one piece of glass breaks, the glass will remain stuck to the interlayer and not fall from the panel. Even if both pieces of glass break, the shards will not separate from the panel, although the panel can deform and potentially separate from its support.

Laminated glass can utilize tinted glass, high-performance coatings, silk-screened patterns and pigmented interlayers together or alone. Laminated glass is required by building codes in overhead applications, and in sloped glazing angled 15 degrees or more off vertical.

Laminated glass is finding increased use in security applications. Multiple laminations, and laminations including a combination of polycarbonate and glass, have been shown to provide resistance to bullet and blast loads. Multi-laminates up to 100mm or more can be produced. (Wiggins 1996, p.263) Impact loads such as those resulting from airborne debris caused by major wind events such as hurricanes are another security concern. The South Florida Building Code stipulates requirements for impact loads, and glass and window systems used there must be tested to show conformance. Laminated glass plays a key role in meeting these performance criteria. Solutia and DuPont both manufacture interlayer products specifically designed for improved performance under extreme loading conditions. SentryGlas Plus, Saflex HP, Vanceva Storm, are trade names for a few of the available materials.

Acoustics is another reason for the use of laminated glass. The interlayer has sound diffusing properties that result in improved acoustic performance. The lamination material and thickness, and the sizes of the laminated glass pieces, all have an impact on the acoustic properties. This is discussed further below.

As a strengthening strategy, laminating has some advantages over heat-strengthening, although the two strategies are often combined in structural glass systems. Laminated annealed glass can be worked after laminating. The glass is also free of the distortions that can occur from the heat-treating process. Some structural glass facades have used a laminated panel comprised of a tempered back ply to provide optimum strength with an annealed outer ply to reduce distortion in the reflected images.

Most laminated glass is simply comprised of the laminating material between two glass sheets; a 2-ply panel. Multi-ply laminates have become common over the past two decades, however, in structural glass applications, and security applications as mentioned previously. Glass stair treads and landings are typically comprised of three or more ply. Beam and column elements integrated into the design of structural glass facades, as well as other forms of all-glass structures, are sometimes comprised of multiple-ply laminations.

Some interlayer materials maintain translucency after laminating, producing an effect similar to sandblasted glass without the problem of keeping it clean (the sandblasted surface picks up smudges and fingerprints very easily). The laminate material can provide a decorative effect also. A range of tinted and patterned laminates have become available, with more choices appearing on a daily basis as the industry competes for the attention of designers. Other laminating materials are available with properties that improve thermal performance, fire safety and security.

As discussed earlier, the weather seal in most structural glass facades, and all point-fixed glass systems, is provided by a field-applied wet silicone joint between adjacent panes of glass, with the silicone adhering to the glass pane edges. With laminated glass the silicone material will be in contact with the exposed laminate at the glass pane edges. (fig) Problems can result if the interlayer is not compatible with silicone. Some laminated glass installations as described here have experienced a clouding of the interlayer emanating from the edge of the glass and spreading inward as much as approximately 1 inch (25mm). (A similar problem can occur with laminated panels whose edges are left exposed to the elements.)

Newer laminates are available that manufacturers claim are compatible with silicone material. Such compatibility should be a clear specification requirement, or measures should be taken to treat the edge to isolate the silicone from the interlayer laminate. Coatings are available for this purpose, and inquiry should be made with the manufacturer of the interlayer.

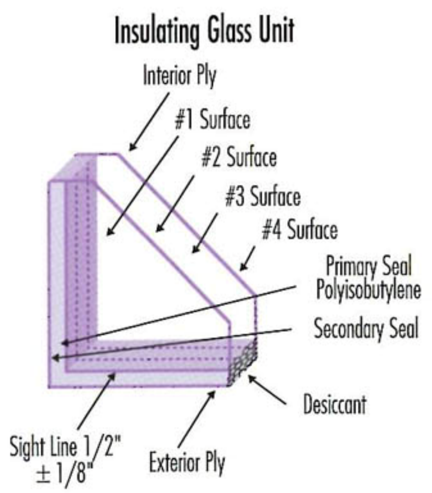


Figure 2.27 Diagram of insulated glass unit (IGU) (Viracon 2006).

2.4.1.7 Insulating Glass Unit (IGU)

Insulating glass is comprised of two glass components separated by an air spacer and hermetically sealed. Inherently, insulating glass increases a window's thermal performance. (Viracon 2008)

Alvar Alto was the first to use multiple-glazed panels in 1930, and by mid-century they had become a standard industry product (Wigginton 1996, p.97). The primary reason for using multiple-glazing, or insulated glass units (IG's) as they are often referred to, is their enhanced thermal performance. The air cavity trapped between the sheets of glass acts as an effective insulator. IG's are most frequently double-glazed panels, but triple-glazed panels are becoming increasingly frequent, and more layers are possible.

Early problems encountered with multiple-glazed panels primarily having to do with moisture entering the air cavity because of a compromised seal, have been largely eliminated. The fabrication process is completely automated for a wide range of configurations, which has improved quality and reduced cost. The process involves the bending of an aluminum spacer bar to match the panel shape, pressing pre-cut and cleaned glass sheet on each side of the spacer, and the application of sealant around the entire perimeter. The perimeter seal is generally comprised of two materials and is called a dual seal; a primary seal of polyisobutylene and a secondary seal of silicone. Other materials are sometimes used as the single seal or secondary seal. As the weather seal in most structural glass facades is provided by a field applied silicone between adjacent glass panels, the silicone material must adhere to the edges of the glass panels. It is therefore critical that silicone, or a material compatible with silicone be used as the outer seal on the IG's.

The aluminum space contains a desiccant material that works to absorb moisture that may inadvertently enter the cavity. The spacers are typically anodized aluminum, and the aluminum color of the spacer is visible within the air cavity. Some manufacturers are offering the spacer in black.

Insulated glass units can be made of varying glass thickness and air cavity depth; the larger the air cavity the better the thermal performance. Other techniques are also used to improve thermal behavior. Certain gasses with improved insulation properties over air, such as argon, can be used to fill the cavity of the IGU. Body-tinted glass can be used, and various coatings such as low-e discussed below, can be combined in the IGU makeup. Various products are on the market that make use of the air cavity to improve thermal properties and light transmittance; infill materials ranging from gels to special miniature Venetian blinds. U-values (see 2.4.3 below) are improving, and ongoing research and development continues to be highly productive in improving the thermal performance of glass. Some of these products are expensive, but as energy costs rise and use of these products increases, product costs can be expected to drop.

2.4.1.8 Laminated Insulating Glass

Glass panel fabrications can be both insulated and laminated. Insulating laminated glass is an IG unit in which the exterior component is a monolithic glass ply and the interior component is a 2-ply laminate. If thermal performance demands necessitate the use of multiple-glazing and the glass is to be used in an overhead or sloped application, it must be both insulated and laminated. The laminated glass would go to the inside of the panel so that breakage of the non-laminated panel would be prevented by the laminated panel from falling within the building enclosure.

Laminated-insulated panels can get quite thick and heavy, and consideration must be given to their size. They can also be expensive in point-fixed drilled glazing systems, as every IGU will require at least 12 machined holes. The do however, offer great flexibility in the application of frits and coatings because of the additional surfaces interior to the panel. Different frit patters are sometimes silk-screened on to multiple surfaces to interesting effect.

Double Laminated Insulating Glass is also available for special applications.

2.4.1.9 Frits and Coatings

Coated glass is a general reference to any glass incorporating a reflective or low-e coating. Glass coating materials and processes is one of the most exciting development areas in the architectural glass industry, with real promise for improving the thermal and acoustical behavior. Although there is much overlap, the various glass manufacturers use different materials and processes, so it is important to research their relative products and capabilities. Information relative to the performance coatings is included in the section on thermal performance below.

Solar Reflective Coatings

Solar reflective coatings are a class of coatings with high solar reflection properties, used to produce solar control glass. Solar control glass can be tinted coated, and reduces the amount of transmitted solar heat gain. Most reflective coatings consist of thin metallic layers applied by a process of vacuum (sputtering) deposition. The coatings come in various metallic colors including bronze, gold, silver and others depending upon the manufacturer.

Solar control glass is used primarily to control solar heat gain, so is most appropriate to hot climates. These coatings were often used in the 1970's and 1980's for their unique aesthetic, effectively creating multi-surfaced mirrors out of high-rise towers. The major drawback of these coatings is that the reflectance of visible light significantly reduces daylight inside the building, often increasing the need for electrical lighting and offsetting any reduction to cooling loads.

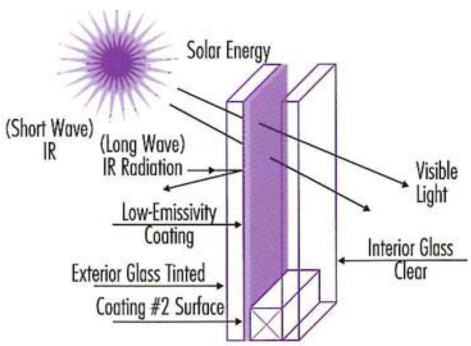


Figure 2.28 Diagram of low-E function (Viracon 2006).

Low-E Coatings

A more effective coating strategy is the Low-E, or low emissivity coating. Emissivity is partially a measure of a surface's ability to emit long-wave infrared radiation, or heat, and Low-E coatings are used to reflect this radiation, thus reducing heat gain or loss by redirecting the heat. In contrast to the reflective coatings discussed above, Low-E coatings have lower reflection and greater light transmission. According to the US Department of Energy's EERE (Energy Efficiency and Renewably Energy), Low-E coatings may add 10-15% to the cost of glass products, but reduce energy loss by as much as 30-50%. As of the end of 2006, the EERE claims that half of all window products sold have Low-E coatings, and that these products have saved the Country over USD 8 billion. (EERE 2005)

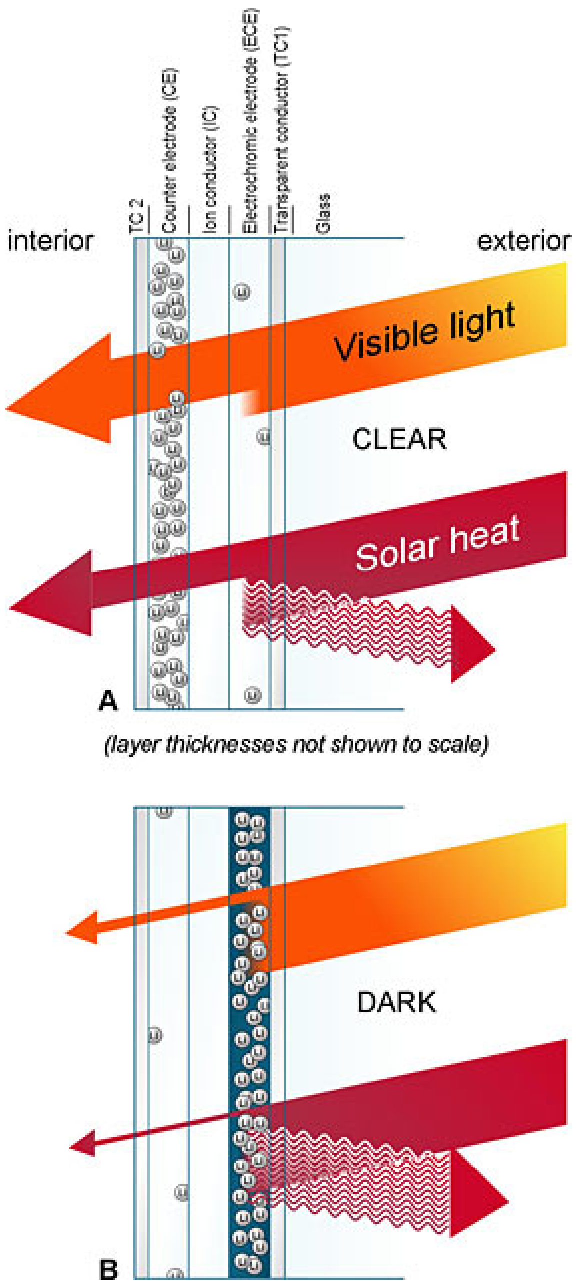
Low-E coatings are often used in combination with tinted glass to reduce heat gain and glare. Short-wave solar energy (IR) strikes the tinted exterior glass ply and is absorbed and converted into long-wave infrared, or heat. A Low-E coating on the #2 surface redirects the heat outdoors (Viracon 2006).

Variations of Low-E coatings provide for high, moderate or low solar gain. Spectrally selective versions are available to prevent reduction to visible transmittance. The coating is a microscopic deposition on a glass surface as with the reflective coatings above. It can be applied to one or more surfaces in IG's. The coatings come in soft and hard coats. The soft coats degrade on exposure to air and moisture, and are easily damaged, so are used on the inner surfaces of an IG. Hard coats are deposited through a process of pyrolytic deposition that takes place as an integral part of the float glass process. Hard coats are tough and can be used on an exterior surface. In hot climates or to keep heat out, the Low-e coating is applied to an outer surface, usually the number 2 surface on a LG or IG. In cold climates where the need is to retain indoor heat, the coating should be applied to the inner glass, or number-3 surface.

Electrochromic and Photochromic Glass

As noted in Chapter 1, the inherently poor thermal behavior of glass is a threat to its future use in a world threatened by rapid climate change and a toxic dependency upon cheap oil for energy. However, possibility of zero net energy glass products grows closer every day, and visionaries see the day when glass can be a net energy producer. Material scientists are developing “intelligent” materials, glass among them, which adapt to change in the environment. Producers are already working to develop a new generation of glazing materials that incorporate these properties. Among the most promising are electrochromic, or switchable glass, and photochromic glass that changes properties in response to changing conditions in the environment, such as light levels or direct solar penetration.

Sage Electrochromics is one such company.



The illustration on the left shows what happens when a SageGlass window is switched. (A) The SageGlass coating on the glass is made up of five layers. When voltage [less than 5V DC] is applied to these layers in their "clear" state, they darken as lithium ions and associated electrons transfer from the counter electrode to the electrochromic electrode layer. (B) Reversing the voltage polarity causes the ions and associated electrons to return to their original layer, the counter electrode, and the glass untints. This solid state electrochromic reaction is controlled through a low voltage DC power supply. When the SageGlass coating darkens, the sun's light and heat are absorbed and subsequently reradiated from the glass surface – much the way low-emissivity glass also keeps out unwanted heat. (Sage n.d.)

Figure 2.29 How Sageglass technology works (Sage n.d.).

Working with the Lawrence Berkley National Laboratory under a grant from the US Department of Energy, Sage Electrochromics is developing new window product utilizing

SageGlass. The diagram and text above, obtained from the Sage website, explain how the product works.

Ceramic Frits

A ceramic frit is an enamel applied to glass for aesthetic purposes or to limit transparency. The ceramic material is usually applied in a pattern using a silk-screening process prior to heat-treating. The glass is then run through an infra-red oven to dry the frit and then a tempering oven and the frit is permanently fused to the glass surface. It is a very tough material and can be applied to the exterior surface of glass, but is often applied to the number-2 and/or number-3 surface of an IG or LG. The frit material comes in various colors, and can simply be used for decorative effect. Most glass producers have standard frit patterns, but custom patterns are easily provided.

Silkscreen Printing

Silkscreen is a printing process used in the glass industry to apply a design or pattern to a glass surface. The process is applied by placing a patterned screen over a glass surface and pressing ceramic frit, by means of a large squeegee, through the pores of the screen.

2.4.1.10 Bent Glass

Glass bending is a specialty field within the architectural glass industry. Monolithic, insulated and laminated bent units are all possible. Annealed glass is typically heated in an oven and allowed to slump over a form to create the bends, then gradually cooled. The curves are generally limited to one direction, although double-curvature glass has been experimented with on some projects such as the Conde Nast interior by Gehry Partners, and the Glass Umbrella by Eric Owen Moss Architects. Special equipment is required to temper bent glass and not all bent glass producers have this capability. Some bent glass may be difficult or impossible to temper, depending upon the surface geometry.

2.4.1.11 Specifying Glass

Specifying glass is challenging simply because of the large number of available options. Viracon offers over 350 different kinds of insulated glass alone. Fortunately, the various glass manufacturers and fabricators have excellent online technical support for this purpose.

Coatings and frits are specified by surface. Monolithic glass has two surfaces, 2-ply laminated glass and insulated glass have four, insulated laminated has six, and so on. The number one surface is to the outside of the building. Most frits and coatings are specified on the number two or three surface where they are better protected. The manufacturers offer recommendation based upon panel makeup, coating material and function.

2.4.2 Glass as Structural Material

Glass is being used increasingly as a structural material. Even before the discovery of heat-treating glass as a means to enhance the strength of the material, the 19th century conservatory designers and builders were using glass as a stressed-skin to stabilize the irons structures supporting them. Glass is a very strong material but its extreme brittleness presents certain challenges in structural applications.

2.4.2.1 Heat-treating

Heat-treating typically refers to the post processing of float glass product to improve its strength and/or to alter its breakage behavior. Glass is annealed as part of the float glass process, and annealing itself is a form of heat-treatment.

Heat-treating or toughening is a process developed by the French in 1928. This process provided the material necessary for the structural glass systems to follow decades later. All point-fixed glass systems utilize heat toughened glass. There are two kinds of heat-treated glass, heat-strengthened and fully tempered. Fabrication requirements, tolerances, and testing procedures for heat-treated glass are defined in the ASTM International document C 1048.

Table 2-7 Characteristics of heat-treated glass (GANA 2005, p.7).

Glass Characteristics

Performance Characteristics	Monolithic Annealed	Heat-Strengthened	Fully Tempered	Laminated Annealed	Laminated Heat-Strengthened[1]	Laminated Fully Tempered[1]
Wind-loading strength	Basic Glass Strength (1x)	Two times basic glass strength of the same thickness (2X)	Four times basic glass strength of the same thickness (4X)	75% - 100% as strong as monolithic annealed of the same thickness	Almost twice as strong as laminated annealed of the same thickness (1.5X - 1.8X)	Almost four times as strong as laminated annealed of the same thickness (3.0X - 3.6X)
Thermal stress breakage resistance (edge-strength)	Low resistance to high thermal stresses	Resists high thermal stresses	Resists high thermal stresses	Low resistance to high thermal stresses	Resists high thermal stresses	Resists high thermal stresses
Impact Resistance[2]	Moderate	Stronger than annealed	Stronger than heat-strengthened. Can qualify as "Safety Glazing"	Moderate. Can qualify as "Safety Glazing"	Stronger than annealed. Can qualify as "Safety Glazing"	Stronger than heat-strengthened. Can qualify as "Safety Glazing"
Break pattern upon impact	Many cracks forming large, long, and narrow shards	Simple, few cracks and larger pieces	Entire lite breaks into small, irregular shaped fragments.	Starburst pattern from impact point, one or both lites may break	Simple, few cracks and larger pieces, one or both lites may break	One or both lites may break into small, irregular shaped fragments.
Penetration resistance (after breakage)	Limited after breakage	Limited after breakage	None after breakage	Good penetration resistance (proportional to interlayer thickness)	Good penetration resistance (proportional to interlayer thickness)	Good penetration resistance (proportional to interlayer thickness)

1 - Laminated heat-treated glass may have more distortion in transmission than laminated annealed glass.
2 - Impact resistance and break pattern after breakage are dependent upon the size, weight and type of impactor and the speed at which it impacts the glass.

2.4.2.2 Annealed Glass

Annealing is a process of controlled heating and cooling of a material in a manner to remove internal stresses. With glass, the term refers to the gradual cooling of manufactured glass for the same general purpose; annealed glass is free of internal stresses that can result in breakage from outside stresses induced by such things as bending (as from wind) or rapid thermal change. Annealing is required to facilitate the easy and uniform cutting of glass. Annealing is incorporated into the float glass process by which the vast majority of the world's architectural glass is produced, and the untreated glass from this process is referred to as annealed glass. Subsequent processing, such as bending during which the glass is heated, may require that the glass be annealed again.

2.4.2.3 Tempering

Tempering or toughening are terms used interchangeably in the glass industry. Tempering is a secondary process whereby annealed glass is subject to a cycle of carefully controlled heating and subsequent rapid cooling. After all cutting and machining work have been completed on a piece of annealed glass it is run over rollers through a tempering oven, heating it to approximately 1,150° F. On reaching this temperature the glass exits the furnace and is rapidly cooled by airflow over both surfaces simultaneously. The glass first cools and contracts at the surface, but as the interior glass cools and contracts more gradually it pulls the contracted outer surface into high compression. The end result is the core in tension and the surface in compression. (Wigginton 1996, pp.262-263)

Improved strength and resistance to thermal stress result from the tempering process. Fully tempered glass is up to four to five times stronger than annealed glass. Tempered glass also possesses a unique behavior when broken; the glass shatters into rounded kernel size pieces without sharp edges. Because of this attribute, tempered glass is sometimes referred to as *safety glass*, and building codes require its use in doors and other public areas. Tempered glass cannot be worked, cut or drilled; all such working must be completed prior to tempering.

Modern day glass produced by the float process is a remarkably flat material of high surface quality. The tempering process involves moving these flat glass panels through a specially designed oven. These ovens are custom in design and can vary substantially in width between fabricators. The tempering oven can be the limiting factor in the maximum glass dimension, and must be considered during façade design, especially if the intent is to use very large pieces of glass.

Fully Tempered Glass (FT)

Glass that has been heat-treated to have either a minimum surface compression of 10,000 psi or an edge compression not less than 9,700 psi in accordance with the requirements of ASTM C 1048, kind FT or meet the requirements of ANSI Z97.1 or CPSC 16 CFR 1201 safety glazing standards. Tempered glass is 4-5 times stronger than annealed glass, and when broken, breaks into small, relatively harmless, pieces.

Glass with fully tempered surfaces is typically four times stronger than annealed glass and two times as strong as heat-strengthened glass of the same thickness, size and type. In the event that fully tempered glass is broken, it will break into fairly small pieces, reducing the chance for injury. In doing so, the small glass shards make it more likely that the glass will become separated from the opening. The minimum surface compression for fully-tempered glass is 10,000 psi. In addition, it complies with the safety glazing requirements as outlined by the American National Standards Institute (ANSI) Z97.1 and the federal safety standard Consumer Products Safety Commission (CPSC) 16 CFR 1201.

2.4.2.4 Roller-wave

The glass panel lies on a horizontal bed of rollers as it moves through the oven. As the glass is heated in the tempering process and approaches its plastic state, it is subject to slumping between the supporting rollers resulting in a wavy glass surface called roller-wave. Glass is seen largely though the reflections it produces, and excessive roller-wave can be seen in the distorted reflections produced by the wavy glass surface.

The direction of the waves should be installed in the horizontal direction, meaning that the vertical dimension of the glass should be parallel to the rollers during tempering. This may not be possible if the glass module has a landscape as opposed to portrait orientation. Laminated glass (two panes of glass glued together with a plastic interlayer as described later) may exhibit worsened distortion if the roller-wave of each piece is coincident, producing a lens affect. (Excessive roller-wave in laminated glass can also cause delamination.) All tempered glass will exhibit some level of roller-wave, but the magnitude can vary widely between manufacturers.

In high quality frameless glass systems, roller-wave is an important consideration, and an appropriate tolerance should be determined and specified. Unfortunately, in the US, the industry standard for heat-treated glass, ASTM C1048 Standard Specification for Heat-Treated Flat Glass-Kind HS, Kind FT Coated and Uncoated Glass, discusses distortion but defines no tolerance or minimum standard. Roller-wave tolerances can be specified within certain limits, although not all manufacturers will be able to meet a more demanding specification.

Bow and edge lift are also possible forms of distortion resulting from the heat-treating process, though of lesser concern. Pilkington has set the leading industry standard with respect to roller wave distortion in the production of their architectural glass, significantly bettering regulatory standards where they exist.

Table 2-8 Data compiled from the websites of Viracon and Pilkington regarding distortion resulting from heat-treatment (Viracon 2008b) (Pilkington n.d.).

Type of distortion		Published Tolerance	
	Viracon	Pilkington	Standards*
Overall bow – in/linear ft	0.031	0.024	0.062
Overall bow – mm/305mm	0.787	0.61	1.575
Roller wave			
(peak to trough in inches)	0.003	0.0008	no standard
(peak to trough in mm)	0.076	0.02	
Edge lift – inches **	0.008	0.009	
Edge lift – mm **	0.20	0.229	

* ASTM C1048 Standard for Heat-treated Flat Glass

** within 10.5 in (267mm) of leading and trailing edges

2.4.2.5 Nickel Sulfide Inclusions and Spontaneous Breakage

Nickel Sulfide is a contaminant, a small stone or crystal that can be present in float glass. In annealed glass it presents no problem, but in tempered glass has been identified as the source for rare occurrences of spontaneous breakage, whereby the glass shatters for no apparent reason. Low quality glass production may result in a higher occurrence of the contaminant.

Interestingly, in Asia and other developing areas of the world where local glass supply may be of lesser quality, some structural glass façade designers are moving away from the use of tempered glass, regarding the spontaneous breakage problem as simply too risky to tolerate. Instead, they are using heat-strengthened laminated glass panels (see laminated glass above). In fact, perhaps owing largely to liability concerns, glass fabricators in North America are cautioning against the use of tempered glass unless required for reasons of safety or strength. Viracon's website includes the following statement:

> *"Although the incidence of tempered glass breakage due to these inclusions is rare, greater publicity of their occurrence has resulted in an increased awareness of this phenomenon. In fact, limiting the use of tempered glass in commercial building applications has become the recommendation of a number of glass suppliers, including Viracon." (Viracon 2008c)*

2.4.2.6 Heat-soaking

Heat-soaking is a process devised in response to the nickel sulfide and spontaneous breakage problem. In this process, glass is heated to a specified temperature, usually about 290°C, held there for some specified time, usually several hours, and occasionally even subjected to several cycles of this heating and cooling. The practice is somewhat controversial in its effectiveness, and adds to the cost of tempered glass product, but has become a standard practice for many structural glass producers and users.

On specification for heat-soaking is the European Din standard requiring a minimum 12 hour cycle at a temperature of 290C.

2.4.2.7 Heat Strengthening (HS)

Partially tempered, partially toughened, or heat strengthened are equivalent terms for a heat-treatment of glass yielding a material with strength properties between that of annealed and fully tempered glass. Heat strengthened glass is two to three times stronger than annealed glass, whereas tempered is four to five times stronger. Heat-strengthened glass has a surface compression between 3,500 and 7,500 psi and conforms to the requirements for ASTM C 1048, kind HS. Heat strengthened glass has improved resistance to thermal stress, but has a break behavior closer to annealed glass, so cannot be used in safety glass applications. HS does not meet the requirements of the American National Standards

Institute (ANSI) Z97.1 or the federal safety standard Consumer Products Safety Commission (CPSC) 16 CFR 1201.

2.4.2.8 Chemical Tempering

Glass can also be tempered chemically as an alternative to a heat-treatment process. These processes are relatively new, and effective only in glass thinner than that typically used in buildings. However, it may emerge as an effective future process that could eliminate the distortion caused by the heat-treatment process, and provide for easier tempering of bent glass.

2.4.2.9 Laminated Glass

As discussed previously, modern techniques of glass lamination are highly effective in enhancing the load-bearing capacity of glass, and the safety of its use. Laminated glass has significant increased usage where issues of safety, security, sound attenuation, and strength are predominant design considerations.

2.4.2.10 Maximum Glass Sizes

Size is often an issue with structural glass facades. Higher transparency can be achieved with larger glass sizes. Supporting structural systems typically follow the glass grid, so as these sizes increase the amount of structure decreases. This can quickly create complexity and cost in the structural systems. There are a number of other practical considerations with respect to glass size, such as handling (glass is heavy and large panel constructs can be challenging to handle through the fabrication and construction process), and transportation. These considerations aside, the façade designer often wants to know the limitations of size. Most glass as used in structural glass facades has some manner of secondary processing involved in its makeup; tempering, insulating, laminating, all these process may impact the maximum width a fabricator may produce as a function of their equipment. Raw float glass is more uniform:

*"Float glass thickness range from below 2 mm to over 25 mm for architectural purposes. They are usually 3, 4, 5, 6, 8, 10 and 12 mm thick, with 15, 19 and 25 mm for special uses. There is only one architectural quality for float glass. Most float lines have ribbon width just over 3 metres [*sic*]; available sizes depend on handling and shipping limitations rather than the manufacturing plant. Sizes which can be manufactured are not necessarily the sizes which can be directly used. Clear float is generally available in maximum size of 3,180 * 6,080 mm for all thickness of 3, 4, 5, 6, 8, 10 and 12 mm. For thick clear float (15, 19 and 25 mm) the maximum size will sometimes be smaller. " (Button et al., 1993, p.356)*

Float sheet from the glass producer generally comes in two sizes; split in 96 by 130 (2438 by 3302) and jumbo in 130 by 204 in (3302 by 5182mm). Working with the jumbo size requires special equipment that many smaller glass fabricators do not possess. There can be efficiency associated with using the jumbo sizes, as less waste glass results from the fabrication process.

Table 2-9 shows the maximum tempered glass sizes available from Viracon. These sizes will vary between manufacturers. If a large glass grid module is desired, it is important to verify glass size availability when determining the glass module as discussed in Chapter 7.

Table 2-9 Maximum glass sizes.

Glass Thickness	Tempered Glass Maximum Size		
3/16" (5mm)	84" x 165" or 96" x 144"	|	mm 2134 x 4191 or 2438 x 3658
1/4" (6mm)	84" x 165" or 96" x 144"	|	mm 2134 x 4191 or 2438 x 3658
5/16" (8mm)	84" x 165" or 96" x 144"	|	mm 2134 x 4191 or 2438 x 3658
3/8" (10mm)	84" x 165" or 96" x 144"	|	mm 2134 x 4191 or 2438 x 3658
1/2" (12mm)	84" x 165" or 96" x 144"	|	mm 2134 x 4191 or 2438 x 3658
5/8" (16mm)	84" x 165" or 96" x 144"	|	mm 2134 x 4191 or 2438 x 3658
3/4" (19mm)	84" x 165" or 96" x 144"	|	mm 2134 x 4191 or 2438 x 3658

Figure 2.30 Size limitations of tempered glass (Viracon 2008d).

In addition to length and width limitations, manufacturers often have limits on the area of the glass pane. The most common maximum recommended glass area is 65 ft^2 (6.04m^2). Glass used in overhead applications is generally required by code to be laminated, and depending upon thermal requirements may be laminated insulated with the lower panel being laminated. Many manufacturers limit the size of overhead panels to 35 ft^2 (3.25m^2).

According to Joe Green, CEO of Glass Pro, a glass fabricator in Southern California that does glass bending and provides glass fabrications for point-fixed applications, the company can provide tempered glass up to 84 by 168 in (2134 by 4267mm), laminated glass up to 120 by 180 in (3048 by 4572mm) (narrower widths can be made longer), and 96 by 130 (2438 by 3302mm) for IGU's (larger sizes can be produced by hand). Glass Pro also has a CNC machine, used for notching, drilling, countersinking, and other glass machining operations, the can handle sheet sizes up to 98 by 170 in (2489 by 4318mm). (J Green 2008, pers. comm., 18 Mar.)

Viracon publishes size guidelines that are available for download as an Acrobat (*.pdf) file; Vircon size guidelines

2.4.3 Thermal and Acoustic Performance Issues

2.4.3.1 Thermal Performance vs. Transparency

As noted earlier, monolithic or laminated glass provides the highest level of transparency in structural glass façade applications. While insulated glass units provide superior thermal performance, and are often used for this most excellent reason, there is a price to pay in relative transparency. The edges of the spacer in the IGU are sealed to the glass with a black material, so there is a visible black band around the perimeter of an IGU that is the thickness of the spacer; about 3/8". An opaque sight line is formed between two glass panels, spanning from the inner spacer edge of one panel, across the weather seal between the panels, and to the inner spacer edge of the adjacent panel. The weather seal is typically approximately equal to the overall thickness of the IGU. A common IGU makeup is two 1/4" pieces of glass with a ½” air space, for an overall panel size of 1”. (Point-fixed applications may sometimes require larger thickness in one or both pieces of glass, increasing the overall size of the panel.) Thus, the overall sealant site-line (corresponding to the glazing grid) is over 1-3/4” wide. Framed glazing systems can approach this same dimension, and are sometimes selected over point-fixed systems in these applications as they may provide improved economy at little or no relative loss of overall facade transparency.

The thermal performance of glass is at odds with transparency. The offsetting attribute of transparency, however, is daylighting. The balancing of these behaviors is a challenge in the design of any enclosure with a large glazed area. Too often this problem has been dealt with by the MEP engineer specifying some massive HVAC equipment. Fortunately, the façade designer has an increasing array of materials and techniques. This topic, while of critical importance, is not central to this thesis and the material beyond the scope of this document. It is imperative however, that the designer understand the performance issues involving glass, a primary material in the technology of structural glass facades. Toward that end, what follows is a definition of key terms and concepts taken from the Viracon website that every designer must understand in order to select and specify an appropriate glass material on any façade project.

The following informative definitions and information are from the Viracon website, a valuable resource for the façade designer. (Viracon 2008e)

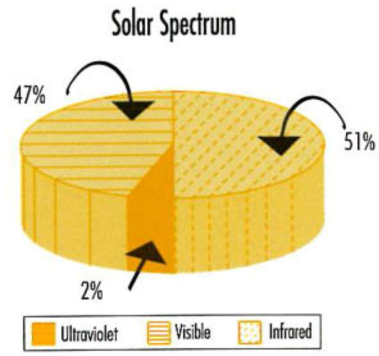


Figure 2.31 Chart of solar spectrum (Viracon 2006, p.4.)

Solar Spectrum

Sunlight is comprised of 2% ultraviolet light (UV), 47% visible light and 51% infrared (IR). Wavelength is a measure of the solar spectrum; a nanometer (nm) is a unit of length where 1nm = 10^{-9m}. Visible is in the middle of the spectrum in the range of ~380 – 780 nm. UV is in the range of ~300 – 380, and can have damaging effects on everything from skin to plastic and upholstery. IR is in the range of ~ 780 – 3000 nm and can have a problematic heat effect; short-wave IR converts to heat energy when absorbed by an object.

Solar Energy and the RAT Equation

When solar energy meets glass, portions of it are reflected, absorbed or transmitted – giving you the RAT equation – which accounts for 100% of solar energy, which is equal to the sum of solar reflectance, absorption and transmittance. Example: a single pane of 1/8 in (3mm) clear glass transmits 83%, reflects 8% and absorbs 9%. Absorbed energy is emitted back partially to the interior and partially to the exterior. (See Figure 2.32 and Figure 2.33 following.)

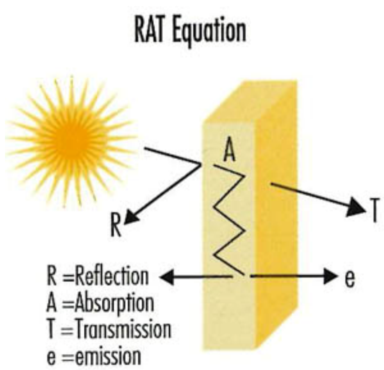


Figure 2.32 RAT equation (Viracon 2006).

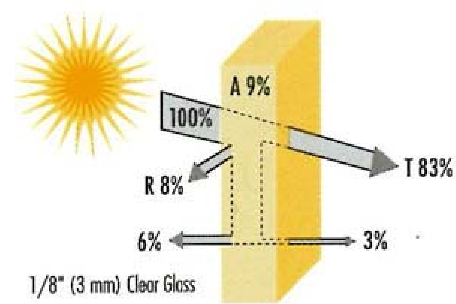


Figure 2.33 RAT equation example (Viracon 2006).

Visible Light Transmittance

The percentage of visible light (380 - 780 nm) that is transmitted through the glass.

Solar Transmittance

The percentage of ultraviolet, visible and near infrared energy (300 - 3000 nm) that is transmitted through the glass.

Visible Light Reflectance

The percentage of light that is reflected from the glass surface(s).

Solar Reflectance

The percentage of solar energy that is reflected from the glass surface(s).

NFRC U-Value

A measure of heat gain or heat loss through glass due to the differences between indoor and outdoor temperatures. These are center pane values based on NFRC standard winter nighttime and summer daytime conditions.

U-values are given in BTU/(hr*ft2*°F) for the English system. Metric U-values are given in W/(m2*°K). To convert from English to metric, multiply the English U-value by 5.6783.

NFRC winter nighttime U-values are based on an outdoor temperature of 0°F (-17.8°C), an indoor temperature of 70°F (21°C) and a 12.3 mph (19.8 km/h) outdoor air velocity.

NFRC summer daytime U-values are based on an outdoor temperature of 89°F (32°C), an indoor temperature of 75°F (24°C), a 6.2 mph (10.1 km/h) outdoor air velocity and a solar intensity of 248 BTU/(hr*ft2*°F) (782 W/m2).

R-Value
Thermal resistance is expressed in ft2*hr*°F/BTU. It is the reciprocal of U-value. The higher the R-value, the less heat is transmitted through the glazing material.

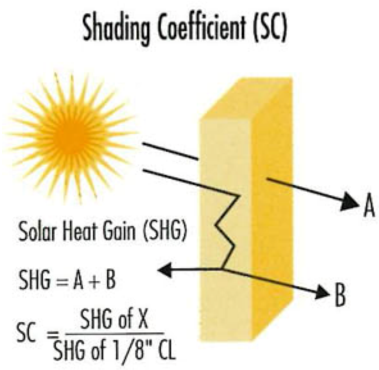


Figure 2.34 Diagram of shading coefficient (Viracon 2006, p.4).

Shading Coefficient
Shading coefficient is the ratio of solar heat gain through a specific type of glass that is relative to the solar heat gain through a 1/8" (3 mm) ply of clear glass under identical conditions (see Figure 8). As the shading coefficient number decreases, heat gain is reduced, which means a better performing product.

Relative Heat Gain (RHG)
The amount of heat gained through glass taking into consideration U-value and shading coefficient. Using the NFRC standard, relative heat gain is calculated as follows:

English System:

RHG = Summer U-value x 14°F + shading coefficient x 200.

Metric System:

RHG = Summer U-value x 7.8°C + shading coefficient x 630.

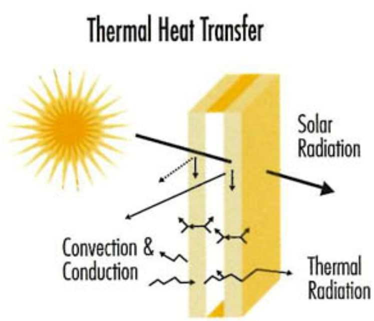


Figure 2.35 Diagram of thermal heat transfer mechanisms (Viracon 2006, p.4)

Solar Heat Gain Coefficient (SHGC)
The portion of directly transmitted and absorbed solar energy that enters into the building's interior. The higher the SHGC, the higher the heat gain.

Light-to-Solar-Gain Ratio (LSG)
The ratio is equal to the Visible Light Transmittance divided by the Solar Heat Gain Coefficient. The Department of Energy's Federal Technology Alert publication of the Federal Energy Management Program (FEMP) views an LSG of 1.25 or greater to be Green Glazing/Spectrally Selective Glazing.

European U-Value (formerly K-Value)
Based on ISO-DP10292 draft standard conditions. It is based on an outdoor temperature of 5.5°C, an indoor temperature of 20.5°C and a 4.8 m/s outdoor air velocity.

2.4.3.2 Acoustic Performance: Glass as a Sound Barrier

Glass is an inherently poor acoustical barrier. The acoustic behavior of any wall system, and perhaps especially of glass wall systems, is emerging as an increasingly predominant issue. The world may well be getting warmer, but it is most certainly getting noisier. Noise pollution is a serious problem, especially in major urban environments. The increase in high-rise condominium projects in the cities has many developers and designers concerned about the acoustics of these residential spaces.

Façade acoustic design is a function of utilizing the best performing materials for the frequencies that will be relevant to the architectural purpose. The acoustic considerations for an airport are different than for a shopping mall, and those equally different for a residence. Acoustic design is complex. Different materials display varying behavior as a function of the material properties and the frequency of sound. A sound rating can be determined for a particular glass type, but the glass is usually incorporated into some kind of framing and/or support system, and the system as a whole may exhibit quite different acoustic behavior that the glass in isolation.

Making glass thicker does little to improve its sound transmission loss (STL). In fact, at certain frequencies thicker glass can actually amplify sound. A more productive strategy is to use laminated glass (the PVB interlayer had certain sound dampening behavior), insulated glass, or even better is combinations of the two. Varying the ply-thicknesses of laminated glass can improve acoustic performance.

By evaluating the STL of various tested products, one can optimize the glass performance by carefully selecting the product that provides the greatest STL at the range of frequencies most critical to the building application.

Fortunately, glass producers again provide resources to assist the designer. Producers have tested many combinations of glass type and determined STL ratings. The designer can match STL to the range of frequencies most critical to any particular building application.

Viracon recognizes two rating systems (Viracon 2008e):

> STC Rating
> Abbreviation for Sound Transmission Class Rating. When glass is used on the building interior, the sound transmission classification (STC) value can be used to categorize the glass performance. The STC rating is a single-number rating system for interior building partitions and viewing windows. The STC rating is derived by testing in accordance with ASTM E90, 'Laboratory Measurement of Airborne sound Transmission of Building Partitions". The STC value is achieved by applying the Transmission loss (TL) values to the STC reference contour of ASTM E413, "Determination of Sound Transmission Class". The STC rating is a basis for glass selection. Its original intent was to quantify interior building partitions, not exterior wall components. As a result, it is not recommended for glass selection of exterior wall applications, since the single-number rating was achieved under a specific set of laboratory conditions
>
> OITC Rating
> An abbreviation for Outside-Inside Transmission Class Rating. This rating is used to classify the performance of glazing in exterior applications. It is based on ASTM E-1332 Standard Classification for the Determination of Outdoor-Indoor Transmission Class. While STC rating is based on a "White' noise spectrum, this standard utilizes a source noise spectrum that combines Aircraft/Rail/Truck traffic and is weighted more to lower frequencies.

2.4.4 Glass Specifications

The following specifications are relevant to glass selection.

2.4.4.1 ASTM Specifications

ASTM C1036 Standard Specification for Flat Glass

ASTM C1048 Standard Specification for Heat-Treated Flat Glass

ASTM C1172 Standard Specification for Laminated Architectural Flat Glass

2.4.4.2 Safety Requirements

ANSI Z97.1

CPSC 16 CFR 1201

2.5 Glass Systems

2.5.1 Curtain Wall Systems

Curtain wall systems are cladding systems intended for multi-story buildings. The systems typically span between floor slabs. Early systems used steel framing members, but virtually all contemporary systems are of aluminum. Vertical mullions of extruded aluminum are most commonly used as the spanning members, and the vertical and horizontal mullions provide full perimeter support to the glass. Structural glass facades span longer distances, from roughly 20 feet (or 7 meters), with an upper range defined only by the limits of the structural design. The glass systems used with structural glass facades tend to be different, as discussed following, but curtain wall type systems can and have been used on structural glass facades, but even then their integration with a supporting structural system tends to differentiate them from conventional curtain wall.

The origins of the term “curtain wall” date from medieval times, when the term was used to describe the heavy stone castle walls “draped” between mural towers. They certainly bear little resemblance to the usage that emerged in the early to mid 20th century. The term likely refers to the non-bearing attribute of the cladding technology that emerged at this time and developed through the mid 20th century and on to facilitate the enclosure of the newly developed high-rise steel (and later, reinforced concrete) framing systems. Curtain wall is rather more like a screen that a true curtain. Wigginton (1996, p.110) argues that the suspended glass walls of the Willis Faber & Dumas building are more appropriate to the term, being hung like a curtain from above.

2.5.2 Stick Systems

Most curtain wall systems to date have been constructed of long vertical framing members called mullions, or sticks, spanning across supporting floor slabs. Horizontal mullions span between the verticals. This system is sometimes referred to as a mullion and transom frame. The framing members are shop fabricated, factory painted, and installed a piece at a time. The glass or other cladding panels are then attached to these framing members. The systems are referred to in the industry as "stick-built." This system type is site labor intensive, and site labor, especially in western markets, is at a premium. Consequently, stick systems have been largely replaced by unitized systems (see below).

2.5.3 Veneer Systems

This is a term perhaps not widely recognized in the industry, but useful in describing a variant of the stick system sometimes used with structural glass facades. With conventional curtain wall, the "sticks" must span between floor slabs. Some structure types used with structural glass facades as described in this Chapter, particularly the simple truss systems, provide a high-tolerance steel grid made up of square of rectangular tubing, providing a flat face for the mounting of a continuously supported glazing system (see Figure 2.2). So the aluminum "stick" that is used here requires no spanning capacity; the steel backer is doing all the spanning work. Otherwise, the system is fabricated and installed similarly to the stick system described above. This integration of glazing system and structure provides for greater economy.

2.5.4 Unitized Systems

This is a curtain wall term used to describe systems in which large framed constructs, or units, are built up under factory controlled conditions, shipped to the site, and the entire unit lifted and set into position. Unitized systems allow for maximizing factory labor and minimizing site labor, which provides for the potential of improved quality and greater economy, at least in areas with high field labor rates. Unitized curtain wall is now the system of choice for most curtain wall companies on any large, high-rise building project.

Units are typically designed in response to an installation strategy. Smaller units can be crated and crane-lifted into the building, and small crews can handle the units, installing them from inside. Alternately, large units with transportability being the only restriction on size can be factory assembled, shipped to the site, and each unit crane-lifted separately into position on the building exterior. These units can span multiple floors vertically, and be as wide as transport will allow.

In either case, the factory work involves cutting and fabricating the framing members, assembling the frames, and installing the glass, metal panels, vents, stone, or other cladding materials into the frames. All gaskets and silicone seals are completed in the factory. As each unit must have an autonomous frame, the vertical framing member in the stick system is “split” in the unitized system, sometimes referred to as a split mullion, although the various system designs developed by the industry handle this detail differently. A dry gasket between the units typically provides the weather seal.

Unitized systems are rarely used with structural glass facades, although there is not technical reason to prevent this. The dematerialization of the façade structure, the expression of transparency, was the driving force for the frameless glazing systems most often used on structural glass facades. Unitized systems are inherently framing intensive to provide for the structural integrity of the unit while it is handled in the factory and the field, and would likely prevent a high level of integration between the structural system and cladding as is typical of structural glass facades. However, the reasons for utilizing unitized systems also apply to large structural glass facades, and it is conceivable that a unitized approach could balance the considerations of aesthetics and efficiency.

The rainscreen principle has become a core tenant of contemporary curtain wall design with respect to the prevention of water penetration. While there are variations and subtleties in practice, the basic concept involves the use of two seals, between which sits the glass in what is called the glazing rebate. It is assumed that this seal will be compromised, and water will penetrate into the inner cavity. The chamber is so constructed that moisture is drained to the outside, and ventilated to the outside such that air pressure is equalized between it and the outside. This prevents the possibility of moisture being drawn into joints or defects in the inner seal.

2.5.5 Panel Systems (offset panelized)

Figure 2.36 Detail of a panelized glazing system (ASIDI).

Panelized systems consist of glass panes assembled with framing elements to form a glazed panel. The frames possess structural properties allowing for interim support by the truss system while providing continuous support to the glass pane, thus minimizing deflections to the glass pane itself. The frames can provide two-sided or four-sided support, and can mechanically capture the glass pane or be structurally glued to the glass pane using appropriate silicone glazing materials. When environmental concerns dictate the use of insulated glass units, panelized systems can prove to be more economical solutions than point-fixed glass systems, with little of no loss to façade transparency.

2.5.6 Point-fixed Glass Systems

Point-fixed glazing systems find most frequent use in structural glass façades. The glass panes are either bolted or clamped with components providing attachment to the truss system. The most common system type is often referred to as a “spider” system. A four-armed fitting, usually of cast stainless steel, supports four glass panes at adjacent corners on the glazing grid and ties back to the truss system. The spider fitting is designed to provide for glazing system movement under environmental loading, as well as to accommodate specified field tolerance during assembly. A variety of spider systems are available from the suppliers of cable and rod rigging systems.

Cast stainless components can be quite expensive, especially if large, customs spiders are required, as they often are in large glass grids. Alternate strategies can be lower tech, lower cost, and just as effective depending upon the aesthetic goals of the project. Simple stainless spring plates have been used in place of a cast fitting with excellent results.

2.5.7 Point-fixed Drilled

Figure 2.37 Point-fixed insulated glass with butt-glazing (ASIDI).

The dominant strategy for the point-fixing of glass since the advent of the suspended glass wall has been mechanical attachment with a fitting that accommodates a bolt through a hole drilled in the glass panel that ties it to supporting structure. There are variations of these fixings on the market, and the refinement of detailing and performance varies considerably. All use stainless material. Some are large discs that stand out from the glass surface. Pilkington’s version features a custom bolt head that sits flush with the outer glass surface. This requires the added expense of a countersunk hole. One of the early fixings was developed by RFR, the French design firm whose principals were involved in some of the early milestone structural glass facades, like the Glass Serres at LaValette. This fixing is also countersunk, but the design features a bolt with a ball end that sits in a mating fitting that places the ball in the plane of the glass. This strategy allows the glass panel to deflect without creating bending moments at the fixing. This fitting is discussed at length in the important book, Structural Glass by Peter Rice and Hugh Dutton (1995), which also includes case studies of some of the early structural glass facades.

Multi-layer glass panels presented a particular problem at the advent of the point-fixed systems. A method had to be found to seal around the fixing component so as not to compromise the air cavity of the panel. Pilkington developed a ringed spacer that could be sealed around the holes to this purpose. Other glass fabricators had developed this capability and the sourcing of this kind of product is becoming increasingly easier and the products more competitive.

2.5.8 Point-fixed Clamped

Figure 2.38 Detail of a point-fixed clamped system (ASIDI).

The above method of point-fixing has the disadvantage of requiring drilling and countersinking of the glass panes, and with insulated glass units the insertion of a sealing ring in the space between the glass panes around the bolt hole. Each laminated or insulated glass unit requires the drilling of at least eight holes. Insulated-laminated panes require a minimum of 12 holes. Obviously, this adds to the cost of the glass panels.

An alternate strategy that eliminates the need for drilling and instead clamps the glass at the perimeter is frequently referred to as a “pinch-plate” system. With a spider-type system, the spider component is rotated 45 degrees so that the spider arms are aligned with the glass seams. A narrow blade of metal penetrates from the spider through the center of and parallel to the glass joint. A relatively small clamp plate on the outside surface of the glazing plane is then fixed to the blade, clamping in place the two glass panels on either side of the seam.

Another strategy, frequently employed on cable nets, is to set the glass into a specially designed clamp component tied to the supporting structure. A cover plate is then attached over the outside corners of the glass, effectively clamping the glass at the corners. Neoprene pads are used on both faces of the clamps to protect the glass.

2.5.9 Structural Glazing

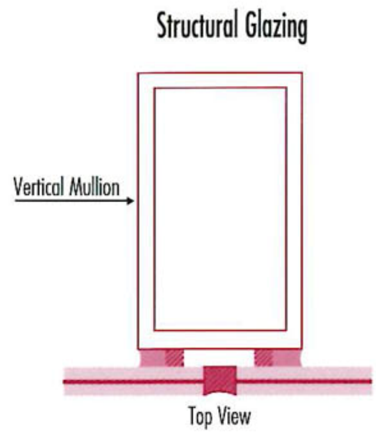


Figure 2.39 Diagram of structural glazing (Viracon 2006).

Structural glazing is a technique whereby glass is essentially glued using a structural silicone material to an aluminum frame, which is then attached to a building. Structural glazing is sometimes done in the field with the glass being glued directly to an aluminum framing member already attached to the building, as with a stick type curtain wall system, but this is rare, the technique is most often used with a unitized curtain wall system. This method eliminates any mechanical capture of the glass, and presents a glass surface interrupted only by the seams between the glass panels; nothing is raised above the glass surface. The practice has a long and successful track record at this point, but is prohibited by some building codes, Los Angeles notable among them. Obviously, the adhesion of the glass to the substrate is critical. Manufacturers of the structural sealants publish guidelines regarding system design, surface preparation and sealant application. They will also provide testing services on sample production components to assure that the process is working.

Structural glazing is seldom used with structural glass facades. The point-fixed systems provide a mechanical attachment of the glass to the structure, with the butt-glazed joint (see Figure 2.40) providing a non-structural weather seal only.

2.5.10 Weather Seals

The glass systems most commonly used with structural glass facades do not employ the rainscreen principle. Most of the systems, and all of the point-fixed systems, make use of field applied silicone as the weather seal, a technique that embraces a "barrier-wall" principle. This technique is referred to as a butt-glazing in the industry, and is illustrated in Figure 2.40. The base assumption here is that if the seal is properly applied, it will not leak, and will provide a reliable and durable weather seal. Silicone is a robust and proven material with a lifespan of over 20 years. The disadvantage of the field applied silicone is the requirement for expensive field labor, the potential for poor craftsmanship in the application, and generally adverse site conditions (adhesion issues related to temperature, moisture and dirt). The materials to be bonded with the silicone must be clean and dry. If manufacturer's recommendations are followed, a quality seal should result. The systems are easily tested after installation of the silicone with a simple water spray. Any leaks are easily identified and repaired, something that can be quite challenging in the case of a leak in a curtain wall system. Craftsmanship is another issue. A well-tooled silicone joint is a handsome thing. Amateurish application can result in a messy, inconsistent, toothpaste appearance that can detract significantly from the façade appearance.

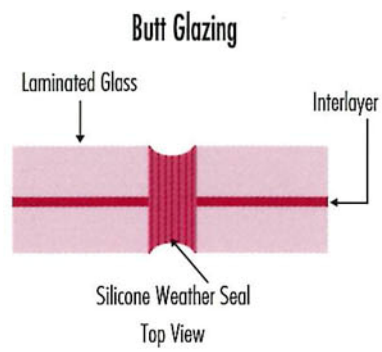


Figure 2.40 Diagram of butt-glazed silicone joint (Viracon 2006).

2.5.11 Silicone Sealants

It is one of the marvels of modern materials that make frameless glazing systems possible. Silicone sealants are used today to glue glass to the outside of high-rise buildings, eliminating any mechanical attachment. In comparison, structural glass facades most frequently mechanically attaché the glass, but use the same, or similar silicone material to provide the weather seal between the glass panels.

2.5.12 Suppliers and Warranty Issues

As discussed previously, Pilkington played an integral role in birthing structural glass façade technology by developing and offering an innovative system as a competitive product to architects and builders. The system was initially developed as a suspended fin-glass wall system as used in the Faber & Dumas building noted earlier. The importance of this development was the manner in which Pilkington technical staff collaborated with architects and façade designers. They provided design, engineering, and when required, testing services to the design community, without which many of these projects would not have been realized.

Pilkington continues this tradition to this day, having developed many variations on the original suspended wall product, and they have been involved in many of the landmark projects that comprise the universe of structural glass facades. Their service goes far beyond merely drilling holes in glass. They provide their clients with conceptual design services through the delivery of a complete glazing system, including glass and all required fixings. Pilkington is located in St. Helens in the UK.

Eckelt Glas GmbH, a Saint Gobain company located in Austria, also offers structural glass products of the highest quality, a comprehensive range of services. They will also provide their structural glass products as complete systems including glass and fixings, and Eckelt also has been involved in many of the great structural glass facades completed world-wide.

As might be imagined, there is a certain premium cost associated with these companies. The value is there for many clients on many projects. A decade ago there was little competition to these companies on any kind of advanced structural glass façade work. It was not until just the last few years that the US has had a source of domestic supply for point-fixed glass with quality material and warranty. Viracon, Inc., located in Minnesota and the largest glass fabricator in the US, now provides laminated and insulated glass panels for use in point-fixed applications. They do not, however, provide a complete system including fixings.

Competitive pressure has increased enormously in the past decade with a plethora of companies producing glass panels for point-fixed applications and various fixing components ranging from stainless steel clamping and bolting systems to stainless rod and cable fittings. Some Asian suppliers have large catalogs with many variations of the basic glass fixing components. The largest is a company called Kin Long Hardware Products Co., but there are many others in nearly all parts of the world.

The Asian glass industry has a reputation of producing lesser quality glass, but that appears to be changing rapidly. Regardless, there are increasing numbers of Asian, especially Chinese, glass makers and fabricators active in world markets. While there is still some concern regarding the quality and reliability of these products, the allure of significantly lower costs have compelled many contractors and building owners to take the risk and utilize these products. The technical service is generally not available from these suppliers, and most specialize in a limited product offering, and not in providing a complete system as does Pilkington and Eckelt. But for the bold and resourceful builders willing to coordinate design, engineering, material supply and installation from various sources, on projects driven by overriding budget concerns, there is certainly substantial money to be saved. As structural glass façade technology matures and the infrastructure of designers, engineers, material suppliers and fabricators, and installation contractors deepens, there are increasing opportunities for this more aggressive style of delivery strategy, and improving odds for a successful outcome.

Alternatively, structural glass facades frequently embody innovative designs and cutting-edge technology, and are often already associated with some level of risk, even in the absence of an aggressive delivery strategy as described above. As the building industry is highly litigious and the various players in this arena equally highly risk-averse, system and material warranties with respect to structural glass facades generally emerge as a predominant concern. Such warranties are currently not available from the low-cost Asian material suppliers.

Warranties follow the supply chain from material supplier up through the subcontractor chain to the general contractor and ultimately, the building owner. Some of the warranties are accepted as "pass-through", meaning that they building owner will directly hold a warranty from a material supplier. Increasingly, the owner is looking for as many subcontractors in the chain as possible to also warranty their scope of work. If façade glass proves to be defective and the glass supplier agrees to provide new glass, who pays for the installation? Many such questions emerge with warranty issues.

There is a difference between a product warranty and a system warranty. There may be many products involved in a structural glass façade; a fabricated steel structural system, glass panels, a glass fixing system and components, and silicone sealant, for example. There may be several contractors involved in the installation of the façade; one for the steel structure, another for the glass, and another to apply the weather seal. This can provide a confusing matrix to the building owner when he contemplates his liabilities in such a case. The result has been an increasing requirement for one of the players in the implementation of a structural glass façade to provide a system warranty.

A system warranty covers the overall performance the glass system, or sometimes even the entire façade, including the structural system. Pilkington pioneered this approach with their Planar point-fixed glazing system, providing a 12-year system warranty covering the design, engineering and material for the glass and fixings, and their application on the given project. This warranty stands as the best in the industry. Eckelt Glas typically offers a warranty up to 10 years, as do some of the other Saint Gobain companies, but have been know to equal Pilkington's warranty in certain instances.

Chapter 3 - Building Products, Processes, Methods, and Delivery Strategies

This section examines what is involved in the realization of structural glass facades, and explores a paradigm for future project implementation that could potentially accelerate the diffusion of the technology into the building arts. As emergent technology, a large percentage of the designs are highly customized, rarely duplicating prior art, often modifying what has come before, and not infrequently, unique, having never been done before. The design innovators and early adopters employing this technology are usually pursuing some level of innovation, driving the design into layers of complexity. The engineering, materials, fabrication and installation are all impacted by the complexity of the design in a manner that typically removes them from conventional practice, placing extraordinary demands on all constituents of the project implementation. The challenge becomes how to implement innovation in a manner that mitigates the risk and uncertainty that can accompany such a pursuit.

These innovators often go off to the next challenge, the next highly custom design and attempt to push the boundaries of the technology once again. The innovators are few, little more than a handful of architecture, engineering and façade design firms. They leave behind them inspiring completed works that are often imitated,[7] each imitation contributing to the maturation of the technology. The early adopters are the first tier imitators. They identify a

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[7] Imitation is a positive and vital act, even a creative act, necessary for the diffusion of innovation into a culture, with the good imitator adding his own bit to the collective evolution of the innovation. The term as used here is in no way meant to be derogatory, but quite the opposite.

design or technology they are interested in using and begin looking for an appropriate project. The early adopters are generally leading design firms with major commissions incorporating high project budgets. They may not be capable of delivering the initial innovation, but observing the innovation, they have the internal resources to assemble a team and develop a program that can adopt the technology and adapt it to their project and program requirements. Most of the currently completed structural glass façades have been implemented by these early adopters.

The innovators and early adopters combined are a small fraction of the design firms active in the commercial construction market. There is a potential tier of secondary adopters that have been following with interest the completion of the various structural glass facades over the past few years, analogous to the group of people charting the experiences of the early adopters of Apple's iPhone; they are watching to see how the technology performs and waiting to see if the prices drop. However, the potential secondary adopters of structural glass façade technology face additional hurdles. One can expect the iPhone to be nicely packaged with Apple's characteristic user-friendly interface, directions as appropriate, and after all, the technology is quite familiar to begin with. The context is quite different for those designers, or other constituents for that matter, interested in working with structural glass façade technology. Access to the technology is fragmented. There is little information to be found beyond pretty pictures and rather non technical project descriptions. There are resources and tools available for glass, cables, castings, and other elements of the technology, but there are no comprehensive, organized technical resources, design guides, or tools available to them to facilitate their use of the technology. Their only option is to hire a specialty consultant, whose fees raise an immediate challenge to implementation, or a specialty vendor or contractor who often have their own agendas that challenge the designer's ability to control the design throughout the design and build process.

New strategies and project delivery methods are needed to encourage and enable the secondary adopters. A review of the current scope of work, work methods and processes, and project delivery strategies may help to suggest some possibilities.

3.1 The Scope of Work

3.1.1 Concept Development and Budgeting

Concept development is the most important part of the design process when dealing with innovative technology. The relative success of the project is most often determined in this phase. Concept development includes the architectural phase of schematic design, and a significant portion of design development. The evaluation of design feasibility should be an ongoing part of this process.[8]

The first item the client-developer typically wants to know is “what is it going to cost.” This is impossible to answer with any confidence in the absence of at least a conceptual design. Beyond that, the concept needs to be developed to the point where preliminary information such as member sizing can be determined so as to facilitate an accurate cost estimate. The building engineer needs preliminary reaction loads from the façade structure impacting the building structure, so that he can approximate the steel design required and estimate its const. HVAC requirements from the mechanical engineer may dictate the type of glass to be used in the façade, or vice versa, and certainly the structure system type, finish, and glass system type will all directly impact cost. The designer requires reference information to create a context for addressing these various concerns.

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[8] The makeup of the evaluation process is a function of the project, but can include material and process research, product development, design development, mockups, prototypes, testing, and cost estimating. An evaluation process should be developed at the commencement of any design and development project, especially one involving unfamiliar or innovative technology, and built into the program.

Especially when dealing with innovative building technology, the designer needs input during design development as to the impact design decisions are having on the material, fabrication, assembly and erection aspects of the design. Designing in the absence of this information is inviting problems during the construction phase of the project. The same applies to cost estimating. If the designer is not informed as to the cost of the various design decisions, the ability to predictably meet target budgets will be significantly compromised. A preliminary level of structural analysis must be undertaken to address these issues. The input that is required is considerable and specialty façade contractors may be reluctant to provide such services up front and without compensation with no assurance of being awarded the project. Design/build and design/assist methods are discussed below as possible strategies to resolve this dilemma and provide adequate technical input early in schematic design when it is most needed.

The need for input early during schematic design can be exacerbated by the materials and processes that are involved in structural glass facades. The architect may be inexperienced with point-fixed glass systems, exposed steel structures, machines and cast stainless steel components, rod and cable rigging systems; all are relatively unfamiliar to most practitioners in the building arts. It is imperative that these elements be properly designed for and specified in the bid documents.

Erection costs can be especially difficult to determine during the early design phase. The project delivery methods described below provide the great potential value of having the installer involved during design development, informing the design, and contributing preliminary costing information regarding the installation work. Much of installation cost is a function of site labor, a particular consideration in highly priced labor markets such as the US, where installation costs can approach half of the total project cost. In contrast, site labor costs are extremely low throughout most of Asia, placing more emphasis on material and fabrication costs.

The costs of structural glass façade projects are driven by a multiplicity of variables and must be carefully evaluated on a case-by-case basis. These are not the kind of projects where rough per square foot budgets in the absence of any significant design can be meaningful predictors of actual cost at bid time. Even with carefully considered budgets there can be surprises at bid time. With conventional structural steel, one can expect competitive bids to fall within a very tight range, typically just a few percentage points. With more innovative technology like structural glass facades, the bids can vary widely and it is not uncommon for bids to vary by as much as 20 or even 30 percent. The very best way to bring predictability to costs presented at bid time is to involve material suppliers, fabricators, installers and/or a specialty consultant or design/builder as early as possible in the design process. Innovative building technologies are often brought to market, at leas initially, by design/build specialty firms. A comment in an article about the cable net wall at the Time Warner Center comments, “Cable net wall contracts are usually arranged as design-build, because nodes and cables are specialty items (Kenter 2007),” a true but incomplete statement. It is more the design component that drives the design/build strategy; there is no practical way for the architect to provide a complete design at bid time. The design/build strategy allows the final design and engineering, including engineer-of-record responsibility, to a specialist.

The alternative to bringing an outside expert to the design team is to inform the architect independent of outside expertise, with the objective of minimizing the need for outside input and possibly eliminating the need for a paid consultant. If, as discussed in Chapter 1, the designer is the potential engine of the secondary adopters, turning out new façade designs that the existing infrastructure of material suppliers, fabricators and erectors can compete for, then the opportunity is to put information, resources, design guidelines, learning programs and tools that facilitate conceptual design into the designer's hands. This strategy could enable the architect to design with some level of structural glass façade technology, although the more advanced and innovative designs will still require the involvement of a specialist, and even more modest designs can benefit from specialist input. It is conceivable, however, to expand the scope of work for the architect and reduce the required input from outside to a level that can be provided by the vendor infrastructure, with all costs deferred to construction.

3.1.2 Design and Engineering

Design and engineering of structural glass facades is a specialty function. Few architects have the expertise to exercise the capabilities of the technology, and few engineers have the skills and experience to provide the required analysis as the design develops. This is true of virtually all custom façade work. A few companies such as Kawneer, Vistawall and YKK offer standard pre-engineered products of limited scope that can be successfully applied to a limited range of façade problems, but most of the custom work is performed by specialty companies that provide complete design/build services.

Alternately, there are a few engineering firms noted for dealing with these specialty structures, Schlaich Bergermann & Partners being one mentioned previously. Werner Sobek Engineering and Design is another that has worked extensively with Helmut Jahn in the realization of some impressive façade structures. But even here the involvement of the engineer is as part of the design team, and final detailing and engineering, and the role engineer-of-record, typically falls to a design/build subcontractor.

Clearly, simplified tools that provided for a preliminary level of analysis and some basic output regarding the behavior of a conceptual design could be very helpful in resolving a design capable of being constructed predictably to a budget and schedule.

3.1.3 Fabrication

Fabrication requirements vary as a function of the selected structural system type and glass system type. Depending upon the glass specification, product cost and availability, the glass may be imported, which can present logistical and scheduling issues. These requirements are not trivial, and how they are dealt with will directly impact the quality, timely completion and cost of the work. Exposed steel structures require a level of craftsmanship in their fabrication that is uncommon in the construction marketplace. Measures must be taken both in properly specifying the work requirements on the design side and assuring that these specifications are in fact met on the build side. Again, some of the materials and processes utilized in structural glass facades, while not new by any means are unfamiliar to much of the construction industry, impacting fabrication and erection processes as much as they do design practices.

On approval of final design by the architect, and often before, the design/build contractor will commence the fabrication scope of work, including material procurement and subcontracting to other service providers as required. The design/builder may or may not have its own fabrication facilities. The project specifications may stipulate that certain materials or services be acquired from a named provider (sole-source) or providers. Such specifications often include an “or equal” clause, that allows the design/builder to submit an alternate provider for approval by the architect.

Fabrication issues are discussed in more detail in Chapter 2.

3.1.4 Erection

The building site is where all prior work converges for assembly and erection; construction can be the most challenging and demanding phase of a project. The financial success of a project is most often determined on the building site, at least in areas with high field labor rates. Here again the previously cited elements that comprise structural glass technology and are frequently present in structural glass façade designs are largely unfamiliar to the majority of erection contractors.

The components of the exposed structural systems are commonly prefabricated and pre-finished with high quality and expensive finishes. Trusses and steel components may have painted or plated finishes that can easily be damaged during assembly, requiring difficult and expensive touch-up painting in the field. Stainless steel components will often have brushed or polished finishes that mar easily. These materials must be stored, handled and assembled with great care so as to preserve these finishes undamaged. An ironworker's "beater" is not usually the right tool for accomplishing this work.

Every design manifestation of structural glass façade technology, unique or otherwise, placed in the context of a specific building project, presents unique considerations for material delivery, storage, handling, assembly, hoisting, and installation. For this reason, the project specification should require that the design/builder or erection subcontractor provide a method statement detailing the sequential steps, methods and techniques that will be used in assembling and erecting the structure. This should be reviewed by the architect, and should evidence that proper measures are being taken to protect the materials and material finishes throughout the installation process.

An important role of the design/build contractor and erection contractor is to develop appropriate means and methods for the erection work, and to perform the work in conformance with the contract documents. Means and methods allow the erector to freely employ their expertise in the most efficient erection of the work with respect to the various considerations and constraints presented by the jobsite. As the means and methods are the responsibility of the design/builder, the architect must assure that the project specifications adequately protect the owner without unduly hindering the erection work.

A design/builder may provide installation services directly or subcontract the requirement to a qualified installer. Ironworkers are generally involved in the assembly and erection of the steel works, and glaziers typically install the glass and glass-fixing system.

3.2 Project Delivery Methods

The section explores general building contracting practices in an effort to identify a strategy most appropriate to a portion of the building work having innovative content. Understanding how these practices impact the design phase of the project may indicate opportunities for facilitating innovation in the building arts in general, and structural glass façade projects in particular.

3.2.1 Design/Bid/Build

Design/Bid/Build, or Design/Tender, is the conventional project delivery method in which there is a contractual separation between the design team and the construction team. The owner initially contracts an architecture firm. While the architect's responsibilities typically continue throughout the course of construction with some limited scope involving monitoring, approvals, and managing design related construction problems, the primary design work is clearly demarcated from the construction work. The architect will usually assemble the professional design team to provide the spectrum of mechanical, electrical, structural, landscape and other services required for the project.

The design work progresses through schematic design, design development, and construction or contract documents phases, the culmination of which is a detailed set of drawings, specifications, and contract requirements. The contract documents are then used to solicit bids, or tenders, from competing general contractors. Public works projects are usually "open bid" and strictly regulated to prevent unfair exclusionary practices, and sometimes mandate that the qualifying low bidder must be awarded the project. This qualification process is undertaken by the architect with the owner after the bids are received. Other projects may be “closed,” restricting the bidding to an invited short list of pre-qualified candidates, and there may be extended post-bid negotiations before the project is finally awarded. Once awarded, the successful general contractor proceeds to issue subcontracts to his selected contractors as required to provide the entire scope of construction work; structural, electrical, plumbing, etc.

There is endless discussion in the construction market regarding the relative virtues of the various project delivery methods. The all have their strengths and weaknesses.

3.2.1.1 Strengths of Design/Bid/Build

- Regarded to be the most competitive process as it pits contractors against each other in pursuit of the lowest bid, thus providing the lowest cost to the owner. This outcome is often illusory.

- Comprehensive and complete contract documents provide a level playing field for the bidders.

- The openness assures that highest probability that the owner will find the best and lowest cost contractor available.

- The owner reserves his options until all bids are in and contractors qualified, again helping to assure the highest quality and most cost effective solution.

- There is a clear demarcation between design and construction, and if the owner is not satisfied with the results of the bidding process, he has retained options on how to proceed, including re-bidding or canceling the project.

3.2.1.2 Weaknesses of Design/Bid/Build

- The separation between the design team and construction team is often divisive and contentious, leading to disputes on the project.

- The burden of budgeting is on the design team with minimal involvement from contractors. If the architect is not adequately informed regarding construction costs, the bids can easily exceed the project budget.

- Lack of input by the various contractors during the design process often results in the post-bid discovery of things that do not work or can be done much cheaper and more efficiently, leading to disruptive changes in the work.

- The contract documents must be very comprehensive, accurate and complete. Errors and omissions in the contract documents can easily result in significant delays and additional costs to the owner, as contractors incur and submit costs for changes to their work.

- The low bid selection strategy is not known for dependably delivering the most qualified candidate. Cost pressure and an attempt to maximize profits by the general contractor can result in the selection of substandard subcontractors, even when the provision of approved subcontractors has been included in the project specifications.

- The practice requires virtually flawless contract documents, difficult even without innovative content, as the only protection to the owner and design team against the not uncommon practice of deliberately underbidding the work with the specific intent of aggressively finding flaws in the contract documents and using these to drive up the contract value through change orders.

- The process is inherently inefficient because of the duplication of effort in multiple teams bidding on the same work.

3.2.2 Design/Build

Here the design and construction services are both provided by a single entity. The term is most commonly used in reference to an entire building project. The design/build contractor is most often a general contractor that elects to provide design services, but architects have also acted as design/builders, providing contracting services in addition to their usual design services. This strategy requires that the owner qualify design/build candidates up front and make a commitment to proceed with the selected entity.

As a modification of this strategy of most relevance to this thesis, it is also possible for an owner or general contractor to employ the services of a design/build subcontractor for some limited scope of work in a conventional design/bid/build project. This strategy is especially suitable to specialty work where the number of service providers is limited, and to any work with high innovation content. In the design/build scenario, the design/build subcontractor generally acts as engineer-of-record for their scope of work.

3.2.2.1 Strengths of Design/Build

- Allows for the overlap of the processes of design and construction, better accommodating fast-track scheduling.

- Allows for extensive involvement of material suppliers, fabricators and subcontractors early in the design process, thus informing the project design as to these relevant considerations.

- Especially effective in projects involving cutting-edge technology or new materials where designers may be uninformed as to details and costs.

- The budget can be developed along with the design, and accommodations and adjustments made as appropriate, acting as a kind of value-engineering built in to the process.

- Provides single-source responsibility to the owner or general contractor, simplifying management and mitigating risk.

- Minimizes the design scope for the architect by allowing most of the design development and final detailing and engineering to be passed on to a specialty subcontractor.

- The potential for schedule compression can result in major savings over the design/bid/build method.

3.2.2.2 Weaknesses of Design/Build

- The architect can easily lose control over the design, resulting in compromises to the design and the quality of the finished work.

- Involving the façade contractor into the design process can present a conflict of interest, rather like asking the fox to guard the hen house. An disreputable subcontractor can sacrifice the quality of the design and completed work to their own gain, again placing the burden and challenge of identifying a qualified and reputable entity very early in the process on the owner or general contractor.

- Budgets and costs can drift and the development of the budget must be carefully managed to assure maximum value to the owner.

- Success relies heavily on the owner or general contractor's ability to qualify and select a competent, appropriate and reputable subcontractor.

- The overlap of design and engineering means that sometimes things are being designed virtually as they are being built, leaving no margin for error.

The Design/Build Institute of America is a trade organization providing resources, training and other support.

http://www.dbia.org/

3.2.3 Design/Assist

The design/assist is a relatively new project delivery method that strikes something of a compromise between the design/bid/build and design/build methods, especially when circumstances make it very difficult to commit early in the process to a full design/build contract. The design/assist is usually employed on projects with early involvement of a general contractor, meaning the projects are most likely negotiated contracts between the owner and general contractor and not design/bid/build. With this strategy the necessary expertise is brought in early in the process, either by the architect or the general contractor, but only to provide assistance to the design team, with no commitment regarding the build portion of the work. The scope of work under a design/assist contract involves assisting in concept and design development, and the preparation of a performance-based set of drawings and specifications adequate for the purpose of soliciting a design/build bid. Final design, detailing, and engineering will be the responsibility of the design/builder subject to the review and approval of the architect. As above, the design/builder will act as the engineer-of-record. The design/assist entity is usually desirous of providing build services, and generally they are allowed, if not expected to pursue the construction scope of work under a separate contract. In many instances the design/assist provider has gone on to provide complete design/build services.

3.2.3.1 Strengths of Design/Assist

- Allows for the early involvement of the necessary technical expertise without a commitment to the construction of the work.

- Maintains the competitive environment for the owner or general contractor’s benefit, as appropriate.

- Allows for a change in the design consultant all the way up to start of construction.

3.2.3.2 Weaknesses of Design/Assist

- Some of the most qualified specialty subcontractors are reluctant to provide design/assist services, owing to the possibility that they may lose the build part of the work to a competitor. Nobody like watching a competitor build their own design.

- The design/assist entity may try to develop a design that favors them for the build portion of the work. If successful, it may be difficult to find competitive bidders for the construction work.

3.3 A Project Delivery Strategy for Innovative Technology

The architect has been identified as the primary adapter of structural glass façade technology. The keys to the technology must be handed to the architect, in the form of information, resources, learning programs and tools. These things can only be determined in the context of a delivery method. The delivery method for designs involving innovative technology must reduce to a minimum the work required by the architect, while still providing for their control over design and construction quality all the way through the design and build process. It must also provide for the involvement of critical material suppliers, fabrication vendors and erection subcontractors early in the design process.

Clearly, the design/bid/build method is inappropriate for any design involving innovative materials or building technology; the designer is left without access to critical input from material suppliers, fabricators and specialty subcontractors, maximizing the risk of problems with the design in the execution phase. Either of the other two methods provide for this input. The design/build method is optimum if a suitable service provider with the necessary expertise in the required technology can be identified and contracted early in the process. If circumstances prohibit, the design/assist method provides a workable alternative, providing for assistance to the architect in the completion of a performance-based bid package that can then be used to solicit competitive design/build bids. Most specialty design/builders are willing to participate on this basis. In many cases, depending on the degree of design difficulty, and with the support of appropriate design tools, guidelines and resources, the designer may be able to assembly a design/build bid package as described below without any outside assistance.

3.3.1 Scope of Work

The strategy for implementing structural glass façade technology must include the following design methodology, whether provided solely by the architect or with the assistance of a specialist:

3.3.1.1 Select glass type

When very large grid dimensions and glass panel sizes are desired, maximum dimensions may be limited by the glass type. In point-fixed applications for example, the glass is commonly heat-treated, and the maximum panel sizes will be a function of the fabricator's tempering oven. The glass type will also ultimately determine the thermal performance of the façade, some type of insulated glass commonly being used in conditions where thermal performance is a priority consideration. Glass options are discussed in chapters 2 and 6.

3.3.1.2 Develop an appropriate surface geometry and glazing grid

This is the foundation point of a façade design, regardless of structure type, glazing type or other considerations. The definition of the glass grid will inform the subsequent decision-making process.

3.3.1.3 Select a glass system type

Point-fixed systems are most commonly used with structural glass facades, but may not be the cheapest solution if cost is the predominant consideration. Options are discussed in chapters 2 and 6.

3.3.1.4 Select a structure type

Evaluate and select a structure type to function as the structural support system for the façade. The various systems are quite flexible in terms of supporting any of the glass system options. Structure options are discussed in chapters 2 and 6.

3.3.1.5 Execute a preliminary structure analysis

A preliminary analysis of the structure should represent a reasonably close approximation of the final design, within 10 to 15 percent. Assumed member sizes will be tested as a function system deflection, and adjusted as appropriate. The analysis should yield preliminary deflections, member loads and reactions. Determination of member sizes can then be used for costing purposes. Reaction loads are important to the building engineer in the sizing of boundary steel supporting the façade structural system.

3.3.1.6 Develop a preliminary cost estimate

The output from the preliminary analysis combined with the selections for glass and glass system should provide for a close approximation cost estimate for budgeting purposes. At this point, potential design/build contractors can also be invited to provide preliminary costing and budget confirmation.

3.3.1.7 Adjust the design as required to match cost with budget

Evaluate cost against budget and consider design modifications as required. Depending upon the initial design assumptions, less expensive alternatives for glass, glass system and structure type may be possible.

3.3.1.8 Prepare a design/build bid package

Once a basic preliminary design is determined and evaluated for performance and cost, performance-based bid documents as suitable for a design/build project delivery method can be prepared.

3.3.2 Minimum Bid Documents for Design/Build Bid

Virtually all structural glass façade construction is ultimately completed under a design/build project delivery method as discussed above, regardless of the scope of work provided by the design team. Most or little of the design work can be provided by the architect, but the design/builder is generally responsible for final design and engineering, acting as engineer-of-record for the façade work.

The function of the performance-based bid package is to communicate as clearly as possible the architect’s design intent, while leaving flexibility in the final design and detailing, which will be the responsibility of the design/builder subject to review and approval by the architect.

3.3.2.1 Representative Drawings

Plans, elevations and sections as required to adequately describe the project. Member sizing is not called out on the drawings. Typical connection details of the structure and glass system as appropriate.

3.3.2.2 Specifications

Performance-based specifications for the following as appropriate (refer to chapters 2 and 6):

- Glass
- Glass System
- Structure System

The specifications are best combined under a single section that details the responsibilities of the design/builder. These should include some provision for an interim design submittal at 50 to 60 percent completion for review and approval by the architect as a mechanism to control the design. Some projects stipulate additional interim reviews, even requiring 30, 60 and 90 percent reviews.

Chapter 4 - Precedents; Design Guidelines, Design and Teaching Tools, Learning Resources

Design guidelines, tools and learning resources can play an important role in facilitating the diffusion of innovative technology in a market by enabling potential adopters to acquire a base competency in utilizing the new technology. There is little or nothing in the way of existing design guidelines or teaching tools, and no centralized resource dedicated to structural glass facades. The author is aware of no book or website dedicated to structural glass façade technology, although examples of structural glass façade projects have been included in published material and websites. There are very few companies currently specializing in this technology, providing very limited resources to aspiring users (see Chapter 1.3.6). There may be an opportunity to employ learning programs and design aids to considerable affect in this context. The following is a brief review of some relevant tools, methods and techniques, including some examples drawn from technology or disciplines loosely related to structural glass facades. The purpose here is to identify the broad classes of learning-aides that can potentially enable groups of adopters and facilitate the diffusion of innovative technology into a broader market.

Note that the trend is for these various formats and methods to converge into a multi-dimensional program around a subject matter of interest. Book projects often start out as websites; a website can be quickly constructed to accommodate and present book material as it develops, and can provide useful input into how the material is being received. The website often becomes a repository for reference information, tools, news, tutorials, and links to related websites. In the case of a successful book launch, the book and website can provide a true synergy as they play off each other, the sum being greater than the parts.

4.1 Design Guidelines

Design principles compiled to provide general guidance to the user with respect to a particular design problem or process are called design guidelines. They are often presented in terms of “dos and don’ts,” as checklists, or as a series of stated objectives. They are frequently designed to act as decision-making aids to the designer, sometimes prescribing an answer based upon certain conditions, sometimes providing evaluation criteria to support performance-based decision-making.

There are many design guidelines providing “high-performance” building criteria regarding sustainable or “green” building practice. The most visible of these is the LEED program provided by the US Green Building Council. This program actually provides design guidelines and a tool in the form of a guided certification program.

> *The Leadership in Energy and Environmental Design (LEED™) Green Building Rating System represents the U.S. Green Building Council’s effort to provide a national standard for what consistitutes* [sic] *a “green building.” Through* ***its use as a design guideline and third-party certification tool****, it aims to improve occupant well-being, environmental performance and economic returns of buildings using established and innovative practices, standards and technologies” (U.S. Green Building Council 2002 p.i).*

Similarly, a website resource for universal design, the practice of designing to enhance accessibility and ease of use by the disabled in particular and the broader population in general, provides “General Concepts, Universal Design Principles and Guidelines,” (Trace Center 2007). The guidelines here are presented with respect to a series of design principles (The Center for Universal Design 1997):

"PRINCIPLE ONE: Equitable Use
The design is useful and marketable to people with diverse abilities.
Guidelines:
1a. Provide the same means of use for all users: identical whenever possible; equivalent when not.
1b. Avoid segregating or stigmatizing any users.
1c. Provisions for privacy, security, and safety should be equally available to all users.
1d. Make the design appealing to all users."

Design guidelines can be used as the basis of a process, and the process can then be mapped, guiding the user in a series of steps constructed to best facilitate that process and yield a predictable outcome. The process and steps embody the design guidelines, functioning as a design wizard or even an expert system. In this form the guidelines become part of a design tool as discussed below.

4.2 Design Tools

Design tools facilitate some aspect of the design scope of work; AutoCad is a robust, broad-based design tool in the form of a software program that facilitates the design drawing process. Today, most design tools come in the form of computer-automated software programs for such applications as; computer-aided design (CAD), 3-d modeling, animation, web authoring, desktop publishing, illustration, imaging, structural analysis, building information modeling (BIM), daylight modeling, climate analysis, and energy modeling, among others. The tools can be broad-based and intended to provide comprehensive support of a design process, or finely tuned to some particular aspect of a process. Some are intended to simplify a process or some part of a process, making it faster and/or more easily accessible to a user.

There are also a great variety of digital tools available online. These are generally limited in scope and focused on some particular aspect of a process or product. Many product providers maintain websites that include design tools specific to their products that provide support for selecting options, sizing, specifying, as well as costing and ordering information.

4.2.1 Wizards

A common type of design tool found on the web is a guided, interactive program that incorporates relevant guideline information and steps the user through a process to arrive at a problem solution. Software wizards would fall into this general category.

A simple example of such a tool can be found on the website of PPG Industries (2008). PPG is a large producer of glass and glazing products. Their website provides considerable resources to designers in the form of technical bulletins, design guidelines and tools. One of the tools is called the "Interactive Glass Product Selector," which is accessed through a link on the main glass resource webpage. The tool is intended to facilitate the glass selection process (Figure 4.1 - Figure 4.4).

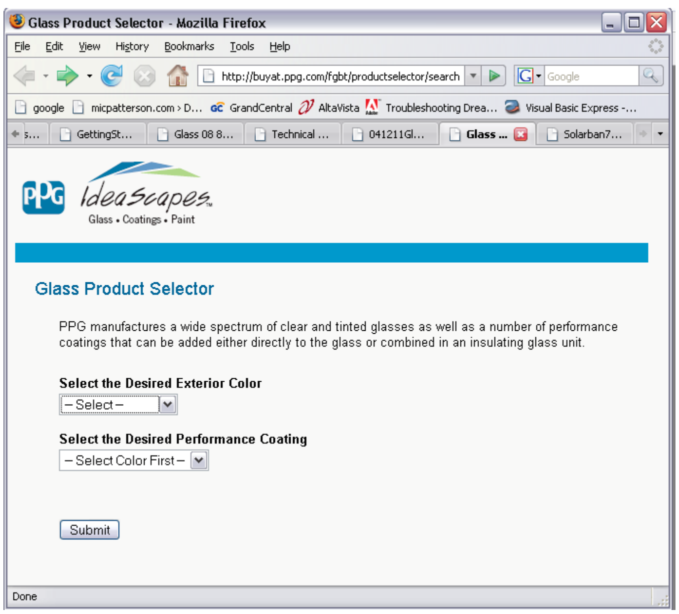


Figure 4.1 Product selection tool, screen 1.

The user is first directed to make a selection from the "exterior color" box first. Clicking in the box reveals the drop down menu.

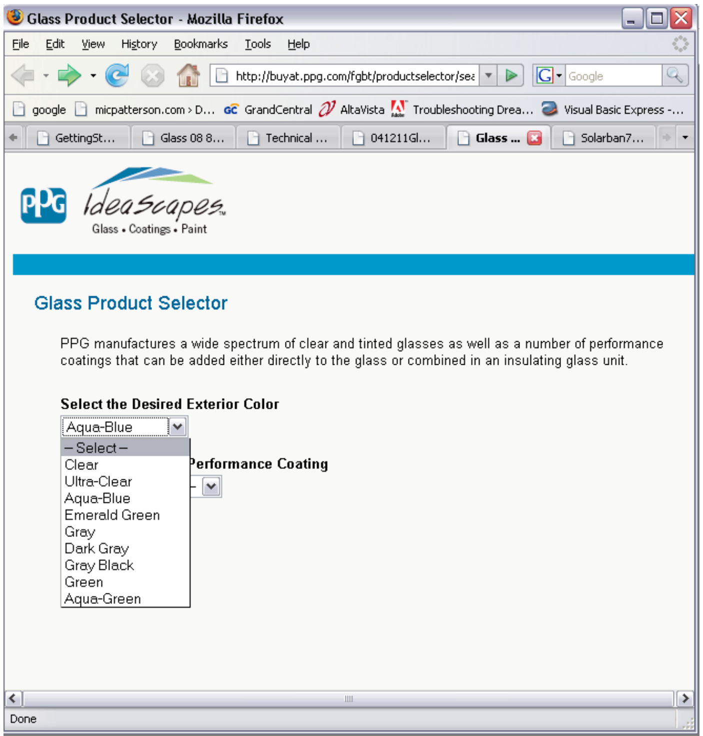


Figure 4.2 Product selection tool, screen 2.

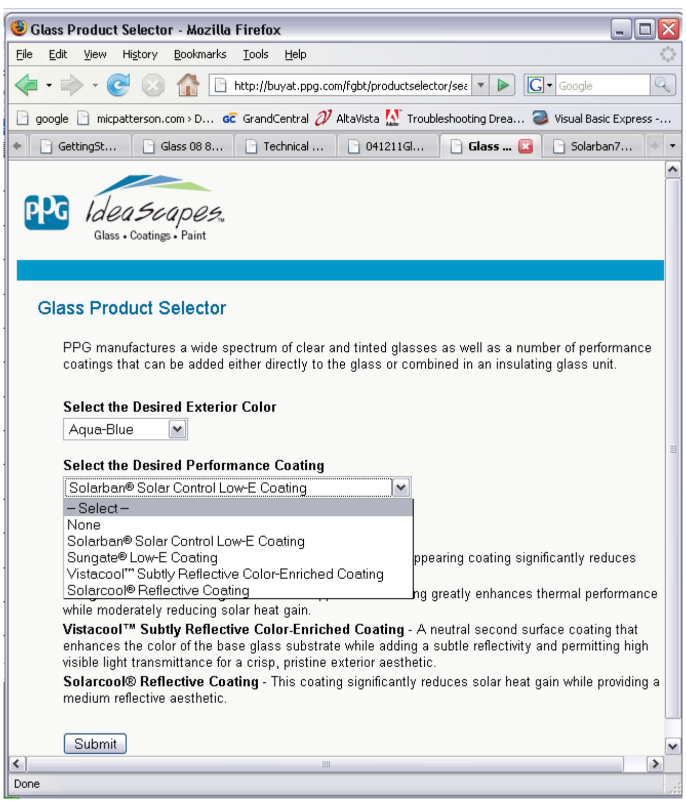


Figure 4.3 Product selection tool, screen 3.

On selection of an exterior color from the first list box, the second box (Figure 4.3) is activated with a list of available options for that color. Product names and brief descriptions appear below the text box to provide some preliminary information prior to selecting the performance coating. The selections are submitted, and a final page (Figure 4.4) provides links to product specifications in pdf file format.

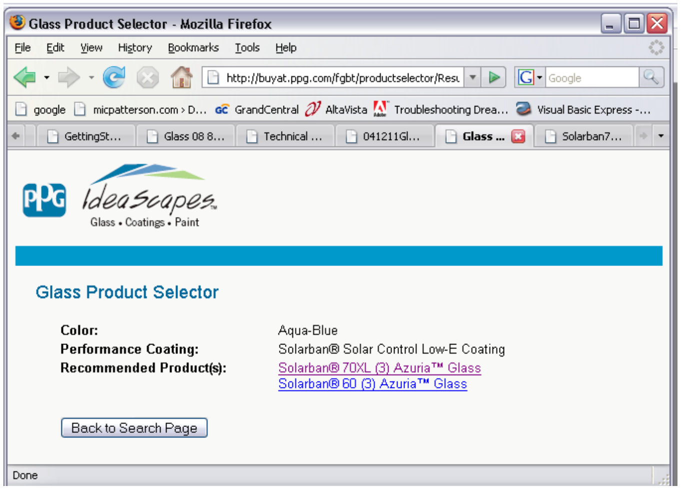


Figure 4.4 Product selection tool, screen 4.

4.2.2 Design Tools Supporting Simplified Processes

The simplification and clarification of complex processes is a primary objective in the design of tools and guidelines. Even old technology can sometimes benefit from new simplified methods, but the maturation of a technology is typically accompanied by the development of simplified tools and processes. In some, if not many cases the simplified tools are a primary contributor to the diffusion of a technology into a broader market. The so-called user-friendly computer interface is a good example of this; growth in personal computing accelerated following the commercial introduction of the graphical user interface (GUI) developed at the Palo Alto Research Center, which simplified the computer interface making the machine more accessible to a new tier of adopters. In this respect, it is generally newer technologies that stand to gain the biggest boost from the development of simplified tools and processes.

The more a tool can do the more complex it tends to be. AutoCad is a powerful CAD tool, but is difficult and time consuming to learn. AutoCad is a primary program for architectural designers, meaning that many of them must spend the time to develop some level of competency with the tool, as the development of drawings is fundamental to their work. Other functions may be less so. An example is daylighting, which involves the optimization of natural lighting in commercial buildings so as to reduce the need for artificial lighting (with resultant energy savings), the provision of adequate light levels to support work functions to as large an area as possible, and the control of direct sunlight and glare.

Most architects would agree that this is an important function. Yet many of them do not incorporate daylighting design in their practice. There are sophisticated design tools, software programs, to facilitate daylighting design, such as Radiance, a highly accurate ray-tracing program developed by the Lawrence Berkley National Laboratory and supported by the US Department of Energy. However, both the subject and the tools are complex, requiring a significant investment on the part of the designer to develop competency with the issues and the tools. Many architects simply do not have the time. An alternative is to hire a specialty consultant to provide the services. This will impact the design budget, and still will require coordination by the architect. Christopher Reinhart (2004, p.1) comments:

> *"With a rapidly developing knowledge base, architects rely more than ever on solid performance measures to support their design decisions. Yet many aspects of design compete for the team's attention. In today's competitive environment, the value of information gained through any one simulation tool must be constantly weighed against the time and financial resources required."*

Daylighting as a design consideration does not lend itself to wizard type design tools. Something between a wizard and a program such as Radiance may be able to open up the practice of daylighting design to a new tier of adopters. Reinhart again:

> *"Because daylighting is such an important feature of virtually all sustainable buildings and because its quality and quantity are difficult to predict and evaluate through simple rules of thumb, there is a need for daylighting software with a high rate of acceptance and adoption by design professionals."*

Reinhart is promoting a daylighting program called "Lightswitch Wizard" (now Daylight 1-2-3) developed by the Lighting Group at the National Research Council Canada (NRC), in partnership with the Buildings Group at Natural Resources Canada (NRCan). The tool is available by free download from a dedicated web resource (Daylight 1-2-3 2008). The website acts as a resource in support of the tool, providing a guidelines and various other technical information. Reinhart represents that, "…users do not require any previous knowledge of daylight simulation techniques because all simulation inputs are explained in the online technical background and the glossary sections."

Of course, there are limitations to this simplified tool, but it claims to provide enough information to design offices and classrooms with "enough but not too much" light. As with many simplified analytical tools, the program utilizes the shortcut of coefficients (in this case pre-calculated with Radiance ray-tracer) to shorten the analysis time and simplify inputs (see input screen Figure 4.5). The results represent a less accurate but useful approximation, good for comparative analysis, and intended as input to the building designer during schematic and early design development project phases.

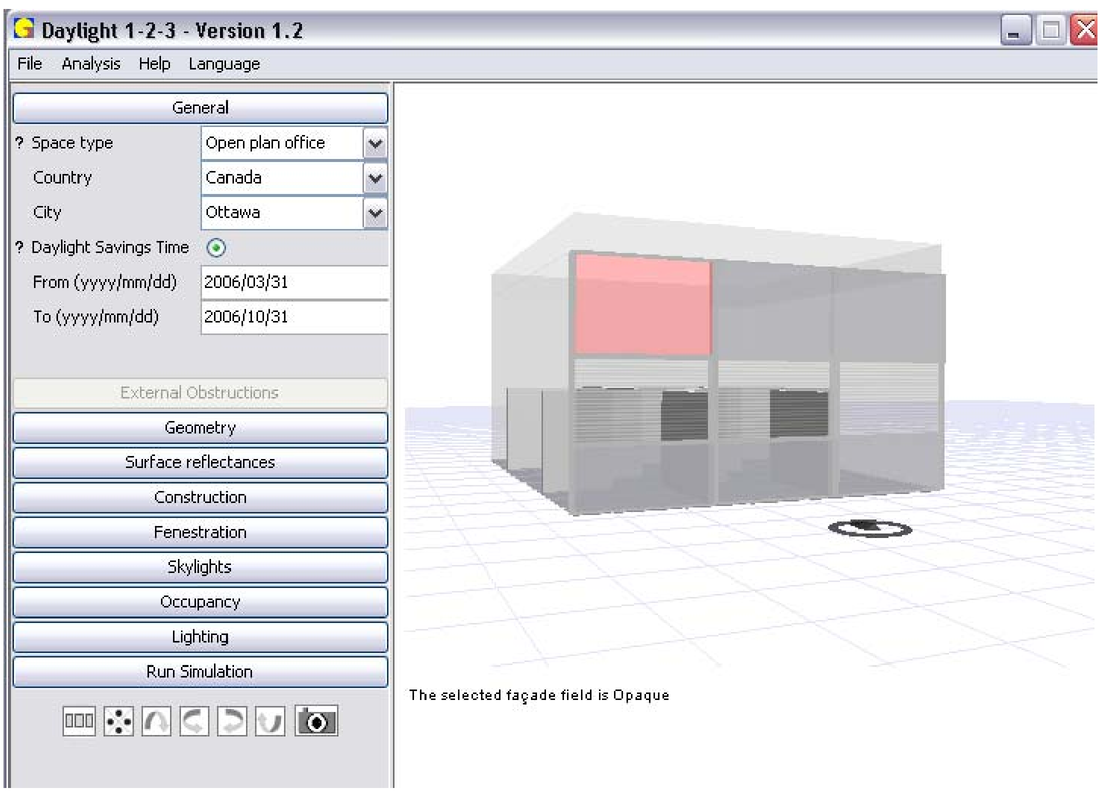
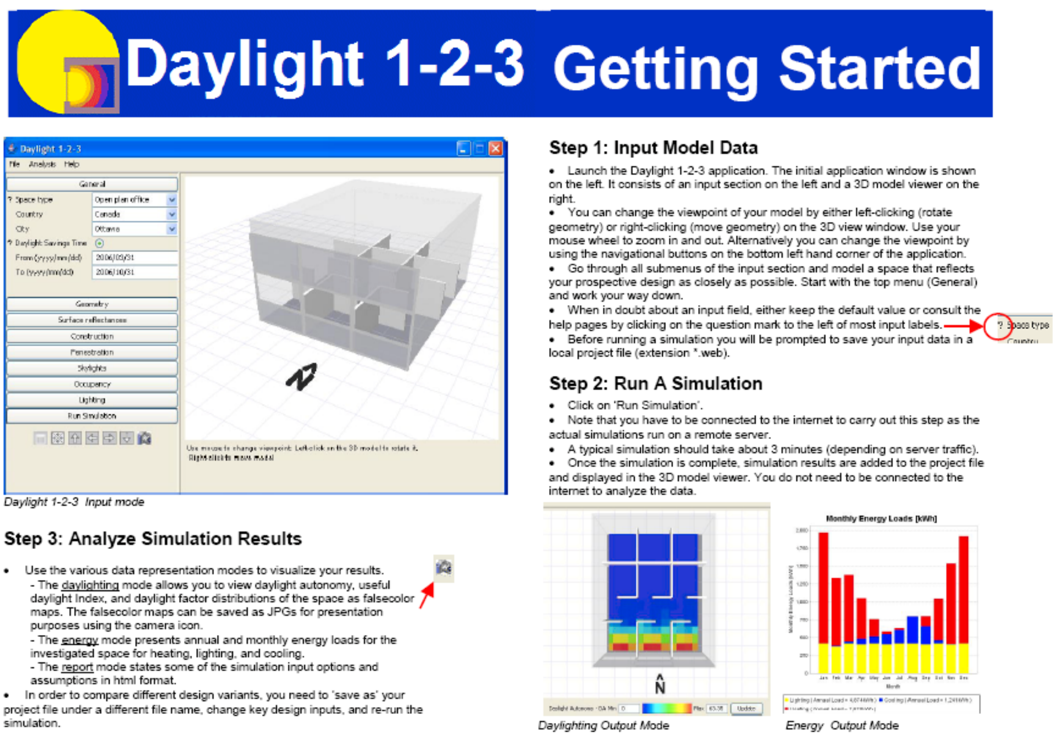


Figure 4.5 Input screen for Daylight 1-2-3.

The program utilizes a single screen for data input as the sole user interface. A generic building form is used with minimal geometry input, eliminating the complexity of inputting and analyzing a custom geometric model. Question marks adjacent to input fields on the form queue the user to a relational technical support system. A single-page “getting started” document can also be downloaded from the website, that informs the user of everything they need to operate the program in a 3-step process. These are essentially the guidelines for using the program.



Daylight 1-2-3 Getting Started

Daylight 1-2-3 Input mode

Step 1: Input Model Data

- Launch the Daylight 1-2-3 application. The initial application window is shown on the left. It consists of an input section on the left and a 3D model viewer on the right.
- You can change the viewpoint of your model by either left-clicking (rotate geometry) or right-clicking (move geometry) on the 3D view window. Use your mouse wheel to zoom in and out. Alternatively you can change the viewpoint by using the navigational buttons on the bottom left hand corner of the application.
- Go through all submenus of the input section and model a space that reflects your prospective design as closely as possible. Start with the top menu (General) and work your way down.
- When in doubt about an input field, either keep the default value or consult the help pages by clicking on the question mark to the left of most input labels.
- Before running a simulation you will be prompted to save your input data in a local project file (extension *.web).

Step 2: Run A Simulation

- Click on 'Run Simulation'.
- Note that you have to be connected to the internet to carry out this step as the actual simulations run on a remote server.
- A typical simulation should take about 3 minutes (depending on server traffic).
- Once the simulation is complete, simulation results are added to the project file and displayed in the 3D model viewer. You do not need to be connected to the internet to analyze the data.

Daylighting Output Mode

Energy Output Mode

Step 3: Analyze Simulation Results

- Use the various data representation modes to visualize your results.
  - The daylighting mode allows you to view daylight autonomy, useful daylight Index, and daylight factor distributions of the space as falsecolor maps. The falsecolor maps can be saved as JPGs for presentation purposes using the camera icon.
  - The energy mode presents annual and monthly energy loads for the investigated space for heating, lighting, and cooling.
  - The report mode states some of the simulation input options and assumptions in html format.
- In order to compare different design variants, you need to 'save as' your project file under a different file name, change key design inputs, and re-run the simulation.

Figure 4.6 Start-up document for Daylight 1-2-3.

The program that is downloaded and resident on the user’s computer interfaces with the hosting server to run the actual simulation, which requires approximately 3 minutes, depending on server availability. Some simple output forms are then available to the user, documenting the results. The program is quite simple and provides access to a level of daylighting analysis and input to the design process that that is quite useful and typically unavailable to the design architect.

It is interesting to note that tools that simplify processes are not typically simple to create. The development of the Daylight 1-2-3 program represents the involvement of a project team of a dozen people over a four year time period (Daylight 1-2-3 2008a).

4.3 Teaching Tools and Learning Programs

There is a plethora of teaching tools available online, most relatively simple themed programs aimed at informing various segments of the K-12 population, ranging over every academic topic from history to geography to mathematics. The programs are often accessible for free over the internet, are easy to use, and typically designed to be completed on average from five to twenty minutes. Many are interactive, and may take the form of puzzles or games. Most present text and visual material and then a testing option for user response through such means as multiple-choice questions. Feedback in some form is then provided to the user regarding the testing results.

Learning programs are also themed, but are often application specific and more comprehensive in scope. There are, for example, several learning programs available directed toward the LEED certification program discussed previously (U.S. Green Building Council 2008).

4.3.1 Self-paced Learning Programs

The US Green Building Council's (USGBC) LEED Rating System for commercial buildings, rates buildings with respect to a set of criteria focused on issues of sustainability and green building practice. Architects follow LEED guidelines and the building owner applies for LEED certification. A point system is used to score the building design. Depending upon the resulting score, the building can be rated at four levels; platinum, gold, silver, or certified. The USGBC also provides a professional accreditation process for individuals trained to a tested level of proficiency in the program.

For a small fee, three levels of coordinated courses are offered on the USGBC website, along with other technical learning programs regarding the LEED rating system and green building practice. These programs are designed to provide an increasing level of competency to the user. At the third level the user is presumed to be working on a project pursuing LEED certification.

High end self-paced learning programs can approximate in-class coursework. Some even provide online interactivity, ranging from immediate programmed and automated feedback (such as testing and response), to real-time interaction with an instructor.

While comprehensive and effective, these programs require a significant time commitment by the user, arguably the most valuable resource at their disposal. Issues of sustainability and green building practice have become progressively more central to contemporary architectural practice, so many architects are increasingly motivated to acquire a level of competency with respect to these issues. Lacking this motivation, these comprehensive learning programs can become a barrier to the pursuit of new technology and higher levels of competency.

4.3.2 Tutorials

Tutorials are a more focused, pragmatic form of self-paced learning program, less comprehensive than the Design Guidelines discussed above. Many tutorials are intended to get a user engaged with the subject at the novice level as quickly as possible, but tutorials on advanced concepts can also be of value. Many popular software tools, such as the various graphic design programs, are supported by an abundance of tutorials ranging from the novice to the expert levels.

Some tutorials are step-by-step demonstrations; others are interactive, providing the opportunity for the user to work through an exercise in parallel with the tutorial. For practical reasons, many interactive tutorials are hardcopy text. Online tutorials are generally in the form of a passive video-type presentation, which is unfortunate as the reinforcement of "learning-by-doing" is absent. Nonetheless, tutorials can be highly efficient in providing a novice level of competency with a subject so that the user can engage a tool or technology and begin to develop their own experience based upon use. Tutorials are often designed to provide instruction specific to a computer program, or can be designed as topic-based learning tools. Examples of tools and various types of tutorials can be found at the USC-MBS website at http://www.usc.edu/dept/architecture/mbs/tools/index.html.

4.3.3 Workshops and Conferences

In a certain respect, workshops are to interactive tutorials as conferences are to passive tutorials. Conferences, lectures and presentations represent the passive, non-interactive but in-person type of learning event. Workshops, on the other hand, are intended specifically to involve interactivity on the part of the participant. Workshops typically take place in small groups where the necessary tools and information are provided and problem solving exercises are directed by an event leader(s). Workshops provide a unique learning format that is particularly suited to some subject matter and to those users that prefer a face-to-face and hands-on learning environment.

4.3.4 AIA CES Learning Program

The American Institute of Architects Continuing Education Systems (AIA/CES) is a comprehensive program with the mission of assuring the ongoing education of its 77,000 members. AIA members are required to fulfill 18 learning units annually to retain their member status. The AIA/CES has instituted a content provider program comprised of construction industry professionals ranging from architects to materials suppliers. The AIA/CES has published guidelines and standards for the programs, and anyone can submit a program, most frequently comprised of lectures or workshops, to the AIA/CES for review. If the program is found to comply with the AIA/CES standards, the provider is authorized to present the material under the AIA/CES banner, and AIA members attending the program will receive a prescribed credit towards their annual educational units requirement.

The AIA/CES has published some material to aid aspiring providers in putting together effective learning programs. These documents are available on the AIA website (American Institute of Architects 2008). One of the documents is Program Development for Adult Learners that discusses adult learning principles, instructional methods and formats (American Institute of Architects Continuing Education Systems n.d.). Instructional delivery methods include:

> *"Passive: In a passive learning activity, the instructor does most of the presenting and the learner takes a passive role. The learner is mostly listening, watching, and absorbing the information without significant interaction."*
> *"Examples:*
> - *Keynote presentation at a conference*
> - *Lecture series*
> - *Listening to audiocassettes*
> - *Viewing a video*
> - *Slide presentation*
> - *Facility tour*
> - *Reading materials"*
>
> *"Interactive: An interactive learning activity provides significant opportunities for participants to interact with each other and/or the learning resources. The learner is actively engaged in the learning process."*
>
> *"Examples:*
> - *Case studies*
> - *Discussions among presenter and/or other audience members Group exercises and discussion*
> - *Hands-on activity*
> - *Interactive computer software*
> - *Problem solving/workbook exercises*
> - *Roundtable discussion, focus groups*
> - *Simulations, role playing"*

Program resources to be considered are:

"Human Resources

- *In-house expert*
- *Industry representative*
- *Independent expert or consultant*
- *Practitioner in the field*
- *School faculty member*
- *Other persons with appropriate experience, education, references, or certification"*

"Material Resources

- *Journal articles*
- *Computer*
- *Software*
- *Audiotapes*
- *Teleconferences*
- *Tutorial software*
- *On-site observations"*
- *Books or manuals*
- *Program handouts*
- *Videotapes*
- *Slides or overheads*
- *Other resources supported by a bibliography, data, lab tests, or research results*

And finally, the determination of a teaching method or delivery style must be determined on consideration of the program content and learning objectives, and the document outlines examples:

Examples of teaching methods or delivery styles include:

- *Lecture*
- *Tours*
- *Case study*
- *Q&A*
- *Simulations*
- *Roundtable discussion*
- *Hypothetical situation*
- *Demonstration*
- *Panel Discussions*
- *Exhibits*
- *Models*
- *Debate*
- *Worksheets*
- *Video/audio*

The AIA/CES program also includes a provider program for distance education as an alternative to traditional classroom learning or other "in-person" venues like conferences and seminars. They publish related guidelines downloadable from the website (American Institute of Architects 2006). From these guidelines, distance education delivery methods include:

- *Audio tape*
- *Cable TV*
- *CD-ROM/software*
- *Computer based training*
- *Correspondence (written) courses*
- *Email*
- *Fax transmissions*
- *Internet*
- *Publication/articles*
- *Satellite broadcasting*
- *Teleconference/Audio conference*
- *Videotapes*
- *Web cast*
- *Workbooks*

4.4 Reference Materials

The most basic learning resource is the body of existing information related to a subject. The material can be in the form of books, journals, technical papers, brochures, magazines, newspapers, thesis and dissertations, and in the many forms of digital media, and be found for purchase from various sources, in libraries, in broadcast media, and on internet websites. The internet has done much to make such sources of information available, but accessibility is often challenged by the volume of material available on the web. The information relating to a particular subject is not necessarily to be found in a single, centralized easily accessed location. Mature subject matter and technology is far more likely to be easily accessible, with organized, comprehensive industry websites. This is typically far less true of new and emergent technology that may be largely uncategorized and unrecognized as a discrete subject matter.

4.4.1 Case Studies

This is a classic and heavily utilized reference format in the building arts. Case studies can provide significant value to the user by documenting projects in a manner that presents experience based upon completed works. The content can include various aspects of concept, building form, programmatic content, structural design, a unique building form or technology, materials and processes, and detail design. Examples of case study subject matter may include:

- an overall architectural project,
- an architectural material such as glass or flooring,
- an architectural element or building system, such as a curtain wall or structural glass façade.
- or documentation of some performance aspect of a project, such as thermal, daylighting or acoustic.

Many design and architecture books contain case studies relevant to the book topic. Some books are virtually all case studies, but more frequently a set of relevant case studies is presented in support of and following an expositional treatment of the subject matter. Professional journals will often include case studies, and they have become a feature of many websites, ranging from architects to professional associations and product suppliers to trade groups.

- The Sweets Network presents an extensive online group of case studies organized by building type (McGraw Hill Construction Sweets Network 2008). At the same location, links are provided to case studies by the suppliers of various materials.

- Detail is an excellent architectural magazine built around a case study format, with themed issues ranging from facades to concrete construction. Detail generally manages to live up to its name in providing in-depth content, and their website maintains an archive of case studies that can be viewed online or downloaded for a small fee. (Detail portal for architecture 2008).

- *Intelligent Skins* is an example of a book that presents topic chapters of information followed by, in this case, 22 case studies. (Wigginton 2002)

Case studies range in content from superficial, with little but pretty pictures and general description, to comprehensive, with extensive detail information. A few images accompanied by some marketing text, as often found within product supplier's websites, does not constitute a case study. The text should be free of "sales pitch" and obvious marketing language, and should attempt to tell a meaningful story.

A good case study will present a problem and work towards the solution. There is quite often a lot of blood, sweat and teams buried beneath the buildings featured in those coffee-table architecture books; good case studies reveal the pain in story format, and thus provide a learning opportunity for the reader. Exemplary case studies contain the following at minimum:

- contextual imagery and a general description of the project.
- key project statistics; size, quantity, duration, cost, as relevant.
- imagery ranging from contextual through midrange to detail.
- drawings as required to communicate key concepts and details.
- descriptive test to accompany imagery and drawings.
- charts and graphs to visually communicate critical data.
- extensive project credits.

The American Institute of Architects (AIA) has launched a case study initiative in recognition of the value the format brings to the profession. The case studies are intended to document recent and ongoing architectural projects. They chart the following benefits of the case study (American Institute of Architects 2008a):

Firms and schools
• Provide an opportunity for practitioners to reflect on their practice and approach to their next project, and to incorporate new ideas (including ideas from students) into their work
• Expose interns and students to practice issues and promote professional development within firms
• Provide an effective teaching tool and opportunity to publish faculty work that has gone through a peer review process to satisfy academic requirements for promotion and tenure
• Provide a basis for collaboration between firms and schools
• Provide a vehicle for mentoring and structure for sharing knowledge
• Earn continuing education learning units for research on and discussion of case studies

Knowledge agenda
• Develop the discipline of architecture through teaching, scholarship, and research
• Capture and share the knowledge, experience, and expertise of both educators and practitioners
• Make this information accessible through a searchable database, which the AIA is currently developing

Clients and the public
• Make case studies available to clients and the public to better inform these constituencies

The AIA guidelines reveal the expectation of a very comprehensive treatment of the case (American Institute of Architects 2008b):

- *a concise abstract describing the most significant elements of the case and identifying key team members, including the client and user representatives. (no more than one-half page)*
- *learning objectives that articulate the topics to be studied and provide a guide to understanding the lessons learned from the project (two pages)*
- *perspectives, including protocols for decision-making, stories of practice, innovative ideas, and the value placed on innovation, measures of success, and graphic illustrations. Various "voices" should be considered, including client perspectives and those from the prime professional firm, consultants, contractors, and regulators. (approximately 10 pages)*
- *analysis of and reflection on the specific relevant details of the case, focused on a particular topic or considering a series of practice issues. The analysis may include measures of success or difficulty, often reconstructing decision-making to understand a project's flow. Client concerns, business issues within the practice, design considerations, project delivery issues within the firm as well as project delivery in the construction process are among the issues to be considered. The format for this section can parallel that of The Architect's Handbook of Professional Practice. (approximately 10 pages)*
-

These are excellent guidelines primarily intended to provide consistency to the body of studies collected by the AIA, but may need modification for different subject matter, depending upon the presentation medium, target audience and other factors.

Case studies are one of the best ways to create a knowledge-based asset for a learning resource, and there is certainly significant potential value for any design-based resource in the inclusion of case study content.

4.5 The Medium

4.5.1 Print

Digital media is long way from replacing print. For many, books, journals, magazines, newspapers, product brochures, technical papers and other forms of printed literature remain a preferred way to communicate information and images. In spite of the convenience provided by the internet, many people would still rather access information in printed form. In fact, much of the information on the internet is also available in print. Material suppliers and manufacturers have for the most part simply made their printed literature available on a website. The McGraw-Hill Construction Sweets Network is the largest industry resource for construction products. While the network has gone largely digital, they still provide one of the largest catalog programs in the industry, including multiple volumes of product literature to over 70 thousand architects annually.

Books are arguably still the popular choice when communicating a large volume of in-depth, comprehensive information and analysis on a subject.

4.5.2 Digital Media

Digital media include CD-ROM and DVD, digital video, cable TV and satellite broadcasting, computer software and E-mail. Digital media emerged in dramatic fashion starting in the 1980’s, and has replaced much of the earlier analog technology. The spread of digital media was enabled by, or at least paralleled, the diffusion of the personal computer into mainstream culture. In turn, digital media have facilitated the diffusion of information into the culture.

4.5.3 Software Programs

Software programs are a compilation of digital code that can be processed by a computer to perform certain functions. They are great for automating processes, especially analytical processes involving many computations. The programs can also embody procedural guidelines and the kind of logical branching systems characteristic of design guidelines (if this, then this, otherwise this). Most contemporary design tools are comprised of some kind of computer enabled software program.

Most software programs run on a user's computer. The program can be purchased on a compact disc(s) and installed on the computer, or downloaded from the internet. Increasingly, software programs can be accessed on a website through the internet, with the program running on the server and just inputs and results being passed between the server and user (client). Alternately, the computing code can be passed to the client, executed on the client's computer, with certain resulting data stored on the client computer and other data transferred back to the server for storage in a database.

Much of this can be transparent to the client. In the case of Daylight 1-2-3, the daylighting analysis program discussed above, a combination approach was used where the user downloaded a program and installed it on the client computer. The program was executed to provide inputs back to the server, where the analysis was subsequently done and the results passed back to the client. The best way of structuring this interaction is a function of a great many interrelated variables, among them; cost, security, speed, liability, and the requirements for data analysis and storage.

4.5.4 Websites

The new book is the website and the new library is the internet. It is hard to argue that the internet now provides the most convenient access to information, tools and other resources. Unfortunately, much of the information available for free on the World Wide Web is increasingly comprised of online brochures and other marketing information, requiring discrimination by the user to qualify the information. Access to scholarly works and research may be more convenient on the Web, but this access comes with increasing frequency at a cost ranging from 25 to 50 dollars per paper; there may yet be substantial value in a trip to a good library for those involved in extensive research, and regardless of opinion to the contrary, there is still much in the library that will not be found online, especially with older works.

Nonetheless, internet websites provide a powerful resource. Select industry producers provide excellent technical data, design guidelines for their products, product selection tools, and even design tools on their websites. Industry associations have also provided some excellent examples of effective and efficient websites, some of which are represented in this thesis. An example in the glass industry is Glass Processing Days (GPD), an organization that sponsors one of the largest international architectural and automotive glass conferences, held every odd year in Tampere, Finland. GPD hosts a website that features sections on industry news, a library, of articles, a product listing, a directory of suppliers, magazine reviews, and a calendar of events. Hundreds of technical articles are available for free download. Registration is required but there is no charge. The stated intent of the GPD reflects the perceived potential value of a website:

> *"…provide a Web service for Glass Professionals.*
> *The idea is to establish a forum for exchanging information on the ever more advanced environment, technologies and processes that exist within the industry – today and tomorrow. The difference lies in the medium. As a web service, glassfiles.com provides a forum that continuously offers easy access to educational and useful information – anywhere, anytime" (Glass Processing Days 2008).*

Most established technologies have at least one website acting as a resource and providing reference materials along with tools. The glass industry, a large and mature industry, has many.

Universities are another place where valuable websites are often found. An excellent example is a website resource and learning program regarding structures sponsored by the

University of Southern California School of Architecture (Schierle n.d.) The material on the site is intended to augment coursework as part of the architecture and building science curriculum (Figure 4.7).

Figure 4.7 Structures website homepage.

In addition to general resource information regarding structures and the Chase L. Leavitt Graduate Building Science Program, the site contains course information for various levels of structure courses provided by the School of Architecture. Drilling down to the specific course offerings, a new menu presents the course syllabus, project case studies, and lectures.

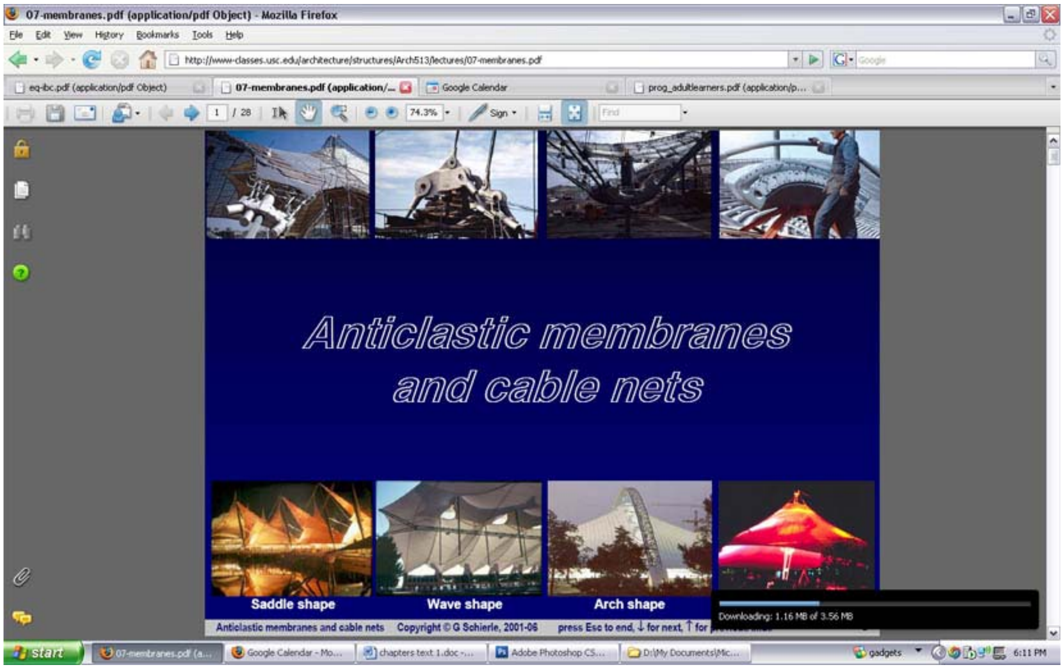


Figure 4.8 PowerPoint presentation in pdf format from the Structures website.

Clicking a lesson link downloads a Microsoft PowerPoint presentation in Adobe Acrobat pdf format into the browser (Figure 4.8). These act as effective self-paced tutorials with the same general content as the lectures, (complete with sample problems) providing a convenient means for students (or anyone else) to review the material before or after the lecture. There are approximately 75 of these lesson programs included on the website.

Chapter 5 - Thesis Intent

The first section of this chapter is used to summarize the research of the preceding four chapters, and to reiterate and summarize relevant conclusions. The second section defines the work to be completed in the upcoming chapters.

5.1 Research Summary and Conclusions

5.1.1 Structural glass facades represent a unique building technology.

This represents the fundamental hypothesis herein. Chapters 1 and 2 define the technology, establish its lineage, and explore the various ways this technology is differentiated from related building technology. In the process a common nomenclature is presented. In following chapters the technology and various components of the technology will be categorized and further described through comparative analysis.

5.1.2 Structural glass facades can be best categorized by the structural systems used as support.

A review of structural glass facades completed to date reveals that the most distinguishing characteristic in virtually every case is the structure. It is the structural systems used in the facades that most differentiates them from related building technology. This hypothesis will be developed in Chapter 6 with a categorization of structure types.

5.1.3 Barriers Exist

Clearly, the design/bid/build method is inappropriate for any design involving innovative materials or building technology

5.1.4 It is conceivable to facilitate the adoption of innovative technology and thus accelerate its diffusion into the marketplace.

Innovative technology often emerges and matures slowly. Structural glass façades have a history of over 30 years, with roots dating back much further. The diffusion of an innovative technology into a culture is a potential; not a given, not simply a matter of time. Without the necessary tools and information to enable aspiring adopters, an innovative technology can languish and even disappear.

5.1.5 The architect is the technology user of most influence.

While many are involved in the building process and require varying levels of competency; the owner, consultant, contractor, material supplier, and building engineer, the architect is the key player, the generator of new projects, the engine of diffusion with respect to innovative building technology. The architect evaluates, selects and specifies the systems and materials used to construct. The most potent strategy in diffusing an innovative technology in the building arts is to get the design community to deliver more designs incorporating the technology. This means both enabling and inspiring the designers to use the technology.

5.1.6 The provision of learning and information resources is critical to the adoption of the technology.

Structural glass facade technology is comprised of many unique considerations, including diverse techniques, materials and processes with which the designer must have familiarity.

5.1.7 Specialized technology requires specialized project delivery strategies and design methodologies.

Implementation is always an issue with innovative building technology, and creative strategies for project delivery are critical to project realization and ultimately to the diffusion of the technology. There are many barriers to the implementation of innovative building technology. Design methodologies and project delivery strategies must be carefully conceived to mitigate the risk associated with innovative technology, and thus encourage its adoption.

5.1.8 Structural glass façade technology is well-positioned for accelerated growth into a broader market.

The technology is mature, the infrastructure robust. Early development costs have largely been paid by innovators and early adopters. A simpler, standardized, more efficient and economical version of the technology is latent but poised to emerge.

5.1.9 Productization is an opportunity.

Productization, the packaging of some aspect of a technology into a simplified, standardized product(s), is an opportunity with structural glass façade technology. The technology has been created by the innovators and early adopters, and used almost exclusively in highly customized, high-design, high cost applications. The basis of the technology however, encompasses a broad base comprised of a largely unarticulated vocabulary of simplified form, materials and methods. A wealth of material is present for new tiers of adopters to utilize the technology in much broader applications, with simpler designs and more standardization of the technology. Standardized products based on structural glass façade technology could provide a highly effective bridge between the technology and a new tier of users.

5.2 Thesis Product

5.2.1 A Thesis Paper

5.2.1.1 Research Documentation

Background research will be documented in chapters 1-4.

- Chapter 1 defines structural glass façade technology, explores its historical context, and describes the current state of the technology in the marketplace.

- Chapter 2 explores the various structural and glass systems used in structural glass facades, as well as the materials and processes that comprise the technology. The information in this Chapter becomes more than simply background information. As this thesis explores the diffusion of innovative technology into the mainstream market and the affect of information and learning resources in facilitating this diffusion, the information in Chapter 2 becomes content for such a resource.

- Project implementation or delivery methods need to be as creative as the designs when dealing with new and innovative building technology. Chapter 3 explores the relative merit of the various strategies that are employed in realizing project designs incorporating innovative technology.

- As mentioned above, this thesis explores the potential impact of available design resources and learning programs on the diffusion of innovative technology into a broader market. This is accomplished by facilitating initial competency and providing continued learning opportunities for aspiring adopters. Chapter 4 explores various means and methods for accomplishing this.

5.2.1.2 Morphological Categorization by Structure Type and Comparative Evaluation

It is a hypothesis of this document that there exists a unique building technology referred to herein as structural glass façade technology, and furthermore that this technology can be best categorized by the structure types that are used in support of the facades. A comparative evaluation is then possible between the structure types to clearly differentiate them and provide the basis for decision making with respect to which type is most appropriate for use on a given building project. This will be developed in Chapter 6.

5.2.1.3 Categorization of Glass and Comparative Evaluation

A contention of this thesis is that glass is an important component of structural glass façade technology, and while sharing many considerations with the use of glass in any application, the application of glass in structural glass facades involves additional unique considerations. Here again, the categorization allows for comparative evaluation that can provide the basis for appropriate decision-making regarding glass selection. This will be developed in Chapter 6.

5.2.1.4 Categorization of Glass-Fixing Systems and Comparative Evaluation

As with glass, glass-fixing systems represent another important component of structural glass façade technology. Some of these systems are used almost exclusively in structural glass facades, some find use in other applications as well. The use of point-fixed glass in itself does not make a structural glass façade. Point-fixed glass is often used in single-story storefronts, and these would not represent structural glass facades as defined herein. At the same type, the various glass-fixing systems can be used relatively interchangeably on the various structural systems that make up the technology. This presents another decision-making nexus, and here again the intent is to categorize and describe the systems in a manner that provides for comparative evaluation. This also will be developed in Chapter 6.

5.2.2 A Web-Based Resource for Structural Glass Façade Technology

This thesis proposes the creation of a web-based resource for structural glass façade technology as a means to enable new tiers of adopters and facilitate the diffusion of the technology into the mainstream construction marketplace. A prototype website has been developed as part of this thesis and is described in Chapter 7. The following items will also be developed in Chapter 7.

5.2.2.1 Design Methodology

A design methodology is inextricably linked with the project delivery method, especially when utilizing innovative building technology. As a fundamental principle, design must always be informed and shaped by the entire building process, ranging from feasibility through procurement, fabrication, assembly, erection, and lifecycle maintenance. The delivery method determines who does what when. A project delivery method for projects incorporating innovative technology is explored in Chapter 3.3 and will be used as the basis for developing a simplified design methodology for structural glass facades.

5.2.2.2 A Conceptual Design Tool

As discussed previously, the architect is the key player, the target user who must achieve a reasonable level of competency before adopting a new technology.

In this context, this thesis proposes that the most effective way to accomplish this is to develop tools to facilitate the conceptual design process that typically involves schematic design and design development. A simplified project delivery method is defined, a simplified design methodology is developed in response to this delivery method, and now tools can potentially embody and facilitate this simplified design methodology.

The tool proposed here is a software program created with Microsoft Visual Basic that facilitates glass selection and structure type selection, and performs structure analysis on a simplified model to provide preliminary information required to inform ongoing design and budgeting. The tool can provide comparative analysis on different structure types to assist evaluation by the designer. A prototype has been developed as part of this thesis and is described in Chapter 7.6.

5.2.2.3 Reference Materials

Reference materials are a key part of any resource, and websites are an excellent means of providing convenient and easy access to these materials. Reference materials include relevant papers, articles, case studies, system and product descriptions and specifications, example details, and links to related manufacturer's websites.

5.2.2.4 Learning Programs

Tools are not enough by themselves. Users must be taught how to use the tools for them to be effective. And it takes more than a hammer to build a house; the user must learn the context, the full breadth of the technology in which the tool will be used. This is a critical component of any effective resource, and vital to enabling aspiring adopters. A tutorial-based learning program for structural glass facades is developed here within the context of the AIA/CES guidelines (see Chapter 4.3.4).

Chapter 6 - Categorization and Organization of Materials, Processes and Systems

Chapter 2 discussed in general terms attributes of the various materials, processes, and system types that comprise structural glass façade technology. This Chapter will categorize the structural systems, glass types, and glass systems that make up the technology. A strategy for categorization is defined, and each system type is addressed. A distinct set of evaluation criteria is developed for each of the primary systems; structure type, glass type, and glass system type. Each categorized element is then evaluated with respect to the appropriate criteria. The resulting attributes provide a detailed basis for comparison between the categorized items.

The identification of a body of completed works comprised of glass-clad façade structures with certain differentiating attributes as characterized herein has been hypothesized as representing a unique building technology. Certain evidence has been provided in this regard. A core test of this hypothesis will be the development of a rational organization and categorization scheme for the elements perceived as comprising this technology. The hypothesis further states that this body of façade constructs is best categorized by the integral structural systems supporting the facades. Secondary elements of glass and glass system are recognized as lesser opportunities for such treatment. The discussion in this Chapter will be limited to brief system descriptions, categorization issues, and comparative analysis of the defined classes. An expanded discussion of the structural system, glass and glass system types is included in Chapter 2.

6.1 Façade Structure Types: Categorization Scheme and Comparative Analysis

As postulated previously, structural glass facades can best be categorized by the structure types used to support them. The structure types categorized below have been discussed in some detail in Chapter 2.2.

6.1.1 Morphological Categorization Scheme

The structure types discussed in this thesis are not unique to structural glass facades; cable trusses can and have been used to support long-span roofs, for example. But their adaptation to the requirements of structural glass facades has rendered them unique, and together they represent a distinct class of structures. Primary attributes of this class include:

Table 6-1 Attributes of structure types.

Attributes of Structural Glass Façade Structure Types	
• *Exposed structure and connections*	• *Tension-based structural systems*
• *Minimalized structural systems*	• *Frequent use of tensile elements in rigid systems*
• *Refined craftsmanship*	• *Lightweight structures*
• *Machined components*	• *High flexibility; high deflections*
• *High quality materials and finishes*	• *Optimized transparency as a frequent design objective*

The structural system types used in structural glass facades are categorized in Table 6-2 below. They are categorized here by inherent stability (open or closed system) and spanning behavior (unidirectional and multidirectional), explained further below.

Table 6-2 Morphological categorization of facade structure types.

Morphological Categorization of Façade Structure Types	
Closed Systems	**Open Systems**
Unidirectional Spanning Closed Systems	

Strongback
Glass Fin
Simple Truss
    with cable/rod bracing
    without cable/rod bracing
Mast Truss
	Cable Truss
	Cable Hung

Multidirectional Spanning Closed Systems	

Space Truss / Space Frame
 	
Grid Shell (moment resistant)
Tensegrity
	Cable Net
	    flat surface geometry
	    anticlastic surface geometry
	Grid Shell with Cable Bracing
	Hybrid Tensegrity

6.1.1.1 Open and Closed Systems

Closed System: A structure whose primary stability is achieved internally, without the requirement for pre-tension forces applied against an anchoring boundary structure.

Open System: A structure whose primary stability is achieved only through the application of pre-tension forces applied against an anchoring boundary structure.

Consider a simple truss, even one with internal cable bracing. It possesses its morphology independent of its inclusion in an overall structural system; it is internally stable. A cable truss on the other hand, has no such inherent stability. A cable truss released from anchoring boundary structure against which it has been pre-tensioned by the development of prestress loads in the tension components immediately collapses into formlessness.

There are then two distinct classes of structure systems used in structural glass facades; closed and open systems. The primary attribute that differentiates them as a function of this classification is the requirement for prestress, which must be determined as a function of the design process and must be realized on site during the installation of the structure.

6.1.1.2 Spanning Behavior

Unidirectional Spanning: Systems spanning in one primary direction.

Two dimensional (flat) trusses can span in only one direction, and systems built of such trusses are referred to as 1-way systems with respect to spanning. Morphologically flat trusses of any kind are only capable of unidirectional spanning. Strongbacks, fin-supported, and cable-hung structures are also only capable of unidirectional spanning.

Multidirectional Spanning: Systems spanning in two or more primary directions.

Additional spanning directions increase the efficiency of a structure, allowing for a more uniform stress distribution. Most common are 2-way systems. Orthogonal grid space frames and cable nets are examples of 2-way spanning systems. Triangular grid space frames and cable nets displaying 3-way spanning behavior are also conceivable. More complex geometries as can be developed with grid shell structures are capable of complex, highly efficient multidirectional spanning behavior along multiple load paths.

Multidirectional spanning is not simply a matter of utilizing a 2-way system. A square grid octet truss space frame, rectangular in plan will at some point, as the plan length increases relative to the plan width, span only in the short dimension, behaving as a 1-way system with no benefit in efficiency from the other potential spanning direction. A square plan will span most efficiently, evenly distributing stresses along both spanning paths.

6.1.2 Definition of Evaluation Criteria: Façade Structure Types

Following is the format and the criteria by which the various systems will be presented and evaluated.

6.1.2.1 Summary of Predominant Attributes

A brief bullet-point summary of the primary attributes identified and discussed in greater detail following. Figure 6.1 orders a predominant subset of structure types by a generalized attribute of inherent complexity.

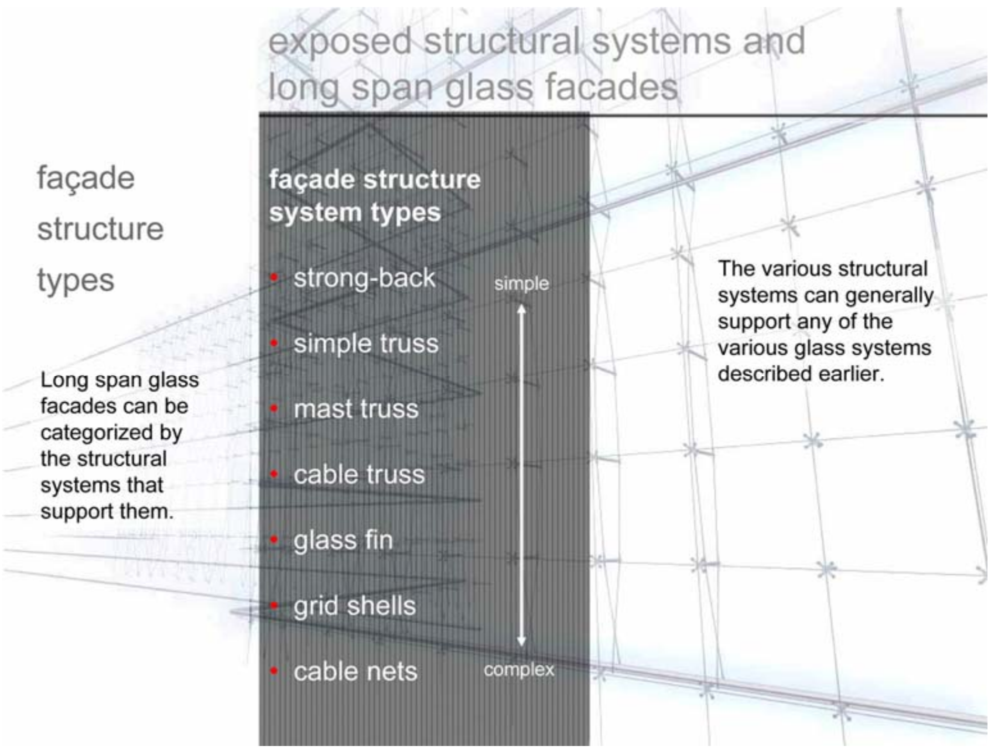


Figure 6.1 Generalized complexity of structure types; listed in order of increasing complexity.

6.1.2.2 Morphology

Each system will be briefly described correlating general function and form. (A more generalized description of the systems can be found in Chapter 2.)

6.1.2.3 Design Considerations

- Aesthetics

Each of the different structural types, while sharing many common attributes, possesses a unique general aesthetic. Here the aesthetic attributes that characterize the systems are identified.

- Transparency (and control):

The pursuit of maximum transparency in the building envelope has been a primary driver of structural glass façade technology, although by no means the only one, and the relative importance and manifestation of transparency varies widely between projects. The result in any case has been an increasing generalized dematerialization of structure, achieved largely through an increasing predominance of tensile bracing elements in closed, rigid systems, and the open systems comprised mostly or completely of tensile elements. More and more, however, the control of transparency as a means to *control* daylight is becoming the predominant concern, not simply the maximization of transparency with no thought to issues of thermal performance and glare. As a primary attribute of glass itself, the consideration of structure transparency is nonetheless relevant. Here the systems characterized as having the least and most generalized transparency will be identified, with the remaining systems classified in comparison to these and each other.

- Geometric flexibility

This consideration involves the relative ability of the various structure types to accommodate curves, folds, and other surface geometry. Structural glass façade technology enables a remarkably broad vocabulary of form for the designer. There are however, important differences between the system types that comprise the technology. This criterion is a measure of the relative ease of design using the system, a function of the constraints imposed by the structural system type and the technical savvy required by the designer to achieve competency in the use of the system.

- Design issues

This criterion identifies design considerations particular to each of the various systems. These include considerations of structure, anchorage, and add-on systems.

- Form-finding

Form-finding is a term used to identify an interactive and iterative process used in developing form (Lewis 2005, p.178). Various computational techniques are employed. The term was originally used to identify a process by which form is determined in highly flexible structures, such as membrane structures requiring prestress loads as a condition of stability, although Lewis (2005) recommends its broader application to rigid structures as a means to optimize shape and stress distribution. Form in these non-rigid structures is purely performance driven, deriving solely from the combined forces acting on structural materials in a defined boundary geometry. From the initial condition, the process adjusts the form incrementally and iteratively until static equilibrium is achieved. Only at this point is the final shape determined.

This presents an obvious dilemma to the architect; they cannot simply define the shape as part of their normal design development. The form cannot be determined arbitrarily and then constructed. Someone with the analytical tools and know-how must be involved to provide this specialized service. If the design can proceed with only a rough approximation of the final form this may not present a problem; a specialist can be involved in the build phase of the work to determine final form. If not, a means will have to be found to involve a specialist during the design phase of work.

It should be noted that the term form-finding is being applied to a related conceptual design process of parametric modeling whereby mathematical parameters are developed for generating building form (Autodesk 2007).

In the context of this thesis the criterion of form-finding will be evaluated with respect to the various structure types as either required or not required.

6.1.2.4 Resources and Technology

- Maturity

As discussed previously herein, structural glass façade technology has reached a level of maturity over the past three decades that may not be widely recognized in the building industry. This is relevant with respect to the industry's general recognition and acceptance of the technology. At the system level however, there are differences in relative maturity. Glass-fin facades are a more mature type than cable nets, for example. Relative maturity between the systems will be identified for this criterion.

- Materials and Processes

While structural glass façade technology is a powerful form generator for the designer, it is essentially a performance-based technology deeply rooted in the materials and processes of which it is comprised. For this criterion, a brief description of the most common materials and processes used, and the identification of any relevant issues with respect to them, will be provided.

- Material Suppliers and Subcontractors

A challenge in delivering innovative building design and technology can be finding qualified suppliers and subcontractors to facilitate the construction phase of the project. The newer a technology is the greater the likelihood of this being a problem. Because of this there is some correlation between this criterion and that of maturity as discussed above. At the risk of some redundancy, this will be discussed as a distinct criterion.

- Glass System Interface

The various glass and glass system choices can be mixed and matched to the structure types identified here with considerable freedom. Relevant considerations with respect to the different systems will be identified here.

- Durability and Maintenance

The materials that comprise structural glass façade technology are all prime materials with long life expectancy in normal applications. Differences do exist however, between the systems. Lifecycle and lifecycle maintenance considerations will be identified and discussed here.

- Sustainability

Discussions of sustainability often ignore the important aspect of contextual appropriateness. A technology incorporating high performance materials and processes may not be sustainable on a widespread basis, but may be quite sustainable on commercial office and public buildings as a feature element. Certainly structural glass façade technology is sustainable in some appropriate context.

Another often neglected aspect of sustainability and green building is structural efficiency. This is discussed further in the following criterion of structural efficiency.

Glass and steel, the predominant material base of structural glass facades, are both recyclable. Architectural glass however, cannot be produced from recycled material because of the risk of contaminants that could compromise the mechanical properties. A Pilkington (2008, p.2) technical bulletin has the following to say about glass recycling:

> *The float glass process recycles virtually all the glass waste from the in-plant production melting and cutting processes. This broken glass, known as cullet, is reintroduced with the raw materials batch mix in the furnace as an aid to melting. It takes half the amount of energy to produce glass from cullet as it does to produce it from raw materials. For LEED™ certification calculations: Pilkington (NA) Float Glass contains approximately 20% post-industrial cullet (recycled glass). It does not contain any post-consumer recycled content because unidentified glass from unknown sources might not blend fully with Pilkington's glass formulations.*

Neither steel nor glass however, can typically be regarded as local materials. Smaller and more efficient float glass manufacturing plants have resulted in a considerable decentralization of the manufacturing base over the past few decades, but glass is still frequently shipped long distances to many construction sites. Owing to quality and warranty issues, much of the glass in point-fixed applications has been imported from England and Austria to all parts of the world. This is changing, and domestic supply sources have increased throughout the developed world.

Steel production is also a relatively centralized industry, while steel fabrication can be found at some level in virtually every locality, although the level of craftsmanship is often not suited to exposed structural systems. Specialized steel products like strand and wire rope for application in architecture are also highly centralized, being distributed globally from relatively few locations, Germany chief among them.

The daylighting provided by these systems should be regarded as an offsetting resource, although in most cases much more could be done in harvesting this resource and putting it to work. There is great opportunity here in the future development and application of a more sustainable, green version of structural glass façade technology. The issues here are deep, interesting, and well beyond the scope of this thesis, but are strongly recommended as a focus for future work.

Whatever the realities of sustainable building practice with structural glass façade technology, there is general parity between the structure systems, with only some few differences regarding material efficiency that will be discussed.

6.1.2.5 Structural Performance

- Spanning capacity

Structural glass façades are long-spanning systems intended for spans of approximately 20 feet and up. All the structural systems except strongbacks are capable of long spans of 100 feet or more, and while the implications of span vary between the systems, a general rule is that complexity increases with span. Also, the longer the span, the more important the efficiency of the spanning system.

MacDonald (2001, p.60-67) has interesting comments on the relationship between complexity and efficiency in structural design. Right or wrong, the design considerations that drive the form of structural glass facades and other structures in architecture often do not equate efficiency to economy.

- Span/Depth (L/d) characteristics

Typical span/depth varies among the systems; rules of thumb will be provided.

- Typical deflection criteria

Deflection criteria vary among the systems; rules of thumb will be provided.

- Pre-tension requirements

Open systems as discussed above require prestress forces to achieve stability. This complicates the design process sometimes requiring the involvement of a specialist. Such structures also require pre-tensioning in the field to achieve the prestress requirements, which can complicate the field work, especially depending upon the magnitude of the prestress loads. This criterion is generally not an issue with closed systems.

- Reaction Loads

A number of factors influence the way these structural systems load the anchoring structural system. The open systems in particular can result in significant reaction loading that must be understood and identified to the building engineer early in the design process. The relative differences between the systems will be identified.

The open systems typically apply high reaction forces to the anchoring systems because of the prestress forces required to stabilize these systems. Such reaction forces, or close approximations thereof, must be identified early on the to the building engineer responsible for the anchoring structure. These reaction loads require special consideration because they are applied continuously, not intermittently like ordinary design loads.

- Structural Efficiency (strength to weight)

Many of the structure types identified herein qualify as lightweight building systems. Structures designed using these systems can be half the weight of conventional systems, being extremely efficient on a strength-to-weight basis. While this efficiency does not often translate into cost savings and in fact may result in higher cost (materials are cheap, efficiency is not (Macdonald 2001, p.64), the material savings are becoming of increasing value. The higher material (and energy) costs become, the higher the value of efficiency in structural design. It must be acknowledged that there is a compelling aesthetic associated with these highly efficient structures that accounts for much of the reason for their use, especially when the structure can be showcased in such dramatic fashion as is often possible with structural glass facades. This attribute is discussed in general terms where relevant.

- Seismic behavior

The structural systems used in structural glass facades range from flexible to very flexible with respect to movement under load. Wind load deflection criteria ranges from L/45 to L/175. The facades are designed to accommodate this movement. Butt-glazed silicon joint provide remarkable elasticity to the glazing systems. The structural systems are relatively lightweight, as discussed above. Glass however, is relatively heavy; laminated glass of 2-ply ¼ inch (7mm) panes weighs nearly 7 psf (3.2kg). Structural fabric membrane materials are mere ounces per foot. Force is calculated as mass times acceleration, thus weight is a disadvantage with seismic forces, but an advantage in resisting wind loads. The structure types represented here are typically light enough that maximum loads typically result from wind loads.

- Behavior under extreme loading conditions

Highly flexible structures perform better under blast and impact loading; in combination with laminated glass, they are capable of greater and quicker deflections under load, mitigating blast effect (Schoeberg et al. 2005, p.24).

6.1.2.6 Constructability

- Fabrication

Fabrication issues vary between the systems and relevant considerations will be discussed for each.

- Installation

Installation issues vary between the systems and relevant considerations will be discussed for each. A predominant consideration is between the open and closed systems as discussed following and in the pre-tension requirements section above. Open systems will require pre-tensioning of the system during installation, which complicates the installation process.

Installation is a critical aspect to the successful implementation of a structural glass façade design. The closed and rigid structures are the easiest to control with respect to field tolerances. The open tension-based systems present challenges. Accurate survey becomes of paramount importance. If the structures are installed correctly and within tolerances, the glass system will install quickly and easily. If not, much expensive field labor time can be wasted adjusting the structure to accommodate the glass systems.

6.1.2.7 Economy

Cost ultimately has more to do with the variables of application of any one of the various systems described here than with the relative inherent costliness of the systems. Costs of each structure type can vary widely as a function of design. The cost volatility is often evident at bid time. It is commonplace for bids for commodity type services like structural steel fabrication and/or erection to come in within a few percent of each other. It is not uncommon for bids on specialty structure work as in structural glass facades to vary as much as 20-30 percent. Thus, it is critical for the designer to begin cost analysis in parallel with conceptual design development, thus providing this vital input as part of the decision-making process. The goal is to balance the program requirements and design intent for the façade with the budget objectives in a manner to achieve the most economical solution for a given problem. Structural glass façade technology is capable of delivering solutions to a broad range of budgets; the body of completed works includes examples ranging from less than 100 to over 500 USD/ft² (750 to 3700 EUR/m²).[9]

In addition, the relative costs between the systems will vary to some extent as a function of the application. While a glass fin-supported wall may be cheaper then a cable net at shorter spans, this may not be the case with longer spans. This makes establishing costing guidelines between the systems challenging at best. For this and other reasons, the strategy here is to establish a base level with the structure type that most frequently provides the most cost effective solution to the broadest range of problem. The simple truss system will be the base case. The other systems will be treated as a multiple of the base case.

Span and complexity are most directly related to cost, regardless of structure type; the longer the span and the more complex the design the higher the cost. Figure 6.1 indicates the relative inherent complexity of the predominant structure system types; cost will bear the same general relationship. These are very general guidelines intended only to provide a feel for the relative cost between the systems, and are in no way intended as a substitute for a rigorous estimating program started very early in the design process.

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[9] The currency conversion from USD to the Euro equivalent was made in the March 2008 timeframe, a time in which the USD was falling rapidly against the Euro. Use the USD values indicated here to calculate a current conversion to the Euro.

6.1.2.8 Summary

There are wide areas of overlap in applying these criteria to the structure types, resulting from the many interacting variables present in any specific application of a system. While cable net may be generally the most expensive of the façade types and simple truss systems the least, it is entirely possible to have a simple and efficient application of a cable net façade that is little or no more expensive that a simple truss system in the same application, depending on the variables. Similarly, a highly transparent cable net structure combined with a panelized glazing system using insulated glass may display less transparency than a cable-braced simple truss system using monolithic glass. Nonetheless, there are some important inherent differences between the systems with respect to the criteria presented here, knowledge of which should prove useful to the designer in selecting a structural system for a façade design. Figure 6.2 indicates some generalized behavioral characteristics of the most predominant structure types.

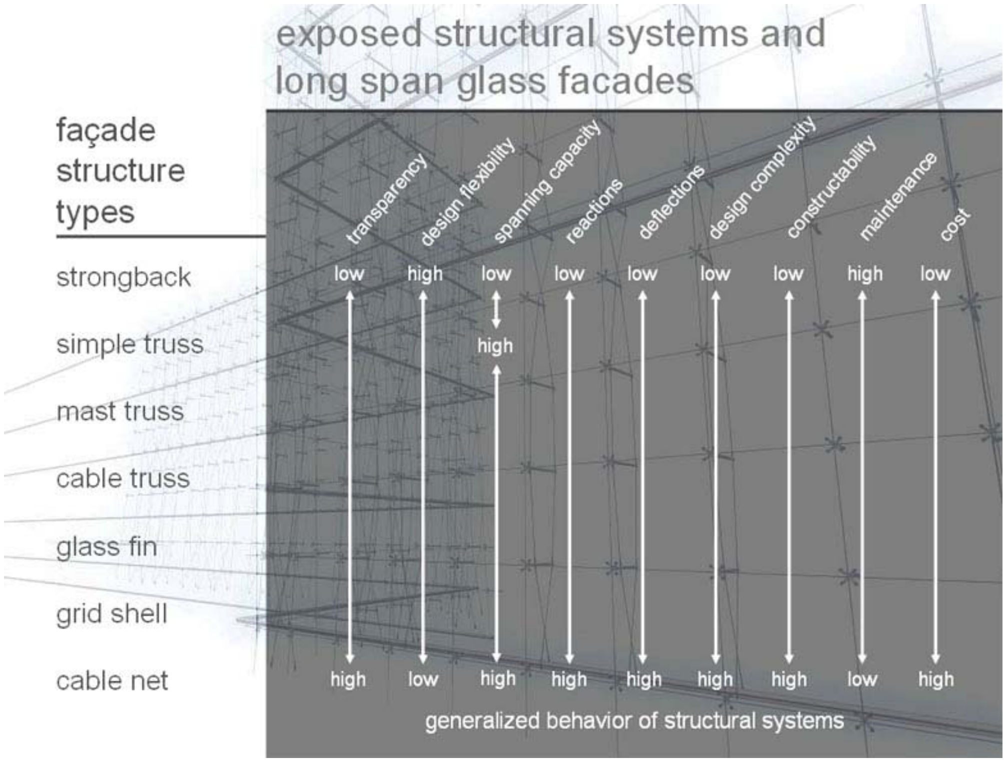

Figure 6.2 Generalized behavior attributes of structural system types.

What follows is a consideration of each system type identified above with respect to the criteria just presented.

6.1.3 Class Comparisons: Application of Evaluation Criteria to Structure Types

The various structure system types are evaluated following. The structure systems were described in detail previously in Chapter 2. The focus in this section is a comparative analysis with respect to the evaluation criteria established in the previous section. Note that space frame and space truss have been combined, as have the grid shell and tensegrity types.

The systems are presented in a sequence of increasing use of tensile components and tension-based design.

6.1.3.1 Strongback

Table 6-3 Strongback attributes.

Strongback: Summary of Predominant Attributes
• *Tube steel to custom built-up sections can be used*
• *Transparency decreases as span increases*
• *If used in multi-story applications, glazing system must be able to accommodate full range of building movements*
• *No prestress loads; tributary loading only*
• *Primary function is to integrate with long-span façade systems in short span areas to provide a seamless building facade*
• *Efficient only in spans under approximately 20 ft (6m)*
• *High relative value in short span applications*

Morphology

Strongbacks are structural framing members used in short-span applications. An approximate spanning range is 8 to 20 ft (2.4 to 6m). Strongbacks can be used in simple floor-to-floor spans as required to support exterior façade elements. In their simplest form a steel tube section is often used as a cost effective solution. The simple tube section can also be modified to accommodate the connections of various interface systems, or to provide attachment to supporting structure. Their inclusion here is in support of a strategy to provide a uniform cladding solution on a building incorporating different spanning conditions. The strongback can be made to mimic the outer chord of a simple truss, allowing for the cladding system to continue across the varied spanning condition uninterrupted.

Design Considerations

The strongback component can be a simple tube or a custom built-up section. So called “improved” sections can increase efficiency and appearance, but generally do both at some cost.

Transparency: As the span increases the section properties of the strongback will increase and transparency will be compromised. Still, the relatively thin profile made possible by the use of steel yields a comparatively high level of perceived transparency.

Geometric flexibility: The strongback can be designed to accommodate any surface variation required.

Design issues: The section properties of the strongback member will increase with span, becoming increasingly inefficient from a material utilization standpoint in comparison to a simple truss. The designer must make the determination of when to use a strongback verses a simple truss based upon the variables of application, among them: span, design loads, depth constraints, budget and aesthetic considerations.

Form-finding: Not required.

Glass system interface: The concept is for the strongback to provide a glass interface matching a longer spanning system(s). Any of the glass systems can be accommodated with strongback support.

Resources and Technology

Maturity: General parity with simple truss systems.

Materials and Processes: A fabricated steel component, galvanized and painted.

Material suppliers and subcontractors: All readily available.

Durability and Maintenance: Steel strongbacks will require some form or finish protection depending upon conditions of use. Inside surfaces of tube sections must also be considered if the tubes are left open.

Sustainability: General parity with truss systems in short-span applications. Efficiency decreases as span increases.

Structural Performance

Spanning capacity: Typically used in the range of approximately 8 to 20 ft (2.4 to 6m).

Span/Depth (L/d) characteristics: 15 to 20.

Typical deflection criteria: Design depth to match long-span structure system type.

Prestress requirements: None.

Reaction Loads: Tributary area.

Structural Efficiency: Relatively low efficiency. Improved shapes can provide somewhat improved efficiency over open sections.

Seismic behavior: A function of section properties.

Behavior under extreme loading conditions: Will not perform as well as more flexible systems.

Constructability

Fabrication: The choice of steel fabricator will depend upon the complexity of the strongback design.

Installation: Relatively simple; typically tied off at outside of floor slabs.

Economy

Strongback systems are in general parity with conventional curtain wall systems. Used only for smaller spans, so cost comparison to long-span structure types is not relevant.

6.1.3.2 Glass Fin

Table 6-4 Glass fin attributes.

Glass Fin: Summary of Predominant Attributes
• *The closest thing to an all glass facade* • *Very high transparency, but less than flat cable nets* • *Surface geometry is limited; flat or curved vertical surfaces are most common* • *Vertical glass fins, full or partial height depending on span, located at each vertical glass grid joint* • *Maximum fin length approximately 15 to 17 ft (4.6 to 5.2m); longer spans require metal splice plates* • *Systems most often suspended, but small spans can be base loaded* • *Suspended fin-supported glass walls were the seminal technology for structural glass facades.* • *Drilled or pinched point-fixed glazing systems typical* • *span/depth = 8 to 10* • *Deflection criteria = L/175* • *Dead load reactions to overhead structure with suspended system must be accounted for* • *Costs ranges from moderate to high depending upon span and load, but increases rapidly with span; cost factor 2.0*

Morphology

Another technique for the structure to diminish in appearance and thereby enhance transparency in long-span facades is to substitute glass components for conventional metallic components; a strongback or truss is replaced with a glass fin construct. With a glass fin supported system, monolithic or laminated glass fins are positioned perpendicular to the glass plane at the vertical glass seam to stiffen the wall against wind loads. Early systems utilized a patch fitting to attach the glass, effectively restraining the glass at its corners while providing for building and thermal movement. Contemporary systems commonly use drilled glass panels and countersunk stainless steel fittings to fix the glass to the fin. This structure type provides for an all-glass façade in spans under approximately 15 ft (4.6m), and a near all-glass façade in spans of up to 100 ft (30m), and of indefinite length.

Design Considerations

Aesthetics: These are minimalist systems with a unique transparent aesthetic.

Transparency (and control): The origins, while not the roots, of structural glass facades can be traced to this structure type. Some would argue that this remains the most transparent of the façade types. After all, there is virtually nothing but glass in the system, not even the cables of the cable net structures; how could it not be the most transparent. However, the lateral stability for this these systems is provided by glass fins that extend back perpendicular to the glass surface, creating a layering of glass that is easily read from most vantage points. This affect is not present with the membranes provided by the cable nets. This is and will always remain one of the most transparent systems, but it is the opinion of the author that the flat cable nets and cable hung structures provide optimum transparency.

Geometric flexibility: Heat-treated laminated glass is being used increasingly in structural applications as beam and column elements. The latest high-profile example of this is the glass cube by Apple in Manhattan; the entire structure and cladding are glass. There are opportunities for exploring faceting and other articulations of the façade surface with this technology, but most applications are vertical walls either straight or curved in plan. apple cube

Design issues: Whatever type of glass-fixing system is used, building and façade movements must be accounted for. Glass panels can be suspended from above like links of a chain, with the attachment to the fin allowed to slip vertically, but restrained against out-of-plane movement. Spans over approximately 15 to 17 ft (4.6 to 5.2m) will require spliced fins of more complex design, fabrication and installation.

Form-finding; not required.

Glass system interface: The glass module is typically oriented vertically to maximize the number of fins supports. Glass cladding connections to the fin occur at the intersections of the glass grid where various types of point-fixing options are available.

Resources and Technology

Maturity: This is the oldest of the structural glass façade structure types categorized herein. Even so, application is everything, and long-span glass fin facades approaching 100 ft (30m) remain cutting-edge.

Materials and Processes: Glass fins are tempered and/or laminated. Splice plates are stainless steel with neoprene washers sandwiched between plate and glass to protect the glass surface. In very long spans, multi-ply laminated fins are sometimes used. All hardware and components are typically stainless steel.

Material suppliers and subcontractors: Several glass manufacturers including Pilkington and Eckelt provide complete systems including design support and all materials and hardware. Less costly solutions are possible with the façade designer detailing the system and a local glass fabricator providing the glass; although the extended warranty provided by companies like Pilkington will likely not be available. The strategy here is to find a design/builder for the façade. Even with the high-end product approach, a willing contractor must be identified.

Durability and maintenance; just clean the glass.

Sustainability: Relative parity between systems.

Structural Performance

Spanning capacity: Spans up to 100 ft (30m) have been built.

Span/Depth (L/d) characteristics: varies

Typical deflection criteria: L/175.

Pretension requirements: None.

Reaction Loads: Suspended systems require overhead structure to support system dead load.

Structural Efficiency: N/A

Seismic behavior: Provision must be made for movement at the connections of the glass cladding to the glass fins.

Behavior under extreme loading conditions: This attribute of glass fin-supported facades presents a relative disadvantage in comparison with the more flexible tension-based systems.

Constructability

Fabrication: If spans are near the limit of a non-spliced fin, it is important to verify the maximum single-piece fin length available, which will vary between manufacturers.

Installation: There are currently quite a few local and regional glazing companies that have some experience with glass fin-supported walls. The installation of these systems is not particularly challenging, at least with the shorter span systems.

Economy

Cost increases exponentially with increased span. Systems are most cost effective in the spanning range where spliced fins are not required. Costs can vary considerably between product suppliers depending upon quality and warranty. A cost factor of 1.5 is based on a normalized 30 ft (9m) span system. Low span systems using a non-spliced fin will provide improved relative economy.

6.1.3.3 Space Frame/Space Truss

Table 6-5 Space frame/space truss attributes.

Space Frame / Space Truss: Summary of Predominant Attributes
• *A unique aesthetic of exposed double-layer grid structure*
• *Least transparent of the structure types*
• *Complex structural geometries and resulting surface geometries are possible*
• *Grid module can constrain design*
• *Mature technology, but few system providers*
• *span/depth = 15 to 20*
• *Typically very rigid and lightweight structures with low deflections*
• *Most efficient when working as multidirectional spanning structures (spanning directions must be close to the same dimension)*
• *Fabrication is a specialty with relatively few producers*
• *As a simple half-octahedral geometry, parity with simple truss*

Morphology

Figure 6.3 Biosphere 2; a large glass-clad space frame enclosure (Biosphere 2 2006).

Space frames and space trusses are the same except for the member connections; space frame structures are moment connected (as in welded connections restrained from rotating), space trusses are pin connected (as in unrestrained connections free to rotate). (G G Schierle 2008, pers. comm., 29 Jan.) These structure types are typically comprised of repeating geometric unit cells that combine to form a 3-dimensional truss network. The most common is the so-called square-on-offset-square derived from the same basic geometry as octet-truss patented by Fuller (1961); a repeating combination of close-packed half-octahedrons and tetrahedrons that form two layers of square or rectangular surface grid separated by interstitial web members. Space trusses are the more common form, and there are industry specialists providing various componentized, prefabricated and pre-finished systems made to order. The industry typically refers to both forms of structure as space frames.

Design Considerations

Aesthetics: There is a density of members and a continuous depth of structure that is often objectionable to the façade designer, and for this reason their application as façade structures has been limited.

Transparency (and control): The density of members and continuous layers of structure directly impact the perceived transparency of the structure. Even simple truss systems can exhibit more transparency than either space trusses or frames.

Geometric flexibility: Interesting form can be generated by the repetition of a 3-dimensional unit cell in space. While many space truss and space frame structures have been built since the 1970’s, very few have really explored this potential. Deviation from the unit cell geometry immediately complicates the design, and can easily make fabrication and installation impractical, so the surface geometry of the overall form is generally constrained by the properties of the unit cell. However, virtually any surface geometry can be generated, but results in a great diversity of part types.

Design issues: The space truss relies on geometric triangulation to provide stability. Because of the moment connections, space frames are less constrained in unit cell geometry, but are impractical in many applications because of the requirements for developing the moment connections, such as joint welding or multi-bolt connections. Space trusses are most efficient in the range of an 8 to 10 ft grid (2.5 to 3 meters), and are generally suitable for mirroring the glazing grid. For reasons of connection geometry, a rectangular grid space truss will typically be at least as deep as half the dimension of its longest chord member.

Form-finding: not required.

Glass system interface: Space trusses and space frames are best loaded at the node, so any glazing system capable of spanning node-to-node can be used, including point-fixed systems. Veneer systems are also possible with a special chord design to receive the glazing system.

Resources and Technology

Maturity: Space frame is a mature technology, but a languishing on as well. Thousands of space truss structures have been built since the 1970’s, but architectural interest in the building form peaked in the 1980’s.

Materials and Processes: Most systems are comprised of steel hollow section tube struts with some kind of node connector. The most common system utilizes a forged and machined steel ball as the node piece. All components and hardware are galvanized and painted.

Material suppliers and subcontractors: Space frame fabrication is a specialty; the local steel fabricator will not be able to provide a componentized space frame system under normal circumstances. The services of a specialty fabricator or design/builder will have to be acquired. A potential problem is that there are currently very few to select from in the marketplace.

Glass system interface: Any glass system type can be supported from the node on the space truss grid. Veneer systems will require a special outer chord to provide continuous support.

Durability and Maintenance: Space trusses and space frames are durable structures requiring low maintenance under normal circumstances. The typical space truss is comprised of many pieces, each pre-finished in the factory. This is superior to field painting. In the event that the finish is compromised for any reason, it can be extremely difficult and costly to repair. Also, the configuration and constant depth of the structures combined with the large number of parts can make cleaning of the structure difficult if required, and furthermore can effectively block access from the structure side to the glass for cleaning purposes. The simple truss systems can provide significant advantages here.

Sustainability: General parity with other systems.

Structural Performance

Spanning capacity: Space frames and space trusses are multidirectional spanning systems capable of long spans. Spanning capacity can be compromised by plan geometry that effectively limits the spanning action to a single direction. For example, a square grid structural system built to a rectangular plan of 50 ft by 100 ft (15m by 30m), will effectively span only in the 50 ft direction.

Span/Depth (L/d) characteristics: Span to depth ration is high, in the 15 to 20 range, but the minimum depth of a space truss is typically about one half of its largest grid dimension, to provide for connection geometry. Space frames are not necessarily subject to this constraint, but the structures will become less efficient as depth decreases.

Typical deflection criteria: The triangulated space trusses like the octet-truss are particularly stiff, and will exhibit the lowest deflections of all the structure types discussed here. Such stiffness was once regarded as a primary attribute for glazed structures. It has been found however, that there is benefit in structures that are designed to accommodate significant movement. Beyond the accommodation of building movements under normal design loads, highly flexible structures perform better under extreme seismic, blast and impact loading simply because they are designed to accommodate larger movements and these movements allow them to absorb some of the energy in a manner that mitigates damage to the structure (Schoeberg et al. 2005, p.24).

Pretension requirements: None required.

Reaction Loads: Tributary area.

Structural Efficiency (strength to weight): Space trusses achieve their stability through triangulation, and are thus very lightweight, rigid and efficient. Triangulated space structures have been designed as alternates to conventional structures at as little as half the weight of the conventional structure.

Seismic behavior: Space structures are very rigid and resistant to movement. Problems can occur if differential movement between the space structure and the boundary structure exceed design limits.

Behavior under extreme loading conditions: The rigidity of space structures prevents them from flexing under extreme loading and absorbing some of the energy through tolerable deflection. The more flexible systems are advantageous in this regard.

Constructability

Fabrication: As discussed previously, the fabrication of space structure systems is a specialty, and there are relatively few vendors producing such systems. If the façade designer is considering the use of a space structure support system, it is critical that a provider or providers be identified and pre-qualified prior to committing the design.

Installation: Installation of space structures ranges from simple to highly complex. This is the nature of this structural system; it can be used in the design of very simple structures or applied to extremely complex building form. Complex designs typically involve a huge number of part types and logistics of assembly and erection that are beyond the experience and capability of most steel erectors. Material handling can be facilitated in smaller grid systems where strut components are light enough to be handled by a single person.

Economy

Here again, cost mirrors complexity and the cost of space frame structures can vary widely on a unit basis. In a design of low to moderate complexity, a space truss is here assigned a 1.2 multiple with respect to a simple truss system.

6.1.3.4 Simple Truss

Table 6-6 Simple truss attributes.

Simple Truss: Summary of Predominant Attributes
• *Aesthetic varies widely depending on truss and system design* • *Moderate transparency relative to other structure types* • *Great versatility; system variations and hybrids are easily developed* • *Very flexible in accommodating a variety of glazing systems, spans, form and form articulations* • *Best system to accommodate loading of add-on components (integrated sunshades, canopies, entry portals, etc.)* • *Mature technology* • *Span/depth =15* • *No pre-stress loads, tributary loading only* • *Deflections = L/175 typical* • *Reactions relatively low; systems can be hung or base-loaded* • *Relative economy is largely attributed to ease of installation* • *High relative value at a loss of some transparency compared to tension-based systems* • *Lowest relative cost*

Morphology

Figure 6.4 Typical simple truss configuration.

Vertical trusses are aligned to the glazing grid. Trusses are typically custom steel fabrications with an emphasis on craftsmanship and quality finish, incorporating rod or cable internal bracing. Lateral cable bracing systems and intermittent vertical cable trusses can be used to lighten the system. Bolt-up horizontal members can be used between trusses to form a high tolerance exterior grid, to which a variety of relatively low cost glazing systems can be easily integrated. Rectangular tubes used at the outer truss chord and as the horizontal member can provide enhanced economy by integrating the glazing system with the supporting structure. Horizontal truss orientations are also possible.

Design Considerations

Aesthetics: System designs can be very basic or quite refined.

Transparency (and control): Good; the perceived transparency of these systems can be quite high, but cannot match the tension-based systems. Sunlight control on the other hand, is optimum; simple truss systems are the best in accommodating add-on systems such as awnings and louvers that can be integrated into the façade design. This is far more difficult to do with the tension based systems.

Geometric flexibility: Simple truss system geometries are largely unrestricted in terms of surface geometry. They can be sloped, curved, faceted, dished, stepped, all with relative ease.

Design issues: Simple truss systems are very flexible and adaptive to a range of design objectives, interface systems and add-on components. Truss depth will be determined as a function of truss spacing, span, and design loads. The StructureDesigner tool introduced later in this thesis is intended to provide a simplified technique for the façade designer to determine truss depth and typical member size (Chapter 7.6.2.

Form-finding: Not required.

Resources and Technology

Maturity: The most mature of the system types from the standpoint of employed technology.

Materials and Processes: Fabricated steel trusses and truss system components, stainless steel rod or cable bracing elements, and hardware comprise the bulk of these systems. All trusses and hollow section components should be welded closed to prevent internal moisture and rusting. Top quality paint finishes with manufacturers recommended surface preparation should be used on all mild-steel surfaces.

Material suppliers and subcontractors: There is a solid material supply and subcontractor base in place. Steel truss fabricators can generally be found regionally or locally, although quality of workmanship can vary widely.

Glass system interface: Great flexibility in this regard. Any glass system type can be easily accommodated. If a square or rectangular tube is used for the outer chord of the truss and the horizontals, an inexpensive veneer type glazing system can be continuously supported by the steel structure, providing a high level of system integration. Alternately, trusses built up from round tubing can be designed with brackets extending from the outer chord to attach a conventional curtain wall system or point-fixings for a frameless glass system.

Durability and Maintenance: The concern here is for the painted steel finish. If the structure is interior to the façade the system should easily have a ten-year lifespan with minimal maintenance. However, industry warranties for paint finish are typically for only one year. A longer warranty period can be included in the project specifications.

Sustainability: General parity between systems.

Structural Performance

Spanning capacity: Trusses in the 20 to 70 ft. range are very economical. Longer spans are achievable. Truss design may become more complex as a means to reduce the depth of system.

Span/Depth (L/d) characteristics: L/d = 10 to 15.

Typical deflection criteria: L/175.

Pre-tension requirements: Typically not required. Lateral bracing and internal truss bracing may require simple pre-tensioning to a snug-tight condition.

Reaction Loads: Trusses can be hung or base-loaded. Hung trusses can be lighter, but require heavy steel overhead support. Systems are typically base loaded, and not designed to support the roof, meaning the truss-top connection detail must be designed to transfer out-of-plane lateral loads from the facade into the roof structure, but not pick up any vertical dead or live loads from the roof structure. Roof deflections relative to the façade must be carefully analyzed. Reaction loads are in the normal range for any long-spanning closed system as a function of tributary area of the spanning elements.

Structural Efficiency (strength to weight): Trusses are moderately efficient as structural systems.

Seismic behavior: Good, more lateral restraint for glass than with tension-based systems.

Behavior under extreme loading conditions: Not as good as more flexible systems, but less deflection under wind load.

Constructability

Fabrication: In addition to AWS D1.1, the American Welding Society specification for structural welds, exposed steel structures are generally specified to the AESS (Architecturally Exposed Structural Steel) specification as provided by the AISC (American Institute of Steel Construction). This specification helps to define the expected craftsmanship in the work, such as the dressing of welds. Quality paint finish is predominant concern. All materials must be handled, packed and shipped in a manner to preserve the paint finish throughout the fabrication and installation process.

Installation: The assembly and installation is generally very straight forward, and results in enhanced economy for simple truss systems.

Economy

The simple truss systems are generally the most economical of the structural glass façade system types, and are used as the base case for the rough approximation of costs indicated herein.

6.1.3.5 Mast Truss

Table 6-7 Mast truss attributes.

Summary of Predominant Attributes
• *Mast trusses can be quite elegant as exposed structure*
• *Increased transparency over simple truss by lifting glass surface off structure and increasing use of tensile elements in the truss design*
• *Diversity of form is trickier than with simple trusses, but achievable*
• *Considerably less flexible in accommodating interface systems*
• *span/depth = 15*
• *Pre-tension requirements limited to bracing elements*
• *L/175 typical deflection criterion*
• *Reaction loading based on simple tributary area of truss element*
• *Trusses can be delivered to site preassembled*
• *Trusses require care in handling, shipping and installation*
• *Trusses require installation to high tolerance*
• *Cost factor 1.3*

Morphology

Mast trusses generally take the form of guyed struts; a center compression member, usually a round tubular section, is braced on 2, 3 or 4 sides.

Similar to the mast of a sailing yacht, pin-connected bracing struts extend from the center mast to cable or rod bracing stays, and act to stiffen the mast. Short-span systems can use masts braced on 2 opposing sides to form a 2-dimensional truss element (Figure 6.5), which can then be placed at each glazing grid module. Equally simple cable bracing can be used to stiffen the trusses laterally. Long-span systems can use trusses braced on 3 or 4 sides set at some multiple of the glass grid module, with horizontal mast or cable trusses spanning between them to match the glazing grid (note that horizontal cable trusses would require heavy boundary structure to resolve prestress loads). Glazing support is typically provided by one set of the bracing struts extending out to define the glazing plane and provide attachment for the glass system.

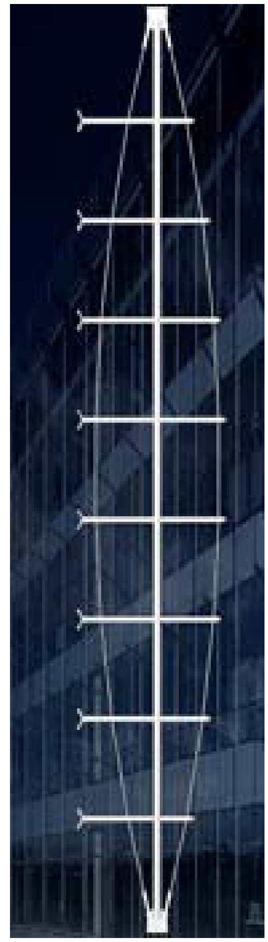

Figure 6.5 Mast truss cable-braced on two sides.

Design Considerations

Aesthetics: System designs can very considerably, but mast trusses typically present a predominant, yet elegant, exposed structure. Some designers prefer a dominant structural presence, to feature the structure rather than minimize it. This system provides an excellent opportunity for this kind of aesthetic treatment.

Transparency (and control): Very good; the transparency of mast truss systems is significantly more than simple truss systems, but still less than the tension-based systems. The enhanced transparency is largely a result of lifting the glazing plane away from the structure. This invariably has the affect of lightening the structural system and increasing the perception of transparency to the envelope. Sunlight control issues start to get more problematic, as the structures are less accommodating to add-on systems such as awnings and louvers.

Geometric flexibility: Form variation is more challenging than with simple trusses, and consequently most applications of this system are relatively simple in overall form, but significant variation is achievable. Truss designs at the interface between geometry changes, as at corners, can become complex.

Design issues: The glass plane is extended out from the truss body and restrained against out-of-plane lateral movement by the truss. The vertical dead load of the glass is typically carried by a suspended dead load cable running immediately behind the glass plane and supporting the ends of the extended bracing struts. Deflection due to the weight of the glazing on the overhead structure should be accounted for in the design and installation of the truss system.

Form-finding: Not required.

Glass system interface: The glass system generally fixes to the extended end of a bracing strut that defines the glazing plane. A spider or clamp can be located here for a frameless system, or the strut ends can support a structural vertical or horizontal mullion.

Resources and Technology

Maturity: Relatively mature system type from the standpoint of employed technology.

Materials and Processes: Fabricated steel mast trusses and bracing, stainless steel rod or cable bracing elements, and hardware comprise the bulk of these systems. All trusses and hollow section components should be welded closed to prevent internal moisture and rusting. Top quality paint finishes with manufacturer’s recommended surface preparation should be used on all mild-steel surfaces.

Material suppliers and subcontractors: Truss fabrication is somewhat more challenging than with simple trusses, and tolerances become more critical, but there is general parity between the simple truss and cable truss in this respect.

Durability and Maintenance: As with the simple truss, the concern is for the painted steel finish. If the structure is interior to the façade the finish should have a 10-year lifespan with minimal maintenance.

Sustainability: General parity between systems.

Structural Performance

Spanning capacity: Mast trusses are flexible in their spanning capacity. Spans in the 20 to 70 ft. range are reasonably economical. Longer span are achievable. Truss design may be complicated by the requirements of accommodating building movement at the interface of façade and supporting structure or other systems (i.e., roof).

Span/Depth (L/d) characteristics: L/d = 8 to10.

Typical deflection criteria: L/175.

Pre-tension requirements: Confined to truss assembly; no prestress loads transferred to boundary structure. Lateral bracing and stay bracing may requires simple pre-tensioning.

Reaction Loads: Trusses can be hung or base-loaded. Hung trusses can be lighter, but require heavy steel overhead support. As with the simple truss, mast truss systems are typically base loaded, and not designed to support the roof, meaning the truss-top connection detail must be designed to transfer lateral loads from the facade into the roof structure, but not pick up any vertical dead or live loads from the roof structure. Roof deflections relative to the façade must be carefully analyzed. Reaction loads are in the normal range for any long-spanning closed system.

Structural Efficiency: Mast trusses exhibit improved efficiency over simple trusses.

Seismic behavior: Good, generally lighter and more flexible than simple trusses, capable of accommodating sizeable movements.

Behavior under extreme loading conditions: Not as good as the cable systems, but better that simple trusses because of increased flexibility.

Constructability

Fabrication: In addition to AWS D1.1, the American Welding Society specification for structural welds, exposed steel structures are generally specified to the AESS (Architecturally Exposed Structural Steel) specification as provided by the AISC (American Institute of Steel Construction). This specification helps to define the expected craftsmanship in the work. Quality paint finish is predominant concern. All materials must be handled, packed and shipped in a manner to preserve the paint finish throughout the fabrication and installation process.

Installation: The assembly and installation is more challenging than with simple trusses. It is critical that the bracing struts supporting the glass plane are located to high tolerances during installation. Cable bracing is often installed in the field to accommodate shipping of the trusses, and the cable tensioning must be done systematically to control truss deformations during assembly. A full section of the structure should be installed and accurately surveyed to determine conformance with specified field tolerances before commencing installation of glazing.

Economy

Mast truss systems present a unique aesthetic and an enhanced transparency over simple truss systems, at a price representing a ballpark premium of 1.3 times the simple truss. Additional cost attributable to typically more elaborate hardware and to added complexity of design, truss fabrication and installation.

6.1.3.6 Cable Truss

Table 6-8 Cable truss attributes.

Cable Truss: Summary of Predominant Attributes
• *Significant dematerialization from mast truss system* • *Increased transparency over mast truss by removal of center mast* • *Spacer struts are sole compression elements* • *Significant diversity of form is difficult to accommodate* • *Interface systems are difficult to accommodate* • *span/depth = 8 to 12* • *Prestress is important as a design and installation issue* • *Deflections = L/175* • *High reactions require heavy boundary steel; prestress forces transferred to anchor structure as high reaction forces* • *Efficiency factor = 0.5* • *Significant installation complexity* • *Cost is increasing as a function of increased complexity; cost factor = 2.0*

Morphology

Cable trusses surpass mast trusses in further dematerialization; cable trusses are quite similar to a mast truss with the mast, the primary compression element and backbone of the truss, removed. Of course, if you remove this component from a mast truss it collapses.

Stability in the cable truss is provided only by pulling it against opposing anchor structures. This boundary structure must be capable of carrying the high reaction loads resulting from the prestress forces required to make the cable trusses work. Lateral in-plane forces are typically handled by a minimal horizontal cable network. It is important to remember the efficiency gained with this system is at the expense of the boundary structure. The impact can thus be mitigated by balancing the cable truss design, truss system design and deflection criteria in a manner to minimize prestress requirements. Horizontal truss orientation is also possible.

Design Considerations

Aesthetics: Cable truss systems are elegant and minimalist expressions of force.

Transparency (and control): System transparency is significantly enhanced over simple or mast truss systems. This is primarily achieved by the elimination of compression members; the only compression members remaining are the spreader struts that put the two tension paths into opposition. The inverted truss design (or fish truss as it is sometimes referred to) most typically used accommodates a shallower truss depth than that required by the mast truss.

Geometric flexibility; Truss geometry is limited. System geometry is also constrained. Complex forms are possible, but result in significant system complexity.

Figure 6.6 Typical cable truss design.

Design issues: A primary design issue is to mitigate the prestress forces required to provide system stability. Deflection criteria can be relaxed if insulated glass is not required. Geometry transitions as with corner trusses, can result in significant complexity; the corner trusses must resolve the in-plane lateral forces coming from each direction (Figure 6.7). As the systems become progressively more minimal, each element becomes increasingly important as an expressive structural element. Truss head and foot details, as well as the spreader/cable connection detail become a prominent concern.

Figure 6.7 A corner truss in a cable truss system.

Form-finding: Actual truss shape will be defined by prestress forces acting on the truss configuration and mechanical properties of the components.

Glass system interface: Interface is provided by spreader struts extending out to define the glass plane, similar to the mast truss systems. Point-fixed glass systems require high tolerance installation; +/- ¼ in typical (6mm) at the interface of glass fixing. A suspended dead load cable tied to the extended spreaders is used just behind the glass plane to support the weight of the glass. A spider fitting can be affixed to the strut end for the attachment of point-fixed glass, as a high transparency option. Alternately, a continuous square or rectangular tube section can be fixed to the strut ends to accommodate the attachment of a veneer system, or virtually any of the glazing system options (see Figure 6.8).

Resources and Technology

Figure 6.8 Horizontal cable truss bracing a rectangular tube.

Maturity: Cable trusses represent newer façade structure technology, especially as a function of design and installation.

Materials and Processes: Materials are minimal. Spreaders can be hollow mild-steel sections of simple and economical construct. However, since they are a predominate element in a minimalist system, they represent an opportunity for expression. Designers frequently elect to develop this component in stainless steel, and even cast stainless that frees the component from the constraints of a uniform section.

Material suppliers and subcontractors

Durability and Maintenance: Advantage should be taken of these minimal material systems by specifying those materials of premium quality. Most cable truss systems utilize stainless rods or cables. Spreaders are stainless steel or mild steel with a premium finish.

Sustainability: General parity with other systems, but advantages are possible with efficient design that minimizes the prestress requirements such that the inherent efficiency of tension-based systems is not compromised by its impact to the anchoring structure.

Structural Performance

Spanning capacity: Complexity increases with span.

Span/Depth (L/d) characteristics: 12 to 15 depending on load combinations, truss and truss system geometry.

Typical deflection criteria: These systems are typically designed to L/175. It is conceivable to lower these criteria if circumstances warrant, but care must be taken to limit deflections to those recommended by the glass supplier if using insulated glass.

Pretension requirements: Cable trusses will require pre-tensioning as a function of prestress forces defined in the design of the system.

Reaction Loads: High reaction loads result from the prestress requirements. It is important to determine a close approximation of these reaction loads early in the design process so the building engineer can account for the impact to the anchoring boundary steel.

Structural Efficiency: Cable trusses are efficient systems and quite light on a span/depth basis, but this efficiency is accomplished at some cost to the boundary steel as discussed above.

Seismic behavior: Systems designed for high flexibility perform well under seismic loading. Cable trusses are very flexible and adaptive to extreme loading. Care must be taken that the glass fixing system can accommodate the movement.

Behavior under extreme loading conditions: Highly flexible systems have been found to benefit from this flexibility when subjected to impact and blast loading (Schoeberg et al. 2005, p.24).

Constructability

Fabrication: No particular fabrication concerns. If spreader struts are developed as cast components, care must be taken to assure the structural and cosmetic properties of the cast component.

Installation: Installation is significantly complicated by the quality materials and finishes of the system components, and the pre-tensioning requirements the installer must accommodate installing the trusses. An appropriate method statement must be provided by the installer or design/build contractor to assure installation of the system in conformance with specifications. This method statement should include appropriate validation of prestress forces in the installed trusses, and provision for accurate survey before and after the installation of the glass.

Economy

Cost increases with complexity and efficiency is not cheap. The cost factor with this system is 1.5.

6.1.3.7 Tensegrity

Table 6-9 Tensegrity attributes.

Tensegrity: Summary of Predominant Attributes
• *A unique structural aesthetic combining tension elements and discontinuous compression elements* • *Relatively high transparency* • *A range of geometric complexity* • *Can be designed as traditional closed systems, or as a hybridized open system* • *Form-finding is required for open system versions* • *Pre-tension is required; most critical with open systems* • *Prestress in open systems will transfer to anchor structure* • *Installation complexity depending upon geometry* • *Varies widely as a function of design, relative cost factor 2.5*

Morphology

There is no body of work to draw on for this evaluation study, because few if any tensegrity structures have been employed in façade applications. Tensegrity structures in the context of the façade structures discussed herein are most closely related to cable trusses and grid shells with cable bracing, in that they combine complementary tension and compression elements in the basic structural form. If cable trusses are developed as 3-dimensional systems with multidirectional spanning behavior, they would qualify as a hybrid tensegrity as categorized in Table 6-2. The original definition of tensegrity derived from the work of Kenneth Snelson included only closed system geometries. Fuller broadened the definition in several respects, and the large stadium tension structures such as the Georgia Dome (see Chapter 2.2.7) are typically referred to as tensegrity structures. Double-layer cable nets are conceivable, with compression struts separating the nets, and could be regarded as hybrid tensegrity structures in this categorization scheme. Tensegrity structures have been built from repeating cellular units, such as the Needle Tower shown in Chapter 2.2.7. It is easy to conceive of geometries such as these being developed into quite interesting façade structures.

Design Considerations

Aesthetics: Tensegrity structures present a compelling aesthetic. Compression elements appear to float in a tensile net.

Transparency: The development of a tensegrity façade design is likely to emphasize the unique structural system more than the pursuit of transparency, although the result will most certainly represent a high-transparency façade.

Geometric flexibility: Many geometric forms have been explored by Snelson and others, and mathematicians have cataloged variations of tensegrity geometries (Connelley & Back 1998) that remain largely unexplored in architectural applications.

Design issues: The determination of an appropriate geometry to meet the various requirements of a façade structure is complex and challenging, and beyond the capability of most façade designers. Designers wishing to explore the potential of this structural form will either have to familiarize themselves with the various geometries or engage the services of a specialist. Detailing will also be challenging, with little precedent. The connection detail between the cable and the strut end will be of particular importance. Robbins (1996) points out from his study of the work of David George Emmerich, that the ratios between strut and cable lengths are important in determining the structures efficiency. Compression elements need to be minimal in length.

Form-finding: Form-finding may be required for the open system tensegrity structures.

Glass system interface: The obvious approach would be to develop a geometry that had a compression element end at the intersections of the glazing grid. This strut could then be treated as with the mast and cable truss structures.

Resources and Technology

Maturity; Tensegrity structures were discovered in the late 1940's and the first architectural applications built in the late 1960's and 1970's, but these have been few. More sculptures have been built than architecture. There are no examples known by the author of tensegrity structures in façade applications.

Materials and Processes: Likely similar to cable truss structures; stainless steel cables and fittings, and some form of fabricated compression element.

Material suppliers and subcontractors: A similar context to cable trusses, with the likelihood that installation will be particularly complex.

Durability and Maintenance: General parity with cable trusses.

Sustainability: Tensegrity structures can be very lightweight and efficient, attributes which are frequently offset by the system complexity.

Structural Performance

Spanning capacity: Tensegrity roof structures have been used to span stadiums. The Georgia Dome spans 766 ft x 610 ft (233.5 m x 186 m). (Castro & Levy 1992)

Span/Depth (L/d) characteristics: Will vary as a function of geometry; approximately 12 to 15.

Typical deflection criteria: L/175. Higher deflection criteria can apply, but care must be taken to assure that the glass system is designed to handle the higher movement. Deflections must be carefully studied. Certain tensegrity geometries have a tendency to twist when they are pushed or pulled. Structure movements need to be studied at the glass interface to understand the potential for bending loads imposed upon the glass.

Prestress requirements; Open systems will require pre-tensioning. Prestress loads will be transferred to the anchor structure. Closed systems will also require pre-tensioning of the cables to avoid excessive deflections, but the prestress forces will remain internal to the system.

Reaction Loads: Reaction loads will be high with the open systems because of the prestress requirements. These reaction loads will impact the anchor structure.

Structural Efficiency: Tensegrity structures in glass façade applications should perform similarly to cable trusses. The will however, likely be of higher density as continuous 3-dimensional systems. They should fall between the mast truss and cable truss systems in efficiency, with an approximate factor of 0.8. As noted in Chapter 2, the Seoul Olympic

Gymnastics Arena fabric clad tensegrity roof weighed in at just 2 psf (9.8 kg/m^2), indicating its remarkable efficiency, but such a structure is inappropriate for a façade application.

Seismic behavior: A continuous 3-dimensional form should perform well under seismic loading, as the multiple load paths provide for an easy redistribution of forces.

Behavior under extreme loading conditions: The factors mentioned above under seismic behavior and the general flexibility of tensegrity structures should provide for damage-mitigating behavior under extreme loads.

Constructability

Fabrication: General parity with cable truss systems (see cable truss in this section). Depending on geometry, machined fittings at strut ends to clamp cables may be more complex.

Installation: General parity with cable truss systems. Depending on geometry, may be more complex.

Economy

General parity with cable truss systems. Depending on geometry, added complexity may drive cost up.

6.1.3.8 Gridshell

Table 6-10 Grid shell attributes.

Grid Shell: Summary of Predominant Attributes
• *A unique form-active thin shell aesthetic*
• *Excellent transparency depending upon geometry and glazing system*
• *An interesting form generator; grid shells can be vaulted or domed, of regular and irregular conical and toroidal sections, or free-form double-curved surfaces*
• *Design of surface geometries can become quite complex*
• *One of the newer façade structure types with largely unexplored design potential*
• *Two types; moment resistant and cable-braced*
• *Multiple spanning paths and shape provide long-spanning capacity and structural efficiency*
• *Local depth of the structural system is significantly reduced from that of truss systems*
• *Glass grid typically follows structure grid*
• *Fabrication and installation can be complex*
• *Costs vary as a function of design complexity; the designs can become quite complex, relative cost factor 2.5*

Morphology

Gridshells are a comprised of a grid of discreet structural members forming squares, triangles or parallelograms that define the shell geometry. Unique shapes can be developed with grid shells that benefit from the combination of shell and arch action (Paoli 2007, p.6). There are two generic structural forms; the closed system type relies on either moment connections or a fully triangulated geometry to achieve stability; the open system employs a quadrilateral grid stabilized by perimeter anchor locations and cable bracing intersecting grid modules. The cable bracing system is pre-tensioned and anchored at the perimeter. A clamping mechanism clamps the cable bracing at the vertices.

Figure 6.9 An overhead curved gridshell structure (Novum Structures 2008).[10]

Design Considerations

Aesthetics: Gridshells invariably provide a unique aesthetic of curving or undulating form. They have been utilized more in overhead structures (see Figure 6.9), but there are interesting possibilities for vertical façade structures as well.

Transparency (and control): The single layer of structure with a minimum depth enhances the transparency of this system type.

Geometric flexibility: There are few limits to the geometric possibilities of this system type. Simple geometric forms are most common, but curved shapes of endless variation are possible.

Design issues: As with any shallow domed structure, global buckling is a concern, and the designer must take care to provide adequate surface curvature and to avoid flat areas unless adequate support is provided.

Form-finding may be required.

Glass system interface: The glass grid typically follows the structure grid, with attachment taking place at the vertices of the structure, or with the glass continuously supported at the surface of the gridshell structural members.

[10] Novum Structures is a specialist provider of structural glass facades and space frames. This skylight application of a gridshell completed by Novum as a design/build project covers the central atrium at the William Wrigley Jr. Global Innovation Center in Chicago. “The skylight contains no pillars or beams for support to maintain optimum transparency. It spans 148 by 137 ft.” (Novum Structures 2008).

Resources and Technology

Maturity: Gridshells emerged as a structural form in the 1970's, but relatively few of the structures have been built.

Materials and Processes: Typical components are welded steel tube struts that bolt together at their ends, or bolt into node components at the grid vertices. All steel components are galvanized and painted. Stainless or galvanized steel cables comprise the cable bracing.

Material suppliers and subcontractors: Steel fabrication is a semi-production item requiring high-tolerances, and is beyond the capability of most steel fabricators. A small number of specialty design/build companies are experienced in providing these services.

Durability and Maintenance: Much depends on the quality of the finish. A high quality galvanized and painted finish should last at least 10-years under normal conditions, although standard system warranties are typically only 1-year. Longer warranties must be specified in contract documents prior to bid.

Sustainability: General parity with other systems, although gridshells can be highly efficient structures.

Structural Performance

Spanning capacity: Spanning depends on curvature; the more shape the higher the spanning capability.

Span/Depth (L/d) characteristics: A curvature ratio of 1 ft (0.3m) of sag over a 10 ft (3m) span is roughly equivalent to an L/d of 10.

Typical deflection criteria: L/175.

Pre-tension requirements: The cable bracing will require pre-tensioning.

Reaction Loads: Prestress forces in the cable bracing will be transferred to anchor structure.

Structural Efficiency: Depending on geometry and construction, gridshells can be the most efficient of structural systems because of the combined affects of shape and multidirectional spanning.

Seismic behavior: Gridshell structures of complex geometry can exhibit unusual behavior under seismic loads, and the seismic behavior of these structures needs to be carefully considered as a function of shape.

Behavior under extreme loading conditions: Gridshell flexibility depends upon geometry and system design. Some systems will be more flexible than others, and will potentially perform better under extreme loading conditions.

Constructability

Fabrication: As discussed above, gridshells are typically built up from the assembly of relatively small components. The tolerance of these components becomes of critical importance. Few fabricators are qualified for this kind of precision production work, but they do exist. Also, there are a few specialty design/build contractors with experience in the fabrication and erection of gridshell structures.

Installation: The same applies to installation as with fabrication. Few erectors have experience with the assembly and installation of gridshell structures, which do involve special consideration. As with any of the systems requiring pre-tensioning and complex assembly methods, the erector should be required to submit a detailed method statement outlining the assembly and erection procedures.

Economy

As gridshell complexity can vary enormously, so can cost. While the structures can be very efficient on a strength-to-weight basis, the complexities of design, fabrication and erection combine to more than offset any material efficiency.

6.1.3.9 Cable-Supported

Cable-hung, flat cable net and double-curved cable net structures share many of the same properties, so have been combined here.

Table 6-11 Cable-supported structure attributes.

Cable-Supported: Summary of Predominant Attributes
• *Elegant, minimalist aesthetic* • *Highest transparency* • *Flat, curved (a plan radius), and double-curved system geometries possible* • *Flat nets are geometrically simple, double-curved complex* • *Cable nets can be pulled into double-curvature membranes providing a more stable structure with considerably less deflection than flat cable nets* • *Double-curved nets require form-finding to determine shape* • *Newest of the façade structure types* • *Flat nets are shallowest of all systems* • *Flat nets are the most flexible of all structure types; largest deflections* • *Typical deflection criterion L/45 to L/50.* • *Critical Pre-tension requirements for design and installation to control deflections* • *Pre-tension loads generate high boundary reactions* • *Critical pre-tensioning can require sophisticated jacking systems and complex installation technique* • *Highest deflections (L/40 to L/50 typical); most flexible, most movement* • *Highest relative cost*

Morphology

Cable-hung structures have cables tensioned along a grid in the vertical direction only. They are similar to cable nets without the bidirectional cable runs. They are also somewhat similar to the suspended glass fin-supported facades without the lateral support provided by the glass fins. Glass-fixing components clamp to the cables along the glass grid. Flat membranes require high prestress cable forces to control deflections. Developing a cable net with the addition of a horizontal cable will be helpful if the horizontal span is not too great. Curvature of the membrane in plan will also act to stiffen the structure.

Flat cable nets are constructed of cables tensioned vertically and horizontally to form a grid. Vertex components clamp the cables at their vertices. The vertex components can also be designed to clamp the glass to the net, or accommodate the attachment of another component to fix the glass to the net.

Boundary geometry can be defined of opposing curvatures, such that the cables in one direction pull against the cables in the opposing direction, thus yielding a double-curved (anticlastic) form. The opposing forces add stability to the net, reducing deflections. Design, fabrication and installation however, are all affected by the added complexity.

Design Considerations

Aesthetics: Extreme dematerialization of structure, the cable net facades provide the closest thing to a soap-bubble like membrane. Stainless steel cables and cast stainless cable clamps provide a minimalist, refined appearance. Low-iron glass and anti-reflective coatings can be employed to maximum advantage with these systems to enhance qualities of transparency. The anticlastic forms provide a striking and unique form to the façade membrane.

Transparency (and control): Highest inherent transparency. Daylight control is problematic; interface systems such as louvers and awnings are difficult to support from the net. Daylight control may be limited to the glass or such passive design features as overhangs.

Geometric flexibility: Geometry considerations are relatively constrained. Flat nets are geometrically simple, anticlastic nets quite complex. Geometry of anticlastic nets must be carefully considered in terms of modularity and symmetry or little repetition in glass sizes can result, increasing complexity. Also, certain geometric configurations can result in warping forces imposed on glass cladding.

Design issues: Generally problematic in accommodating attachment and loading of add-on components (integrated sunshades, canopies, louvers, pv systems). Entryways are typically constructed as portal frames structurally isolated from the net. Cable-supported facades, especially double-curved nets, involve considerable complexity in both the design and build efforts; for these reasons, it is beneficial to involve both design and construction expertise as early in the design process as possible.

Form-finding: Again, the flat nets are simple, the anticlastic nets complex. The actual form of an anticlastic surface is a function of cable properties, boundary stiffness and cable prestress; form finding analysis is required to determine the shape (see form-finding discussion in 6.1.2.3).

Figure 6.10 Cable clamp for cable-hung system; exploded view.

Glass system interface: The interface between structure and glass system occurs at the face of the vertex clamp. Framed-panel and point-fixed systems can be supported. Vertex cable clamps can be designed to clamp glass at corners. Alternately, spider fittings can be attached to the vertex clamps to support drilled glass. As mentioned elsewhere, where system transparency is the overriding design objective, combining a cable net with low-iron monolithic glass coated with an anti-reflective coating will provide the optimum. However, cable nets can be designed to support any glass or glass system type.

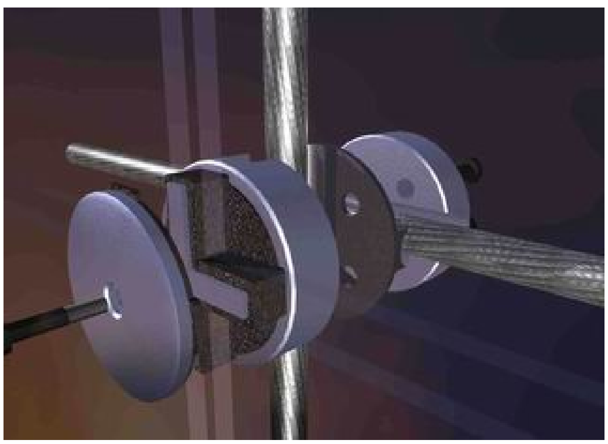

Figure 6.11 Cable clamp for flat cable net.

Resources and Technology

Maturity: Cable nets are the newest of the façade structure types. Their application has been relatively limited to date, but the trend is increasing use. They have been used successfully in a number of high-profile projects, and the building community seems to be gradually accepting this technology as viable in broader applications.

Materials and processes: Cable net facades are constructed of remarkable few materials beyond the glass; cables, end fittings, cable clamps and anchor assemblies; no compression members. Cables and cast clamps are most often stainless steel, but galvanized cables or clamps can be used.

Material suppliers and subcontractors: The marketplace will readily supply all materials; cable systems and cable clamps are available from multiple suppliers. The only concern here is with installation (see below).

Durability and Maintenance

Proper system design and installation will assure a long-lived structure with the minimum of maintenance beyond cleaning the glass. The cable net should be kept to the inside of the glass membrane. The materials are minimal to begin with, and most often made of corrosion resistant stainless steel. Stainless steel strand and wire rope are durable, high performance materials.

Sustainability: The materials are minimal and durable. The minimalism is achieved at a cost to the supporting boundary steel, which must be sized to withstand the relatively large prestress requirements of cable net structures.

Structural Performance

Figure 6.12 New Beijing Poly Plaza; SOM architect (Gritth 2007a).

Spanning capacity: High (with correspondingly high deflections). Designs spanning up to 300 ft. (90m) have been constructed.[11] Spanning range is a function of cable size, grid geometry, design loads, and the accommodation of pre-tension forces to control deflections of the net under live loads. Long spans will generate high pre-tension loads, requiring heavy boundary structure.

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[11] Figure 6.12 and Figure 6.13 show the largest cable net completed to date, and a highly complex structure; "the New Beijing Poly Plaza project includes a 21-story atrium enclosed by a cable net glass wall that is 90 m high and 60 m wide (Sarkisian et. al. 2007).

Figure 6.13 Rocker arm detail on New Beijing Poly Plaza cable net; SOM architect, (Gritth 2007b).

Span/Depth (L/d) characteristics: The depth of the flat nets is minimal; a flat net spanning 100 ft. (30m) can easily have a depth under 1 ft. (300mm), or roughly a span to depth ration of 100. Double-curved nets are locally shallow, but have an overall depth comprised of the maximum displacement between the opposing curvatures, called the sag.

Typical deflection criteria: Cable nets have the highest relative deflections; deflection criteria is typically in the range of L/45 to L/5O. The necessary control of deflections results in design complexity to minimize prestress loads. Flat nets are geometrically simple but deflections are high. The added stability provided by the double-curved nets significantly reduces the prestress requirements necessary to limit deflections, reducing the demands on the boundary steel, but at considerably added complexity to the cable net.

Pre-tension requirements: This consideration renders design efforts to minimize prestress forces of paramount importance. High prestress loads impact boundary structure. Cable nets may be impractical for renovation projects unless boundary support requirements can be efficiently met.

Reaction Loads: As discussed here, high prestress requirements result in high reaction loading which must be accommodated by the boundary structure.

Structural Efficiency (strength to weight): High structural efficiency of the cable net is offset by the requirements for boundary supporting structure. The shape of the anticlastic nets adds significantly to the structural efficiency.

Seismic behavior: With deflection criteria in the L/50 range, these structures are designed to move. Lateral loading capacity is high so as to accommodated wind loads. In plane movement is taken up in the large silicone butt-joints.

Behavior under extreme loading conditions: This class of structures benefits from its high flexibility under impact and blast loading.

Constructability

Fabrication: Fabrication requirements are minimal and easily accommodated. Care must be taken in the specification of cast components to assure quality. Stainless steel material specifications must be carefully selected; similarly with coatings if steel products are used.

Installation: The definition of an installation method statement is important. It should address both net assembly and installation. The nets must be installed to a high tolerance to assure glass fit-up. Accurate survey information is critical. The nets can be assembled in place or remotely, transported to the site, and installed as an assembly. If the latter strategy is used, great care must be taken in handling and transporting the net so as not to damage the cables or clamps. Both flat and anticlastic cable nets will require pre-tensioning during installation, a critical function that requires proper technique, and often involves the use of hydraulic jacking systems to perform the pre-tensioning, and the use of tension measuring devices to assure that the specified prestress values are met.

Economy

Highest relative cost. System costs range widely depending upon system complexity, net geometry, span, deflection criteria, prestress requirements and impact on boundary structure. While it may be the most materially minimal system, this comes with an increase in complexity that generally more than offsets any material savings. It is very important to assess reaction loads early in the design process so that the building engineer can be involved in developing this aspect of the cost. As the newest of the facade structure types, costs are dropping as the technology matures.

6.2 Glass Types: Categorization Scheme and Comparative Analysis

The material considerations for steel are relatively simple compared to glass, an exciting material that has been the focus of considerable development efforts over a long period of time. There are many variables involved in the specification of glass when all of the color options and performance coatings are considered. These considerations are in general parity with any application of architectural glass however, and while very relevant to structural glass facades, there is no intrinsic relationship.

The two considerations that are intrinsic to these facades are the heat-treatment of the glass, which determines the strength of a single pane of glass, and the makeup of the fabricated glass panel. There are different properties and applications for each class and each type within a class. The various heat-treatment and glass panel fabrication options are discussed in Chapter 2. Here, the intent is to categorize the relevant options and criteria to facilitate appropriate glass type selection.

6.2.1 Categorization Scheme

Table 6-12 Glass panel types for structural glass facades.

#	Glass Panel Type	ply 1	ply 2	ply 3	Framed	Frameless
1	monolithic	annealed			yes	no
2		tempered			yes	yes
3	laminated	annealed	annealed		yes	no
4		annealed	heat-treated		yes	no
5		heat-treated	heat-treated		yes*	yes
6	insulated	annealed	annealed		yes	no
7		annealed	heat-treated		yes	no
8		heat-treated	heat-treated		yes*	yes
9	laminated-insulated	annealed	annealed	annealed	yes	no
10		annealed	annealed	tempered	yes	no
11		annealed	heat-treated	annealed	yes	no
12		heat-treated	heat-treated	heat-treated	yes*	yes
	Safety Glass					
	Sloped / Overhead Glass (greater than 15% slope from vertical)					

Notes:

- ** These configurations in a framed application may represent an over-design, unless some unusual loading conditions exist.*
- *"Heat-treated" means either fully tempered or heat-strengthened.*
- *Ply-1 is to the inside.*
- *Panel #8 qualifies as safety glass if both panes are tempered.*
- *Panel #10 qualifies as safety glass in the vertical orientation.*
- *Panel #12 qualifies as safety glass in the vertical orientation if ply-3 is tempered.*

6.2.2 Definition of Evaluation Criteria; Glass Type (Heat-treatment) and Panel Type (Fabricated Panel Makeup)

A virtually identical set of criteria is relevant to both glass pane and fabricated panel. These criteria follow.

- **Description**: A brief description of the glass pane or panel type is provided here. See Chapter 2 for additional discussion.

- **Fabrication**: Describes any fabrication issues with respect to the pane or panel.

- **Strength**: Relative strength attributes of the pane or panel.

- **Break Pattern**: The characteristic pattern of the glass when broken, or behavior of the fabricated glass panel when broken.

- **Spontaneous Breakage**: Whether or not spontaneous breaking of glass due to a nickel-sulfide inclusion is a concern.

- **Safety Glass**: Does the pane or panel qualify as safety glass.

- **Optical Distortion**: Problems of optical distortion are discussed. These can be an issue when the primary attributes of glass, transparency and/or reflection, are primary aesthetic drivers in a project.

- **Size Limitation**: Identifies relevant size limitation factors for pane or panel. Size is limited initially by the width of the float glass production line. Most float glass lines limit width to 130 in (3,302mm). Larger sizes are available from a few glass producers, but may be expensive, unavailable or impractical in many applications. Heat-treated glass is limited by the properties of the manufacturer’s tempering oven. In determining the glazing grid, a source of glass supply for the assumed size must be confirmed, ideally from a provider in relative proximity to the building site.

- **Application**: Primary application(s) of the pane or panel.

6.2.3 Class Comparisons: Application of Evaluation Criteria to Glass and Glass Panel Types

6.2.3.1 Heat-Treatment

Annealed Glass

- **Description**: Glass straight from the float process is in the annealed condition. From the molten state, the glass sheet is slowly cooled in a manner to prevent any residual stresses resulting from the process.

- **Fabrication**: The lack of residual stresses in annealed glass allows the material to be easily cut and machined.

- **Strength**: The modulus of rupture (flexure) based on a 60 second load: 6,000 psi (43N/mm^2). (Loughran 2003, p.110)

- **Break Pattern**: Annealed glass breaks in large sharp shards, and consequently most building codes restrict its use in public areas; near doorways and walkways.

- **Spontaneous Breakage**: Nickel-sulfide causes no problem in annealed glass, even if the contaminant is present.

- **Safety**: Annealed glass does not qualify as safety glass.

- **Optical Distortion**: Good quality annealed glass is remarkably free of optical distortion.

- **Size Limitation**: Up to 130 in width (3,302mm), with larger widths available from a limited number of manufacturers (Loughran 2003, p. 113).

- **Application**: Annealed glass is basic window glass. It is used in any application providing full perimeter support to the glass where safety glass is not a code requirement, and where added strength is not needed to resist localized stresses such as thermal or point-loading.

Heat-strengthened Glass

- **Description**: Glass is strengthened in a heat and quench process referred to as tempering or toughening. Heat-strengthening is a partial tempering as opposed to full tempering, and produces a glass with intermediate strength that is more resistant to thermal stresses than annealed glass.

- **Fabrication**: All fabrication; cutting, holes, counter-sinking, edging, and sandblasting, must be completed before heat-treating.

- **Strength**: The modulus of rupture based on a 60 second load on weathered glass: 12,000 psi (82.7N/mm^2). (Pilkington 2008, p.1) Heat-strengthened glass is approximately twice as strong as annealed glass.

- **Break Pattern**: Heat-strengthened glass still breaks in large sharp shards, similar to annealed glass but with somewhat smaller shards typically, and as with annealed glass, most building codes restrict its use in public areas; near doorways and walkways.

- **Spontaneous Breakage**: Nickel-sulfide is generally regarded as not being a problem with heat-strengthened glass, even if the contaminant is present, because of the low surface and core stresses resulting from the heat-strengthening process.

- **Safety**: Heat-strengthened glass does not qualify as safety glass.

- **Optical Distortion**: The heat-treating process can result in certain distortions to the glass, such as roller-wave (see Chapter 2).

- **Size Limitation**: Viracon, the largest US glass fabricator, limits tempered glass sizes to 84" x 165" or 96" x 144" (2134 x 4191 or 2438 x 3658mm); see Table 2-9.

- **Application**: Heat-strengthened glass is used where higher strength is needed to handle thermal stresses or concentrated loads. It is twice as strong as annealed glass, and can be used in point-fixed glass applications. It is however, only half as strong as fully tempered glass, and a thicker glass may be required for a given application. Heat-strengthened glass has the benefit of being free from the concern of spontaneous breakage. It is sometimes used in point-fixed systems in combination with a tempered ply in a laminated panel in overhead or sloped glazing applications. The heat-strengthened pane is used as the outer ply. In the unlikely circumstance that both panes break, the theory is that the larger shards of the heat-strengthened ply will go into compression as the panel sags, and thus help prevent drop out of the panel.

Tempered Glass

- **Description**: Glass is strengthened in a heat and quench process referred to as tempering or toughening. Tempered, or fully-tempered glass is subject to the same process as heat-strengthened glass, except that it is heated to a higher temperature. Tempering produces a glass with maximum strength properties and a unique break pattern.

- **Fabrication**: All fabrication; cutting, holes, counter-sinking, sandblasting, must be completed before heat-treating.

- **Strength**: The modulus of rupture (flexure) based on a 60 second load: 24,000 psi (165N/mm²). (Pilkington 2008, p.1) Tempered glass is approximately four times as strong as annealed glass and twice as strong as heat-strengthened glass.

- **Break Pattern**: Tempered glass breaks into pebble-sized pieces. This effectively prevents the occurrence of large airborne shards resulting from impact to the glass. For this reason, tempered glass is qualified as safety glass and intended for use in areas of public safety as defined by various building codes.

- **Spontaneous Breakage**: Tempered glass is subject to spontaneous breakage as a result of the contaminant nickel-sulfide (see Chapter 2). Nickel-sulfide is a small stone embedded in a glass pane. The theory is that when subject to heat, the stone can expand faster than the surrounding glass, causing high localized stresses that can break the surface compression of the glass pane leading to spontaneous shattering. (The theory does not explain why this phenomenon appears to happen unpredictably, and not in immediate response to a specific temperature change.) The use of tempered glass in structural glass facades is usually specified to be heat-soaked, a process that cyclically heats and cools the glass to a prescribed temperature, under the theory that if nickel-sulfide is present, the glass will break during the process.

- **Safety**: Tempered glass qualifies as safety glass.

- **Optical Distortion**: The heat-treating process can result in certain distortions to the glass, such as roller-wave (see Chapter 2). As the temperatures used in full tempering are higher, the distortions can be more exaggerated than in heat-strengthening.

- **Size Limitation**: Viracon, the largest US glass fabricator, limits tempered glass sizes to 84" x 165" or 96" x 144" (2134 x 4191 or 2438 x 3658mm); see Table 2-9. Sizes will vary between fabricators.

- **Application**: Tempered glass is used where maximum strength is needed to handle global and local loads. It is generally the material of choice in point-fixed glass applications.

6.2.3.2 Panel Type

Only the basic variations are included here. Laminated, insulated, and laminated-insulated panels can come in multiple-ply configurations in response to various performance criteria. Triple-insulated glazing is increasing in use for reasons of thermal performance. Laminated glass in multiple-ply with varied ply thickness has demonstrated improved acoustic properties, as has laminated-insulated panels in varied ply thickness. The use of glass as a structural material, as in application as stair treads and landings, calls for multiple-ply laminates of at least 3-ply and often 5-ply.

Monolithic

- **Description**: Generally in the industry the term monolithic refers to single glazing; a single pane of glass in application. Building codes however, sometimes also refer to laminated glass panels as monolithic. The highest transparency with respect to a frameless glass system on any façade structure type is provided by monolithic glazing. The smallest butt-glazed silicone joint can be used with monolithic glass. Unfortunately, single-glazing also provides the worst thermal performance.

- **Fabrication**: Annealed monolithic panes are the most flexible in terms of machining. In fact, all machining operations must be completed on annealed glass before any heat-treatment. The universe of glass coatings, discussed in a limited manner in Chapter 2, presents a different challenge; many coatings are fragile and must be protected from exposure, and thus cannot be used on monolithic glass. Coatings such as the low-E coatings discussed in Chapter 2 must be applied to the inner face (the number 2 or 3 face) of a laminated or insulated panel. Such coatings are referred to as "soft" coatings. There are however, "hard" coatings available. These are called pyrolytic coatings, and are applied by the float glass producers as an on-line process such that the coating is fused into the glass surface. The coated surface is used as the number 2 (inside) surface. Different manufacturers offer different products of varying performance.

- **Strength**: Strength is purely a function of the glass material as defined above.

- **Break Pattern**: The break patters is purely a function of the glass material as defined above.

- **Spontaneous Breakage**: As above in the heat-treatment section, spontaneous breakage is only an issue in tempered glass, so a tempered monolithic panel would be subject to this consideration, and should be heat-soaked (see Chapter 2) if used in a frameless glass system.

- **Safety**: Tempered monolithic glass qualifies as safety glass.

- **Optical Distortion**: Optical distortion is a function of heat-treatment, so this potential exists in heat-strengthened and tempered monolithic panels.

- **Size Limitation**: Size is a function of heat-treatment as indicated in the previous section.

- **Application**: Monolithic glass or single-glazing is used where thermal and security considerations are not issues, and where economy is. Monolithic glass is used in structural glass facades where the pursuit of maximum transparency is the overriding objective; monolithic panels of low-iron glass with an anti-reflective coating use in a frameless glass system and provided with a wet-glazed silicone seal, provide the very maximum in transparency. Even though tempered monolithic qualifies as safety glass, it will still fall from the glass support with the potential of damaging property and injuring people. Laminated glass is a superior product in most applications because if is less likely to drop from the support. Laminated glass has other significant benefits over monolithic glass.

Laminated

- **Description**: Laminated glass refers to the fabrication practice of bonding two or more sheets of glass through the use of an interlayer material, typically polyvinyl butyral or PVB. The PVB is a sheet material that is sandwiched between the leaves or plies of glass, and in the presence of pressure and heat provides a continuous bond between the glass plies.

- **Fabrication**: Laminated annealed glass can be easily fabricated. Large sheets of laminated annealed are produced by some fabricators and supplied to small glaziers having no laminating capability, but can cut and machine the panels the same as they would a monolithic piece of glass. However, laminated panels that include heat-treated plies must have all machining work completed prior to laminating. One of the challenges with laminated glass in point-fixed applications requiring drilled tempered glass is assuring that the holes in the two plies of tempered glass remain aligned during the bonding process.

- **Strength**: The combined glass thickness of a laminated panel is generally less strong than a piece of monolithic glass of the same thickness.

"Laminated glass is 50% to 100% as strong (depending on aspect ratio and framing details) as monolithic glass of the same overall thickness and size when subjected to short duration loads at room temperatures" (Pilkington 2005, p.3).

Loughran (2003, p.113) discusses the problem of interlayer creep under long duration loading and in the presence of excessive heat.

- **Break Pattern**: The break pattern is purely a function of the glass material as defined above.

- **Spontaneous Breakage**: An advantage of laminated glass is that even when a single ply breaks the other ply will hold the panel together and keep the broken glass from falling. It is extremely unlikely that both pieces of tempered glass in a laminated unit would break at the same time, so this strategy effectively addresses the concern of spontaneous breakage.

- **Safety**: Most codes recognize a laminated glass panel of any glass type; annealed, heat-strengthened or tempered, or any combination thereof, as safety glass.

- **Optical Distortion**: Two pieces of heat-treated glass laminated into a single unit, each possessing some level of optical distortion because of the heat-treating process, can potentially exhibit the additive affects caused by the combined distortion. However, if laminated panels of annealed glass can be used in lieu of heat-treated glass, sharp, undistorted reflections can be a desirable result. An outer pane of annealed glass laminated to a heat-treated inner pane can provide superior optical properties when the reflective surface is viewed outside.

- **Size Limitation**: The maximum widths of laminate glass can be limited by the width of available interlayer material or the width capacity of the fabricators laminating equipment. Depending upon these variables, laminated glass is generally available in widths up to 100 in (254cm).

- **Application**: Laminated glass is a very versatile product. The safety attribute has been discussed. It is also used in security and extreme loading applications. Bullet-proof glass is a laminated composite of glass and polycarbonate. Laminated glass is the primary strategy in meeting code requirements for impact-resistance in hurricane areas. Low-E and other coatings can be protected when applied to the number 2 or 3 surfaces of a laminated unit, and do not interfere with the bond integrity. DuPont (1995) is a leading manufacturer of interlayer materials for laminating glass. Table 6-13 is derived from information on their website. DuPont Laminated Glass Solutions

Table 6-13 Applications for laminated glass.

Special Applications for Laminated Glass	
Safety	*the panel is held together if one ply breaks; reduces potential for drop-out*
Security	*bulletproof, blast-resistant products available*
Sound Reduction	*interlayer materials with sound reduction properties improve acoustic performance*
Solar Energy Control	*coatings are protected by being encapsulated on the number 2 or 3 surfaces*
UV Control	*interlayer material screens out damaging UV rays*
Extreme Loading	*extra strong interlayers resist impact loads*
Aesthetics	*decorative interlayer materials in colors and patterns*

Laminated glass can also be used as one panel in an insulated glass unit to combine the advantageous of laminated glass with the superior thermal performance of insulated glass panels.

- **Cost**: Cost of laminated glass is a multiple of the glass type used.

Insulated

- **Description**: Insulated glass units (IGU's) are constructed of two or more panes of glass sealed to a spacer inserted between each piece, in a manner to provide a hermetically sealed cavity between the two adjacent panes of glass. The airspace provides significant improvements in thermal performance. Gases such as argon or krypton can be used to fill the airspace and further improve thermal performance. Low-E coatings can be applied to the number 2 or 3 glass surfaces and thus be protected from outside exposure. IGU's can incorporate any of the glass material types. IGU's in frameless glass system applications typically use tempered glass for all panes making up the unit.

- **Fabrication**: All fabrication on the glass panes to comprise an IGU must be completed before assembly of the IGU panel. Fabrication of the IGU is typically an automated process whereby the glass panes are cleaned and dried, an aluminum spacer is inserted between the glass panes completely around the perimeter, and a double seal is applied to hermetically seal the cavity between the glass panes. If the IGU is for application in a point-fixed drilled application, spacers must be positioned and sealed around each hols in the glass panel to preserve the hermetic seal of the cavity.

- **Strength**: The strength of an IGU with two panes of identical thickness will be nearly twice that of a single piece of glass of the same thickness (Pilkington 2005, p.3).

  There is a particular structural issue and an important consideration with respect to insulated glass related to the important seal between the glass panes and the internal spacer. Deflections of the insulated panel result in shear stresses to the seal. If the bond is compromised, the hermetic seal of the cavity is lost resulting in a failure of the IGU. For this reason, many fabricators put deflection limits on the use of their products; if deflections exceed this requirement they will not honor the product warranty. The most common deflection criterion is L/175. Deflections in frameless glass systems using large glass panel sizes can easily exceed this criterion, owning to the absence of full perimeter support to the panel. For this reason, most of the glass used in point-fixed applications has been imported from Europe and the United Kingdom, where fabricators are willing to provide a high-quality product with a 10-year or better warranty with a deflection criterion in the L/90 to L/100 range. Viracon only recently modified their deflection criterion for IGU's to L/140.

- **Break Pattern**: The break pattern is a function of the glass material that make up the panes of the IGU as defined above under heat-treating.

- **Spontaneous Breakage**: Spontaneous breakage is only an issue in tempered glass, so an IGU comprised of one or more pieces of tempered glass would be subject to this consideration, and should be heat-soaked (see Chapter 2) if used in a frameless glass system.

- **Safety**: IGU's with all glass panes tempered qualify as safety glass.

- **Optical Distortion**: Optical distortion is a function of heat-treatment, so this potential exists if heat-strengthened and/or tempered panes are used in the IGU. In addition, differential pressure between the outside air and the cavity internal to the IGU can result in inward or outward bowing to the glass which can be quite visible in the reflections on the glass surface.

- **Size Limitation**: Size is a function of the insulating assembly equipment of the glass fabricator. Some fabricators have the capability to manufacture very large IGU's. If only annealed glass is used in the IGU makeup, the size is not restricted by any heat-treating or laminating limitations.

- **Application**: Insulated glass is used to enhance thermal performance of the transparent envelope. It is thus often combined with other techniques for reduce heat transfer by radiation, conduction, or convection, such as tinted glass, metallic and low-E coatings. The use of triple-glazed IGU's, or IGU's incorporating three panes of glass with two corresponding cavities is increasing. IGU's are easily used in point-fixed clamped glass systems. Their use in point-fixed drilled systems requires special seals in the cavity around the holes to preserve the hermetic seal. Both applications require the use of heat-treated glass, usually tempered.

Laminated-insulated

- **Description**: laminated-insulated glass panels combine the benefits of laminated and insulated glass. In its most basic form, a laminated glass panel is substituted for one of the panes in an IGU.

- **Fabrication**: Laminated-insulated panels involve the fabrication processes of both laminated and insulated glass. Laminating becomes a preparatory step however, and does not produce the final product. IGU's can be built from multiple laminated panels.

- **Strength**: The separate panes of a laminated-insulated unit do not work together structurally, so the strength of the panel is the strength of the individual pieces.

- **Break Pattern**: The break patters is a function of the glass material that make up the panes of the IGU as defined above under heat-treating.

- **Spontaneous Breakage**: Spontaneous breakage is only an issue in tempered glass, so an IGU comprised of one or more pieces of tempered glass would be subject to this consideration, and should be heat-soaked (see Chapter 2) if used in a frameless glass system. The concern is lessened if the tempered pane is only used in the laminated panel.

- **Safety**: Laminated-insulated units with all unlaminated panes in tempered glass would qualify as safety glass under most building codes.

- **Optical Distortion**: Optical distortion in laminated-insulated units is a function of the properties of the other material types. Note that as additional materials are layered into a glazing assembly, the chances for optical distortion increase. Distorted reflections may be mitigated if the outermost glass pane can be annealed.

- **Size Limitation**: Size in a laminated-insulated unit will be further limited over an IGU by any size restrictions issuing from the laminating process.

- **Application**: Again, the laminate-insulated panel effectively combines the significant advantages of laminated and insulated glass. The product is expensive however, and the primary application is in sloped or overhead applications as required by building code. Any glass sloped more than 15% off vertical must use laminated glass. If thermal properties are also important, then laminated insulated glass is the solution. In such an application the laminated panel would be on the inside of the installed unit, so that if the single outer pane were to fail it would be prevented from falling into the interior space below.

6.3 Glass System Types: Categorization Scheme and Comparative Analysis

6.3.1 Categorization Scheme

Table 6-14 Categorization of glass system types.

Glass System Types	
• *Framed Systems*	• *Frameless Systems*
• *stick* • *unitized* • *veneer* • *panel*	• *point-fixed drilled* • *point-fixed clamped*

6.3.2 Definition of Evaluation Criteria: Glass System Type

Following is the format and the criteria by which the various glass systems will be evaluated.

6.3.2.1 Summary of Predominant Attributes

A brief bullet-point summary of the primary attributes identified and discussed in greater detail following.

6.3.2.2 Morphology

Each system will be briefly described correlating general function and form. (A more generalized description of the systems can be found in Chapter 2.)

6.3.2.3 Design Considerations

- Aesthetics

Here the aesthetic attributes that characterize the systems are identified.

- Transparency

Relative transparency of the glass system types.

- Geometric flexibility

This consideration involves the relative ability of the various structure types to accommodate curves, folds, and other surface geometry.

- Design issues

This criterion identifies design considerations particular to each of the various systems.

6.3.2.4 Resources and Technology

- Materials and Processes

For this criterion, a brief description of the most common materials and processes used, and the identification of any relevant issues with respect to them, will be provided.

- Material Suppliers and Subcontractors

A challenge in delivering innovative building design and technology can be finding qualified suppliers and subcontractors to facilitate the construction phase of the project.

- Glass System Interface

The requirements for the glass system will be identified here.

- Durability and Maintenance

Lifecycle and lifecycle maintenance considerations will be identified and discussed here.

6.3.2.5 Structural Performance

- Spanning capacity

The spanning capacity of the glass system will be identified here.

- Typical deflection criteria

Deflection criteria vary among the systems; rules of thumb will be provided.

- Accommodation of movement

As the structures move under design loads the glass system must accommodate this movement. The mechanism for this will be discussed briefly for each system.

6.3.2.6 Constructability

- Fabrication

Fabrication issues vary between the systems and relevant considerations will be discussed for each.

- Installation

Installation issues vary between the systems and relevant considerations will be discussed for each.

6.3.2.7 Economy

General guidelines are intended only to provide a feel for the relative cost between the systems.

What follows is a consideration of each system type identified above with respect to the criteria just presented.

6.3.3 Class Comparisons: Application of Evaluation Criteria to Glass System Types

It would make no sense to use a curtain wall system on a structural glass façade. Such an approach ignores all opportunity for the integration of structure and glass system that is so prominent in structural glass facades. It is informative nonetheless, to have them included in this analysis, and two of the systems here derive from curtain wall technology. The stick and the unitized systems are categorized here as framed system types. While frameless glass systems are virtually synonymous with structural glass facades, there are a number of examples that do not use point-fixed glass systems. These have been categorized here as framed panel glass systems. Further analysis may reveal opportunity for a more refined categorization of these systems.

As a matter of convenience and consistency, the systems are presented similarly to the structure types, with the increasing attribute of transparency. The exception is the point-fixed systems; the point-fixed drilled is arguably a more transparent system. It is presented first, as the clamped version is a derivation best understood in comparison to the drilled system.

6.3.3.1 Stick System

Table 6-15 Stick system attributes.

Stick System: Summary of Predominant Attributes
• *The oldest curtain wall technology* • *Vertical extrusions span between floor plates* • *Shifts much of the work to the building site* • *Quality control more difficult on site* • *Appropriate for geographic regions with cheap site labor*

Morphology

Vertical mullions of aluminum extrusions designed to span between floor plates are installed first, followed by horizontal mullions to complete the framing grid. Glass, metal panels, or stone are then installed as infill. Panel materials are usually mechanically captured. Dry gaskets typically provide the weather seal, but systems are sometimes wet glazed.

Design Considerations

Aesthetics: Conventional curtain wall appearance with strong framing grid.

Transparency: As the mullion is a structural member, they are relatively wide and deep, compromising the perception of transparency from this system type. These systems are not designed nor used for the attribute of transparency. Unitized systems described following generally have wider mullions, so a stick system actually has the potential for higher transparency than a unitized system.

Geometric flexibility: Changes in the glazing plane typically require custom extrusions, which increase fabrication and erection complexity.

Design issues: These systems must be carefully designed to accommodate building movements, and to provide pressure equalization to the system to prevent water and air infiltration.

Glass System Interface: The glass is continuously supported on the frame.

Glass Type: There are no limitations to the glass type used except those imposed by code requirements.

Resources and Technology

Materials and Processes: Extrusions are ordered pre-finished. There is general parity between framed systems with respect to glass and panel materials.

Material Suppliers and Subcontractors: There are storefront and curtain wall subcontractors experienced in the use of stick systems operating locally, regionally and nationally.

Durability and Maintenance: This is a function of two things; good design to keep water out of the system, and a top quality finish to the extrusions.

Structural Performance

Spanning capacity: The systems are generally designed to span between floor plates.

Typical deflection criteria: Primarily a function of the glass type used; insulated glass units will have a deflection limit specified by the glass supplier. This is typically not a problem as the glass is fully perimeter supported.

Accommodation of movement: The systems must be designed to handle vertical, in-plane lateral, and out-of-plane lateral loads as determined by engineering analysis of the building and accounting for all dead and live load conditions.

Constructability

Fabrication: Cutting and drilling is done primarily in the shop and shipped to the field. All assembly work is done in the field.

Installation: Installation is relatively simple, but stick systems tend to concentrate the assembly work in the field where labor rates in Western markets are at a premium.

Economy

Stick systems have been used for decades on a great number of high-rise and other buildings. They are still used in some cases today, but have been largely replaced by unitized systems.

6.3.3.2 Unitized

Table 6-16 Unitized system attributes.

Unitized System: Summary of Predominant Attributes
• *Has largely replaced stick technology*
• *"Units" are assembled in the shop and shipped to the field*
• *Shifts more of the work to factory-controlled conditions*
• *Better quality control from in-factory assembly*
• *Minimizes expensive site labor*

Morphology

Similar to stick curtain walls, but systems are designed to be assembled in large units in the factory, shipped to the site and set into position. Most are designed so that the units are weather sealed when set into position, requiring only a minimum of wet silicone application at the corner intersections.

Design Considerations

Aesthetics: Often similar to stick systems, but there is more flexibility with unitized systems because of the factory assembly. Units can be structurally glazed, meaning the glass is glued to the exterior of the frame with structural silicone, and no cover plate is required on the exterior of the glass. This serves to mitigate the strong framing grid, providing an uninterrupted glass surface. Custom curtain wall designs can become quite elaborate.

Transparency: Typically somewhat less than with stick systems, as the splitting of the mullions around the perimeter of the units results in a wider combined mullion band.

Geometric flexibility: Unitized systems are more complex than stick systems, and are even more impacted by added complexity to the building form.

Design issues: Like stick systems, unitized systems must be carefully designed to accommodate building movements and to provide pressure equalization to the system to prevent water and air infiltration. The necessary requirement to evolve unitized systems from their stick-built predecessors into a modular system was to split the mullion at the intersection of the units. This complicated the unit design while at the same time providing new opportunities for accommodating building movements.

Glass System Interface: The glass is continuously supported on the frame.

Glass type: There are no limitations to the glass type used except those imposed by code requirements.

Resources and Technology

Materials and Processes: The primary difference here is where the work is performed; unitized systems are shop assembled facilitating the processes. There is general parity between framed systems with respect to glass and panel materials.

Material Suppliers and Subcontractors: Unitized systems are provided by the higher realm of the glazing industry and used predominantly in high-rise application, and while there is not an abundance of qualified providers, the industry includes companies operating at the global, national, regional, and even local level.

Durability and Maintenance: This is a function of two things; good design to keep water out of the system, and a top quality finish to the extrusions. Unitized systems have certain design advantages, as well as the significant advantage of being largely assembled under factory controlled conditions.

Structural Performance

Spanning capacity: The units are generally designed to span between floor plates; the bigger the unit that can be efficiently fabricated, shipped, handled and installed, the more effective the unitized strategy. Some systems develop units that are oriented vertically and span between two floors. Most focus on developing as wide a unit as possible spanning just between floor plates.

Typical deflection criteria: Primarily a function of the glass type used; insulated glass units will have a deflection limit specified by the glass supplier. This is typically not a problem as the glass is fully perimeter supported.

Accommodation of movement: The systems must be designed to handle vertical, in-plane lateral, and out-of-plane lateral loads as determined by engineering analysis of the building and accounting for all dead and live load conditions. Unitized systems provide some advantages in this regard, as the split-mullions afford an opportunity to provide more movement to the curtain wall system.

Constructability

Fabrication: All fabrication and assembly of the units is done in the shop.

Installation: Installation is facilitated by the unitized design; large assembled units are shipped to the site and set in place, maximizing the efficiency of the site crews.

Economy

Unitized curtain wall systems represent the state of the art in economical building skins for multi-story buildings. There are shortcomings to the technology, acoustic and thermal performance chief among them, and there is a growing focus on these performance issues.

6.3.3.3 Veneer System

Table 6-17 Veneer system attributes.

Veneer System: Summary of Predominant Attributes
• *A minimal approach borrowing curtain wall technique* • *Similar to a stick system, but non-structural* • *Requires near continuous support to the extrusion receiving the glass* • *Can be used with wet or dry seals* • *Eases the demands on glass supply* • *Very economical*

Morphology

This approach is conceptually similar to a stick system with nearly all of the system depth removed, as it is used in applications where the backer-structure will provide continuous support to the extrusions. The front face of the system that takes care of the business of attaching the glass is all that remains.

Design Considerations

Aesthetics: A minimal system, but with some visible framing. The extrusion sections and site-lines can be kept minimal, generally no bigger than the face of the supporting structure.

Transparency: Moderate; largely a function of the glass grid and backer structure.

Geometric flexibility: Veneer systems can be easily adapted to accommodate form variations and transitions.

Design issues: Veneer systems are typically mechanically captured on 2-sides or 4-sides with a cover plate over the glass joint. 2-sided systems can be supported along the horizontal or vertical gridline. The supported side can be a dry gasket or wet-sealed. The opposing side can be butt-glazed with silicone applied in the field. Again, the systems must be designed to accommodate the structure movements. 2-sided systems are perhaps best wet-sealed throughout, while 4-sided systems can use either method throughout.

Glass System Interface: The glass is continuously supported on 2 or 4 sides by an extrusion integrally supported by a long-span backer structure.

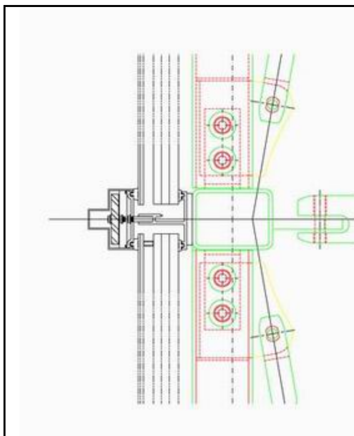


Figure 6.14 Veneer system typical section.

Glass type: There are no limitations to the glass type used except those imposed by code requirements. In a 2-sided support application using insulated glass, the unsupported side needs to be checked that maximum deflections meet the fabricators requirements.

Resources and Technology

Materials and Processes: Similar to stick systems, but the extrusions are smaller and easier to handle and install.

Material Suppliers and Subcontractors: Qualified local glaziers should be available to provide for this system type.

Durability and Maintenance: This is a function of two things; good design to keep water out of the system, and a top quality finish to the extrusions. Wet-glazed silicone weather seals have been found to be very effective in long term performance and are a viable option on this glass system type.

Structural Performance

Spanning capacity: The glass system is effectively integrated into the backer structure, which provides for the spanning capacity; the functions of the glass system are reduced to fixing the glass and providing the weather seal.

Typical deflection criteria: Deflects with the backer structure.

Accommodation of movement: The systems must be designed to handle vertical, in-plane lateral, and out-of-plane lateral loads as determined by engineering analysis of the backer structure.

Constructability

Fabrication: Fabrication of the extrusions in the shop. It is possible to expedite installation by attaching extrusions to the backer structure in the shop, but care must be taken not to damage them in handling and installation.

Installation: Fabricated extrusions are installed on the backer structure and the glass is set in place, with the application of sealants as required.

Economy

Veneer systems are an effective, economical glazing solution providing moderate to high transparency where an appropriate backer structure is utilized.

6.3.3.4 Panel System

Table 6-18 Panel system attributes.

Panel System: Summary of Predominant Attributes
• *Provides moderate to high relative transparency depending upon glass type*
• *Glass surface can be lifted off supporting structure*
• *Minimal butt-glazed silicone joints throughout*
• *Conventional glass fabrication requirements*
• *Facilitates the installation process*
• *Potentially more economical than point-fixed systems*

Morphology

"Panel" is a term often used in reference to a single assembly of fabricated glass, as the term is often used in this thesis. A panel system has a distinctly different meaning as used herein.

The intent of the panel system is to maximize relative transparency while using strictly conventional glass supply. The glass is continuously supported on 2 or 4-sides. Supporting elements are comprised of extruded aluminum or steel rails of minimal width to facilitate a structural silicone bond, and depth as required to provide resistance to deflection in the glass. The rails can be combined to make a full perimeter frame, or used only on the two vertical sides of the glass pane. The glass is structurally glazed in the factory to the rails. The rails can incorporate a facility for attaching the panel into the structure. The panels are then treated identically to point-fixed glass panels, hung on the structure and butt-glazed. It is also possible to provide a captured (a mechanical capture instead of just the silicone adhesive) version of this system if required.

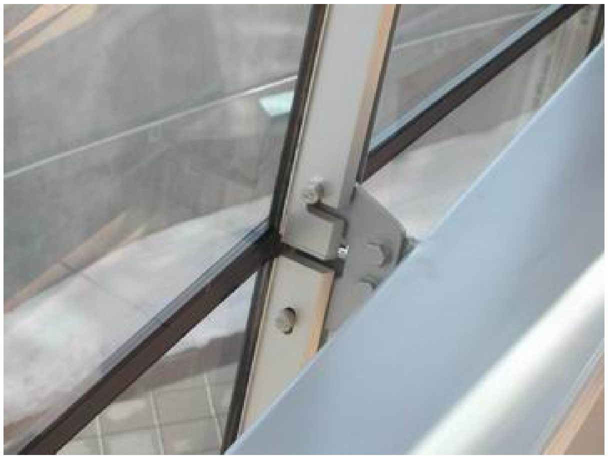
Design Considerations

Aesthetics: This system presents a glass surface very similar to a drilled point-fixed system with even less interruption; the butt-glazed silicone joints are the same but there are no bolted fasteners showing on the surface. As with the point-fixed systems, the greatest affect of perceived transparency comes from the lifting of the glass surface away from the supporting structure.

Transparency: High.

Geometric flexibility: Planar transitions in the glass surface may be complicated by the depth of the panel and the manner of attachment.

Design issues: The means of attachment of the panel to the structure is the primary design issue, and this can be accomplished in a number of ways. Again, the issue is to anticipate the structure movements and assure that the attachment design allows for those movements, plus facilitates installation requirements.



Glass System Interface: The interface generally takes the form of a hole or slot in the side rails of the panel attaching to an offset plate or component tying back to the structural support system.

Glass type: This strategy supports the use of conventional glass fabrication.

Figure 6.15 Panel system connection detail.

Resources and Technology

Materials and Processes: Glass fabrication is conventional. Attachment components are typically simple steel plate assemblies tying back to the backer structure.

Material Suppliers and Subcontractors: The structural glazing must be done by a qualified glazier in strict compliance with the sealant manufacturer's requirements. Adhesion testing is also required.

Durability and Maintenance: Durability will be a function of the materials used, the adequacy of the finish materials, and the quality of their application. This system provides for a butt-glazed silicone seal, which has proven to provide a durable weather seal.

Structural Performance

Spanning capacity: The spanning capacity is picked up by the rails. It is even conceivable to use a heavier rail system that would provide for the glazing of multiple glass panels, as with the unitized systems.

Typical deflection criteria: The glass can be provided perimeter support as required to control deflections.

Accommodation of movement: As with the other glass system types, the structure movements must be identified and the glazing attachment designed to accommodate these movements.

Constructability

Fabrication: As mentioned above, the only issue is assuring an adequate adhesive bond of the glass to the metal rails if a structural silicone method is selected.

Installation: If the glass system interface is properly detailed, these systems will install very rapidly.

As with the point-fixed systems, the installation of the wet silicone seal is of critical importance in a butt-glazed system (see point-fixed drilled), with respect to both appearance and performance.

Economy

This is an economical alternative to a point-fixed system, offering many of the advantages and a reasonable level of system transparency.

6.3.3.5 Point-fixed Drilled System

Table 6-19 Point-fixed drilled system attributes.

Point-fixed Drilled System: Summary of Predominant Attributes
• *Provides for optimum transparency with any given backer structure*
• *Glass can be lifted off supporting structure*
• *Hole drilling adds to system cost*
• *Engineered and waranteed systems are available*
• *Minimal butt-glazed silicone joints throughout*
• *Presents critical glass supply requirements*
• *Requires high-tolerance installation of backer structure*
• *Highest relative cost*

Morphology

The glass panels are provided with holes at the corners and sometimes intermediate points depending upon the glass panel size and makeup. Holes can be simple or countersunk. IGU panels require a sealing-spacer around each hole to maintain the hermetic seal of the unit. Hardware components include stainless steel "glass-bolts" and Delrin bushings that protect the glass from direct contact with the metal bolt. Some method of interface attachment is then employed to bridge from the bolt to the façade structure.

Design Considerations

Aesthetics: This system presents an elegant glass surface with the most minimal of interruptions in the form of butt-glazed silicone joints and bolted fasteners as required. The greatest affect of perceived transparency comes from the lifting of the glass surface away from the supporting structure.

Transparency: Optimum.

Geometric flexibility: One of the advantages of point-fixed systems is the relative ease with which planar transitions in the glass surface can be accommodated.

Design issues: Bolts can be countersunk and flush with the glass surface, or a low profile round headed bolt can be used in a through-hole. The joint size is a function of the thickness of the glass and should be determined in consultation with the glass provider. The number and location of holes is a function of glass size and design loads, and must be determined by a qualified engineer experienced with glass. The bridging component which ties the glass to the backer structure can range from a custom cast stainless steel component, as with a spider type fitting, to a simple spring plate fashioned from bent metal plate. It is important that the glass-fixings provide for two considerations; accommodation of field tolerances with respect to the location of the interface point at the backer structure, and accommodation of movement of the structure and glass under design loads.

Figure 6.16 Point-fixed bolted system with spider fitting and insulated glass.

Glass System Interface: The interface is comprised of a glass bolt and a bridging component that ties the bolt to the backer structure.

Glass type: Glass specification and supply is a critical issue with this system. Tempered glass is typically required, and laminated glass in required in any application sloped off the vertical 15 degrees or more.

Resources and Technology

Materials and Processes: Glass fabrication requires special processes, drilling at minimum. Hardware systems range from machined and/or cast stainless steel components to simple metal plate systems.

Material Suppliers and Subcontractors: At least two suppliers provide complete engineered and waranteed systems including glass and all hardware. These are good options, but expensive. A viable alternative is to specify an off-the-shelf hardware system and a glass supplier offering a point-fixed glass product. Over the past decade many fabricators of hardware systems for point-fixed glass systems have emerged with catalogs full of product. Glass supply for drilled point-fixed applications has been more problematic. For many years the large majority of point-fixed glass came from just a few European sources. However, more glass fabricators have entered this market in recent years providing more local and economical sources of glass supply.

Durability and Maintenance: These are very durable, low maintenance systems beyond the cleaning of the glass. The extensive use of stainless steel and the fact that the structural components are normally inside the glass envelope are a major factor. The butt-glazed silicone seal has proven to be an excellent performer.

Structural Performance

Spanning capacity: This is accommodated solely by the glass panel and is a function of the bolted connection at the glass and the makeup of the glass panel. The deflection of insulated glass units stresses the spacer seal, and manufacturers typically place limits on the amount of deflection for which they will provide a waranteed system. This ranges from L/100 to L/140. The other factor is the glass bolt, of which there are two basic types; one clamps the glass at the hole location preventing rotation and limiting deflections to some extent, but transferring bending forces into the glass as a result; the other type of bolt incorporates a ball-bearing head that provides for free rotation of the glass panel at the bolt connection, thus bending moments are eliminated. If the former type of bolted connection is used, the bending moments must be analyzed. (Rice & Dutton 1995, p.32-42)

Typical deflection criteria: Deflections to be determined as in spanning capacity above.

Accommodation of movement: These systems are capable of significant movement owing to the elasticity of the silicone material at the joints. Beyond that, system movements must be accounted for as part of the structural analysis, and the connection system must be designed to accommodate these movements. Code requirements are increasing in this regard, and some system applications have required custom designed hardware systems to accommodate large movements due to seismic loading (Desai 2005).

Constructability

Fabrication: Point-fixed glass systems are increasingly available; a good source of glass supply is critical.

Installation: The installation of drilled point-fixed glass systems can be easy or extremely tedious, the difference being in the installation of the backer structure; if the supporting façade structure is installed within adequate tolerances supported by adjustability in the glass-fixing components, the glass will install easily and quickly. If not, it can be a long and frustrating process.

The installation of the silicone seal is of critical importance in a minimal system such as this. The entire effect of the façade system can be compromised if the seals look like toothpaste squeezed right from tube. Some subcontractors specialize in the application of butt-glazed silicone. It is important that the specification documents adequately communicate what the expectation of the designer is with respect to the quality and appearance of the silicone seal.

Economy

Drilled point-fixed glass systems can vary considerably in price, ranging from a modest premium for off-the-shelf product to a doubling or tripling of cost for elaborate custom designs. The requirement for holes adds to the cost. Laminated and laminated-insulated panels multiply this cost; each laminated-insulated panel requires 12 holes.

6.3.3.6 Point-fixed Clamped System

Table 6-20 Point-fixed clamped system attributes.

Point-fixed Clamped System: Summary of Predominant Attributes
• *Provides transparency on par with point-fixed drilled systems* • *Glass can be lifted off supporting structure* • *Eliminates the need for and cost of drilled holes* • *Small, localized clamp plates may be visible on exterior glass surface* • *Off-the-shelf systems may not yet be available* • *Minimal butt-glazed silicone joints throughout* • *Eases the glass supply requirements* • *Eases the high-tolerance installation requirements for the backer structure* • *Lower cost alternative to point-fixed drilled systems*

Morphology

The intent with this system type is to provide all the attributes of point-fixed drilled systems without requiring the holes. Although the means can vary, conceptually the spider component of the drilled point-fixed system is rotated 45 degrees such that the blades align with the glass grid. A thin web plate passes through the joint which receives a top plate, effectively clamping the glass to the spider (see fig). The connection mechanism is sometimes referred to as a “pinch-plate.”

Figure 6.17 Point-fixed clamped system with insulated-laminated glass during installation.

There is a difference in the way the glass is supported. With the drilled point-fixed systems the glass panel is typically hung from the top spider connection and allowed movement at the bottom. The reverse is true for the pinch-plate system; the pinch-plates at the bottom of the glass panel supports the dead load of the panel, while it is provided movement at the top.

Design Considerations

Aesthetics: Similar to point-fixed drilled systems with the exception that most clamped systems have a low profile clamp plate interrupting the glass surface. Some designers object to this, some prefer it.

Transparency: Very high; it can be argued that the attention drawn to the pinch-plate caps detracts from the perceived transparency of the façade.

Geometric flexibility: General parity with point-fixed drilled systems.

Design issues: The same as with drilled systems, except that pinch locations are typically restricted to the glass edge.

Glass System Interface: The interface is comprised of a pinch-plate and a bridging component that ties the pinch-plate to the backer structure.

Glass type: Glass specification and supply is a lesser issue with this system than with drilled systems, simply because there is no requirement for special modifications to the fabricated glass panes, such as holes, and seals as required for an insulated panel. The glass is still point-fixed however, and subject to all the fabricators requirements for point-fixed applications, including any limits to deflection.

Resources and Technology

Materials and Processes: Hardware systems range from machined and/or cast stainless steel components to simple metal plate systems. Glass must be appropriate to point-fixed applications.

Material Suppliers and Subcontractors: There is believed to be no manufacturer offering an engineered and waranteed complete pinch-plate system. The pinch-plate components must be custom designed and machined to specification. Glass providers are more readily available than they are for drilled systems.

Durability and Maintenance: General parity with drilled systems.

Structural Performance

Spanning capacity: General parity with drilled systems. The pinch-plate can transfer some bending moment to the glass under design loading; these bending moments must be analyzed as part of the glass system engineering.

Typical deflection criteria: Same as with drilled systems.

Accommodation of movement: Parity with bolted systems.

Constructability

Fabrication: Glass supply is easier; pinch plates may need to be custom designed until manufacturers begin to offer an off-the-shelf product.

Installation: General parity with drilled systems.

Care must be taken with the silicone seal through the pinch plate, as this penetration through the seal can be a potential leak point if not properly sealed. A method statement is required and mockup testing advised.

Economy

This strategy eliminates the cost associated with the holes, which in the case of insulated and insulated-laminated glass can be considerable. However, this advantage is easily offset if the cost of the clamping components is significantly more that the glass bolts used with the drilled systems. While there are numerous suppliers providing various products for bolting drilled glass, there are currently far fewer providing claming systems.

6.4 Other Considerations in Glass Selection

6.4.1 Glass Selection Considerations

The evaluation criteria above were developed specifically with respect to structural glass facades. The following are more general considerations, many of which will ultimately be important to the designer regardless of the glass application. The following are additional considerations for glass selection depending upon project requirements. Relevant considerations will vary between projects. This list has been derived from a Pilkington technical bulletin (Pilkington 2005), and from Button and Pye (1993).

An initial step in developing a conceptual design for a structural glass façade is to select the glass type. This is a relevant as the glass panel type may limit the maximum panels size and thus the glass grid dimensions. All of the glass selection criteria listed here will certainly not be relevant to any given project. It is tempting to let the strength requirements determine the panel makeup. However, the determination may well not be made on the basis of strength alone; code or thermal performance requirements or appearance considerations can be the determining factors. It is worth considering these various criteria as an initial step, although final determination as to such things as color and coatings can be left unresolved at the designer's discretion, while a panel type is selected to use as the basis for the determination of the glass grid. If the glass size to be used is not large and within the parameters established here, the entire issue of glass panel type can be put off until later.

6.4.1.1 Support

This is a key consideration with respect to the use of point-fixed glass systems. The glass panel types that can be used with frameless systems are indicated in Table 6-12. Generally, annealed glass is to be avoided in point-fixed applications.

6.4.1.2 Strength

The ASTM E 1300 Standard Practice for Determining Load Resistance of Glass in Buildings should be consulted for glass capacity under specified loads. The strength properties of glass panes and panels are discussed in Chapters 2.4 and 6.2.3.

DuPont has an online tool that can be used to simply calculate glass stress and deflection. http://www.dupont.com/safetyglass/en/science/calculator/index.html#

Pilkington also has several interesting online tools. http://www.pilkington.com/the+americas/usa/english/building+products/tools+and+calculators/default.htm

For a more sophisticated program used by the glazing industry, Standards Design Group Inc. sells a analysis program called Window Glass Design. For more information, visit www.standardsdesign.com/WGD/2004/Default.htm.

6.4.1.3 Deflection

Deflection is a function of the support of the glass, one-sided, two-sided, three-sided, four-sided and point-fixed all represent different deflection behavior. Deflection behavior in glass is not linear, and heat-treating glass does not affect its deflection properties.

There are no code limits on deflection, however;

"It is a common opinion that center of glass deflections greater than ¾" (19 mm) relative to the undeflected glass plane will be aesthetically objectionable for typical glazing installations." (Pilkington 2005, p.1)

6.4.1.4 Thickness

Thickness is generally a function of strength and deflection. Color and appearance of glass changes with thickness, as does sound transmission.

6.4.1.5 Color and Appearance

The evaluation of glass color is challenging. Evaluating glass colors at a conference table under incandescent lighting from a 2-inch (50mm) sample will provide little information as to the perceived glass color in application. Many things can affect color, including; body tint, laminate, coatings, reflections, and interior colors. At minimum, the glass should be viewed at the building site and in the same orientation as the actual application. A carefully conceived mockup is the best means to assess glass color.

Many colors are possible. Sources of color include body tints, coatings such as low-E and metallic coatings, and colored interlayer material in laminated glass. Color sources can be combined to provide an even broader range of affect. Many glass fabricators provide unique color choices.

Optical distortions were discussed as an evaluation criterion in section 6.2. Heat-treated, insulated and laminated panels will all display subtle variations of color. Evaluating reflections is an important aspect of glass appearance; the primary way we see glass is through reflections on its surface. Optical distortions can be very apparent in the reflections. Some designers find this objectionable.

The appearance should be evaluated both from the inside and outside, in daylight hours and during artificial lighting conditions.

6.4.1.6 Visible Light Transmission

High daylight levels in a building's interior are an increasingly popular strategy among designers to reduce energy consumption from artificial lighting. The visible light transmission property of a glass type determines the natural light levels in the interior. The provision of high levels of natural light must be balanced against the need for solar control. Colored and coated glass is used to limit the amount of visible light transmission providing a range of light levels.

6.4.1.7 Solar Transmission and Absorption

The solar heat gain coefficient (SHGC) is the primary measure of the total solar energy passing through a glazed opening; measuring the full spectrum of solar energy as opposed to just the visible light specturm. A low SHGC coefficient will lower the solar gain and lower air cooling costs. A high coefficient will raise the solar gain, potentially reducing heating costs. Local climate becomes an important evaluation criterion; if heating costs are higher than cooling costs, a high coefficient may be a better choice, and the opposite if cooling costs are higher than heating costs. The potential for harvesting daylight to offset artificial lighting costs should also be figured in to this analysis. If a low SHGC glass is used in a hot climate to reduce cooling costs, but also reduces the available natural light in the buildings interior, the added energy cost and heat generated by the artificial lighting offset the savings in air conditioning. The SHGC simply compares the amount of solar energy on a glass surface to the amount passing through the glass.

Another measure of thermal performance is the shading coefficient (SC). This measure compares the solar energy passing through the glass to that which passes through a 1/8 in (3.2mm) piece of clear glass, and is considered less accurate than the SHGC.

Solar absorption is an issue with respect to thermal stresses as discussed in chapters 2 and 6. Solar absorption can be felt; the glass becomes hot to the touch, and can lead to glass failure, especially if part of the glass is in shade and part in sun such that there is a substantial temperature differential across the face. Glass in an application where high thermal stresses will occur should be heat-strengthened or tempered.

6.4.1.8 Thermal Insulation

This is measured by the thermal conductivity or resistance of the glass panel. The conductivity measure is the U-value, the resistance by the reciprocal R-value. These values are discussed in Chapter 2.4.3.1. When considered in isolation, these values look very bad when compared to conventional wall materials. This must be balanced against the positive aspects of solar gain and visible light transmission.

6.4.1.9 Sound Transmission

The acoustic properties of glass building skins is becoming an increasingly important issue as noise levels increase in urban environments and more residential high-rise condominiums as well as office buildings are constructed in these environments. Most glass fabricators provide acoustic performance data on the products they provide. Laminated glass has proven to be the best generalized strategy in enhancing the acoustic performance characteristics of a glass panel. Different thicknesses of glass effect different frequencies, so it is often beneficial to laminate different thicknesses of glass. Acoustics is discussed in Chapter 2.4.3.2.

6.4.1.10 Fire Rating

Wired glass is the conventional solution to code or specification requirements for a fire rated glass. There are a variety of tested fire-rated products in the marketplace. Pilkington offers its Pyrostop™ clear laminated safety glass for these applications.

6.4.1.11 Electromagnetic Shielding

Glass coatings can now provide some level of electromagnetic shielding for high security buildings.

6.4.1.12 Code and Safety Requirements

Local, regional or national building codes may dictate the type of glass to be used and must always be carefully examined to assure the specification of the appropriate glass type.

6.4.1.13 Durability and Maintenance

Glass is a highly durable material in most applications. Quality and warranties vary, and care must be taken in qualifying an appropriate glass fabricator. Glass requires periodic cleaning. Pilkington has developed a “self-cleaning” glass; a coated glass that helps prevent dirt from adhering to the glass so that it is easily washed from the surface.

Chapter 7 - Tools, Resources, and Concept Development Methodology

The intent of this Chapter is to define a methodology for the development of the conceptual design of a structural glass façade. The mapping of a comprehensive methodology is a prime objective of this thesis, while the requirements of implementation are necessarily limited to the development of those elements which can provide proof of concept. Both the methodology and the design guidelines, tools and resources that support it are discussed and contextualized in this Chapter, regardless of whether they have been developed as part of this thesis.

The methodology developed here incorporates design tools, resources and guidelines as relevant, and attempts to embody the content developed previously in this thesis. The scope of this conceptual design process is discussed in Chapter 3. It does not coincide with the conventional phases of schematic design, design development and contract documents that the architect typically undertakes on design/bid/build projects. Concept development involves activities comprising much of the schematic design phase and key components of the design development phase. This is intended to be a simplified methodology that provides the designer with a streamlined implementation process.

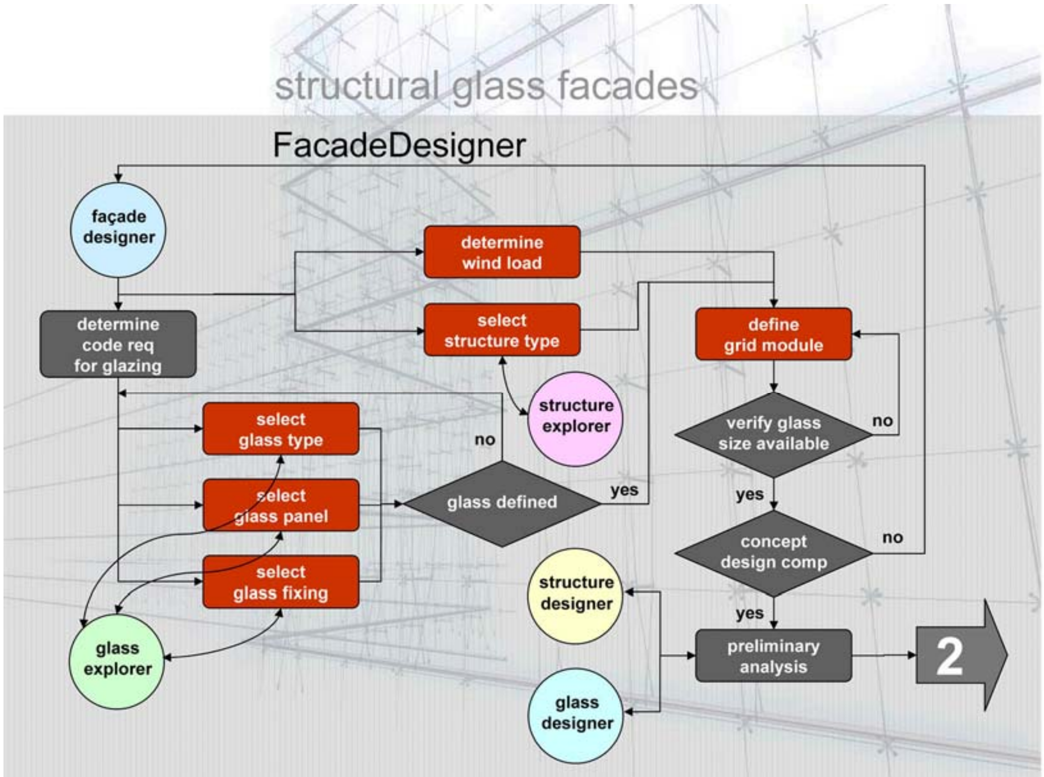
Figure 7.1 below attempts to map this methodology. The methodology is embodied in a program referred to herein as FacadeDesigner. The reddish boxes represent process points requiring user input. The colored circles represent various resource modules as described herein and intended to facilitate the methodology.

As such, it supports the standardized forms of structural glass façade technology as defined in Chapter 6. Designers can of course, at their own discretion, pursue a more elaborate and involved methodology building from this one as desired to develop designs of added complexity, or as a means to more tightly control the development process.

The methodology defined in Figure 7.1 can support a high degree of design complexity. However, depending upon the experience of the architect, complex designs with innovative technology frequently require the involvement of a specialist; in the case of structural glass facades, a specialty consultant or design/build contracting company. The level of involvement required of the specialist in such cases is beyond what they can reasonably be expected to provide for free, and a mechanism for brining them to the design team as a paid consultant is necessary to secure meaningful participation. While this is a viable and effective means to proceed, the requirement often becomes a barrier to the implementation of the technology. A theory of this thesis is that a few strategic simple tools and resources can facilitate a broader use of this technology by enabling the architect to initiate a structural glass façade project with only the minimal outside involvement typically supplied by industry providers (material suppliers, fabricators, design/build specialists) for free as part of their sales support services.

The work product of this process is a developed conceptual design that has been tested for structural, fabrication and economic viability, and represented in a set of contract documents suitable for bidding in a design/build format. The methodology is appropriate for the implementation of any innovative building technology for which there is adequate industry expertise and infrastructure involving material suppliers, fabricators, installers, and/or design/build specialty contractors.

The complexity of structural glass façade designs, as with many other design types, results not so much from the basic design as it does from the boundary interfaces, form transitions, grid anomalies, and other nonstandard atypical manifestations within the design. These are the items that seem to characteristically represent about 20% of a design but take 80% of the resources to complete. A strategy developed herein is that by employing a design/build method, the designer can implement an innovative design, a design involving innovative technology, or both, by addressing in a specific manner just the typical aspect of the design; the 80% of the design that only takes 20% of the time. The remaining work is deferred to the build-phase of the project, where appropriate industry experts can take design/build responsibility for final completion of all design and engineering work subject to the architect's approval.



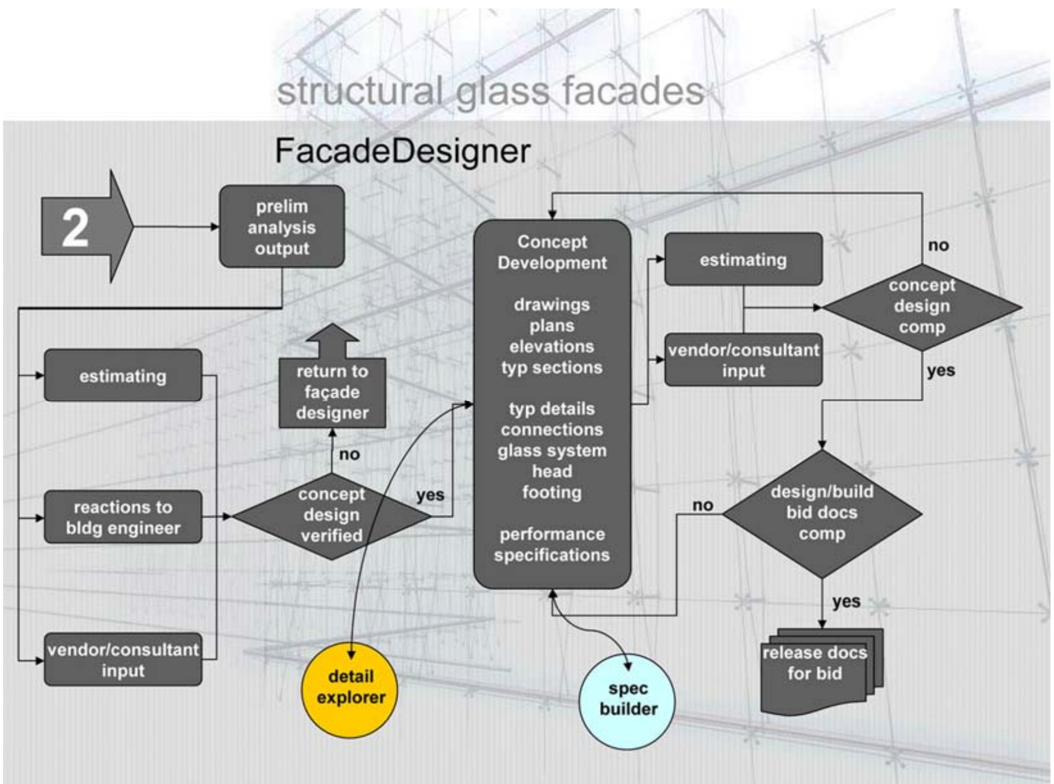


Figure 7.1 Process map of simplified structural glass façade design methodology.

7.1 A Simple Case

The theory is that if the required deliverables are simplified as represented in Figure 7.1, the architect is provided with a contextual methodology for implementing innovative technology. The opportunity in this context is for the architect to develop conceptual designs for structural glass facades without the involvement of paid specialist consultants. If this approach is to work, simplified design tools, techniques, and information to support the methodology must be available to facilitate utilization of the core technology. An effort has been made in this thesis to reduce the technology of structural glass facades as represented by the cumulative completed works as identified herein to a simplified, basic, generalized form. Structural system types, glass types and glass-fixing systems, the primary components of this technology, have all been analyzed, categorized and presented in this manner. The intent now is to combine these generalized façade systems with simplified tools in a manner that enables the designer to generate constructible facades of some reasonable complexity.

7.1.1 Flat Vertical Façade Wall

Good façade designs respond to the context of a building problem and can become quite customized to that particular application. Increased complexity generally accompanies this customization. Anomalies of the glazing grid for example, can result from; changes to the building grid, the intersection of wall planes, changing roof planes, or articulations of the surface geometry in response to a multitude of possible considerations, aesthetics among them. The focus here will be to deal with the typical part of the façade; unique conditions at the perimeter and in transition areas will be largely ignored beyond simple elevation drawings of the glazing grid. If the glazing grid changes in some area of the façade, the simplified methodology should allow for both grids to be analyzed in isolation, as if they were separate structures, thus simplifying the problem and yielding only the most basic and useful information. Complex “phrases” are thus reduced to a simple vocabulary. The information that is needed to support the work product of the design/build delivery strategy is easily accommodated through this reductionist approach. Similarly, it does not matter for the sake of this analysis if the wall is sloped or curved. This representation can be simply made by the designer in schematic plan, elevation and typical section drawings, while the preliminary analysis can be approximated from a more standardized form.

The tools and resources developed herein then, will focus on the basic façade forms as defined in Chapter 6, in the vertical orientation of a regular glazed surface.

7.1.2 Uniform Grid Module

The surface to be glazed needs to be subdivided into an appropriate grid. This is a critical step, as the grid will define the spacing of the façade's supporting structure elements, thus determining the tributary area of the glass surface that will act on the component and consequently define its structural characteristics. This will have implications on all aspects of the design, from transparency to cost.

As discussed above, the façade glass grid is often not uniform throughout for various reasons. Localized deviations in the glass grid will be ignored as part of this simplified methodology, but they should be clearly represented in elevation drawings. If there is a change in the typical grid geometry of significant area, it will be analyzed as an additional case. By segmenting the façade into typical areas and analyzing those areas as afforded by the simplified tools and methods, the development of a complex design can be facilitated.

Every opportunity should be sought to bring uniformity to the glazing grid. If circumstances provide, there should be no deviation from the basic grid geometry. If the façade is designed early in the process, a uniform glazing grid or grids can be determined and the building interface designed around this grid. Considerations of the glazing grid are discussed later in this Chapter.

7.1.3 Vertical Span / Horizontal Span

Another significant determinant of the design is the vertical and horizontal span of the façade. This is related to the grid module, as the vertical grid module will be a subdivision of the vertical span, and the horizontal grid module will be a subdivision of the horizontal span. The structural spanning dimension, most often the vertical span, will be a significant determinant in the complexity and cost of the façade structure. If the vertical or horizontal span is not continuous but steps up or down in areas, the façade geometry will be broken up and analyzed as separate pieces.

7.2 FacadeDesigner.com

The design tools and resources discussed herein are intended to be provided in an internet venue, the portal of which has been designated as FaçadeDesigner.com, and the URL for this designation has been secured for this purpose. http://www.FacadeDesigner.com

Figure 7.2 indicates the site as globally conceived. Only some of the components have been implemented as part of this thesis.

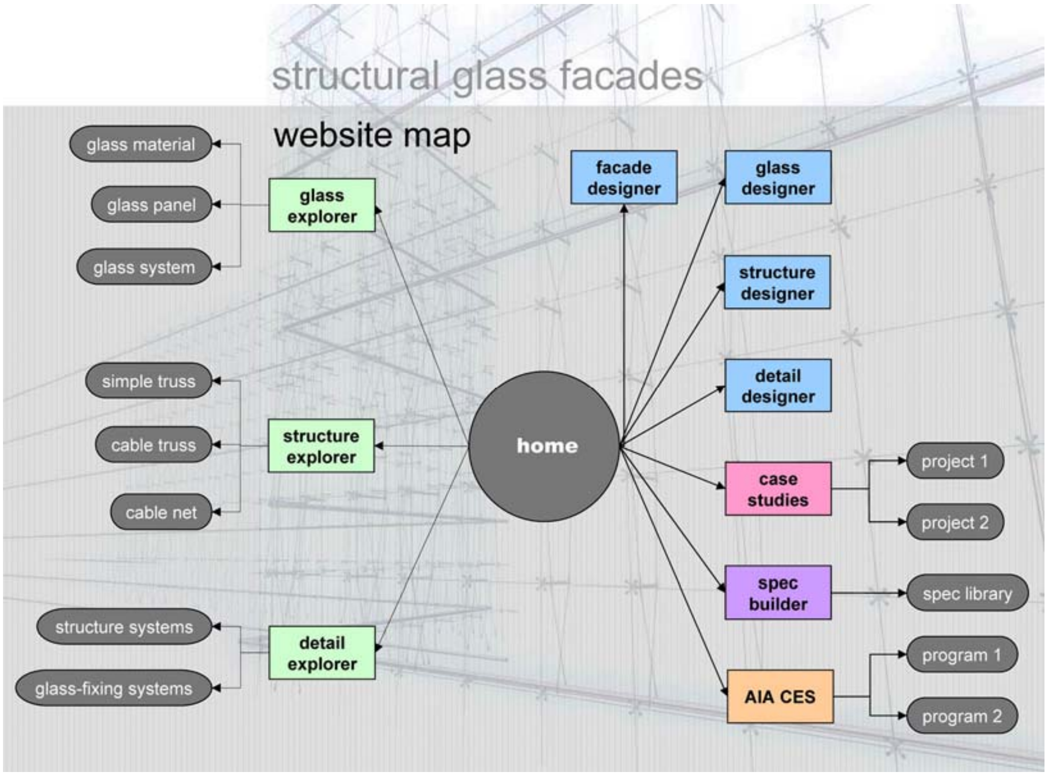


Figure 7.2 Conceptual diagram of FacadeDesigner.com Website.

The website includes a homepage intended to feature generalized topics of interest related to structural glass facades of a more current and timely nature (Figure 7.3). In addition, the home page acts as the portal to the rest of the website, which is structured into the modules as described in the following.

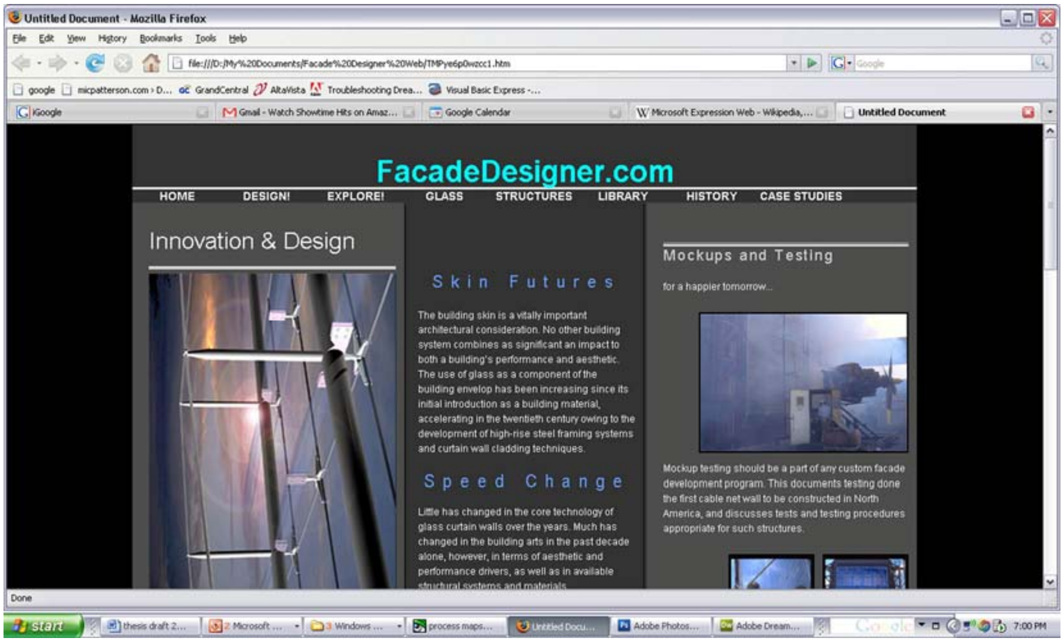


Figure 7.3 FacadeDesigner.com homepage.

Various modules of two types have been conceived to facilitate the methodology presented for the conceptual design development of structural glass facades; the "designer" modules and the "explorer" modules. Several of these modules have been prototyped in support of this thesis. These and the other modules indicated in Figure 7.2 provide opportunities for future work as discussed in Chapter 11.

7.2.1 Site Construction

The website is simple in construction, currently offering no interactive features. The pages were constructed by the author with no previous experience in website development. The FacadeDesigner.com website is a prototype intended to demonstrate the viability of this tool. It is not intended to represent exemplary website design, and the author both acknowledges and takes full responsibility for the inadequacies and shortcomings of the FacadeDesigner.com website. HTML authoring tools were used to develop the web pages.

7.2.1.1 Web Authoring Software

Two HTML authoring programs were used. Dreamweaver (version CS3 was used here) by Adobe Systems is among the most popular, if not the most popular, with those not expert in writing HTML code. The program is a visually-oriented tool for writing HTML code, and greatly facilitates the process. Web authoring has fairly recently moved to the use of Cascading Style Sheets (CSS), a formatting language that has replaced cumbersome HTML techniques. It is used in conjunction with the HTML code, and Dreamweaver supports both, encouraging the user to utilize HTML for the basic structuring of the pages and CSS for formatting. Web development is not simple however, and the use of tools such as Dreamweaver requires some considerable time to master to any significant degree of competency. Good 3rd-party documentation provides valuable support in learning the program. David McFarland (2007, p.2), author of one such book, comments, “Dreamweaver is a complete Web site production and management tool. It works with Web technologies like HTML, XHTML, CSS, and JavaScript.” There are also a large number of online tutorials available, both through Adobe and 3rd-parties.

The other authoring tool used here was Expression Web by Microsoft. It was released in 2006 and intended to replace FrontPage (Microsoft Expression Web 2008). The program is remarkably similar in form and function to Dreamweaver. Owing to its relatively recent release, there is far less documentation supporting the product however, either from Microsoft or 3rd-party vendors, although that can be expected to change. Expression is not merely a new version of FrontPage, it is an entirely new web design platform of Microsoft. The reason for this development is new Web standards that have emerged in recent years, with which FrontPage could not comply. Jim Cheshire (2007, p.XXX) comments, “Microsoft desperately needed a Web design tool that would adhere to current Web standards, and they needed a Web design tool that would make creating and maintaining a standards-driven Web site easy.” Both Dreamweaver and Expression are standards compliant.

The World Wide Web is a unique medium, and there is thus a unique art to the design of Web pages, which should be explored by the aspiring Web designer. There is a remarkable diversity of books on the subject, ranging from useful to mediocre. If one were to be restricted to a single book, the author would recommend *Don't Make Me Think* (Krug 2006).

7.3 The "Explorer" Modules

The explorer modules are intended as information-rich topical resources to be accessed from FacadeDesigner.com. They include the primary systems and categorization developed in this thesis.

7.3.1 GlassExplorer

The GlassExplorer module contains information relative to:

- glass material,
- glass panel fabrications,
- and glass fixing systems,

as discussed in Chapter 2 and categorized in Chapter 6. It is accessed via a link from any page of the website, or from various links strategically placed in the design modules. Figure 7.4 shows the GlassExplorer Webpage in development.

Figure 7.4 GlassExplorer homepage in development.

7.3.2 StructureExplorer

The StructureExplorer module contains information relative to the structural systems discussed in Chapter 2 and categorized in Chapter 6. The structural systems selected as most appropriate for inclusion are indicated in Table 7-1. Figure 7.5 shows the StructureExplorer Webpage in early development.

Table 7-1 StructureExplorer: Included Structure Types.

StructureExplorer: Included Structure Types		
• *Strongback*	• *Cable Truss*	• *Cable Net*
• *Simple Truss*	• *Glass Fin*	
• *Mast Truss*	• *Grid Shell*	

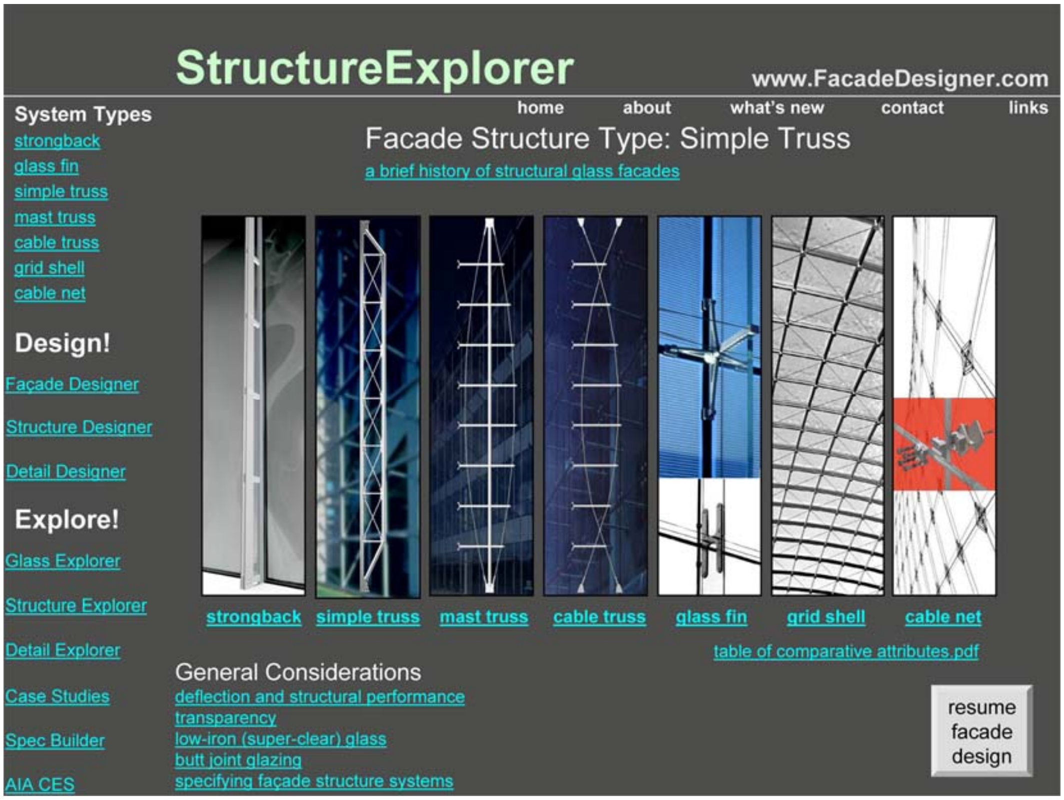


Figure 7.5 StructureExplorer Web page, early development.

7.3.3 DetailExplorer

The DetailExplorer module remains undeveloped, and is included in Chapter 11 as an opportunity for future work. It is however, incorporated into the FacadeDesigner.com concept as represented in Figure 7.2. Many of the details involved with structural glass facades, particularly with the point-fixed glazing systems, are unique in their form, function, and the considerations they embody. In fact, thesis work was recently completed at the University of Southern California involving design guidelines for the development of details in point-fixed glazing systems (Cheng 2007). This work could be incorporated into FacadeDesigner.com with relative ease and to some significant benefit.

7.3.4 SpecBuilder

SpecBuilder is conceived as an expert system or wizard that facilitates the development of an appropriate performance specification in response to user-defined parameters relating to the glass, glass system and structure types selected by the user for a structural glass façade design. Modular text documents would be mixed and matched according to a set of rules and in response to the user-defined parameters. A computer program in Visual Basic or C# would likely be required as an engine for the document assembly. It is possible that all necessary user-inputs could be incorporated into the FacadeDesigner module. This is another area for future work.

7.3.5 Library

Structural glass façade technology incorporates a wide variety of materials and processes as described in Chapter 2. The intent of the Library module is to house all links for the various technical papers, bulletins, reports, specifications, and similar documents in Adobe Acrobat (*.pdf) format. The various documents referenced throughout the site will be linked to the relevant grouping in the Library module. The Library can also be directly accessed from the master navigation menu; here all documents will be grouped by subject and listed alphabetically. The documents that support the SpecBuilder module will also be located in the library.

7.3.6 Learning

Learning programs are intended as a component of the website resource. Various tutorials have been conceived in video and downloadable Acrobat (*.pdf) format. The Learning module may ultimately include an interactive, password protected area of the website. Users would be required to provide a simple registration and be assigned a user name and password. Programs developed for the AIA CES program as discussed in Chapter 4 would be included here. Administration of these programs requires collecting more data from the user and providing certain reports to the AIA. The Learning module will require the development of a server-side database to collect and store data related to users.

This module has not been developed as part of this thesis work, and requires expertise not currently possessed by the author. A prototype learning program has been developed however, per the guidelines of the AIA CES program, and is included in Chapter 9.

7.4 The “Designer” Modules

The designer modules are comprised of design tools supporting some aspect of the façade design process. They go beyond the mere facilitation of reference information as with the Explorer modules, and function as design, analysis, and decision making tools.

7.4.1 StructureDesigner

One of the necessities and challenges of implementing innovative building technology is the development of a budget that represents at least a reasonably close approximation of the cost that qualified subcontractors will put forth on bid day. One of the risks the design team takes with innovative design and technology is that the bids will come in 20, 30, 40% or more over budget. This can result in significant stress to the project; necessary redesign requires extra work for the design team, and/or a loss of control as when the general contractor is directed by the owner to undertake a value-engineering effort to reduce cost. Budgeting is a critical activity, and an estimating program should run in parallel with the conceptual design effort starting very early in the process.

A complication with a structural based technology like the glass facades discussed herein is that there is no effective way to budget such design work in the absence of some preliminary level of structural analysis. Confirmation is needed that the design works at some fundamental level, that the concept is constructible and not fundamentally flawed. Beyond that, there is the very practical need for such basic information as preliminary member sizing and reaction loads into the anchoring perimeter building structure. Hiring a specialty consultant or involving a specialty design/builder early in the process is often problematic, as discussed previously. The StructureDesigner module is an experimental prototype to explore the viability of an alternative strategy in developing this information. The intent is to provide the design team the preliminary information discussed above through a simplified process embodied in a computerized analytical tool. The tool is discussed here; its use as a part of the FacadeDesigner process is discussed in 7.4.4.5 below.

Program Structure

StructureDesigner is a computer program written in the Microsoft Visual Basic programming language. It was written with Microsoft Visual Basic Pro 2005 edition. The program mirrors the appearance of the StructureExplorer module described above. The FacadeDesigner module described following is essentially a front and back end to the StructureDesigner program, with the Explorer modules linked at key decision points to act as a resource to additional information as required. FacadeDesigner guides the user through a series of steps that collect the input necessary for the analysis by StructureDesigner. See Figure 7.1 and Figure 7.2 above. FacadeDesigner embodies the process mapped in Figure 7.1. StructureDesigner is a component of that process as indicated in the Figure.

Variations of the system types are conceivable for inclusion in the StructureDesigner tool. One simple truss system design is incorporated in the tool as represented schematically in Figure 7.14. Each system variation would require a simplified analytical method fine-tuned to the system design; it is this customization that provides for the simplicity and efficiency of the analysis. The analytical results of the simplified method are intended to represent a close approximation to a finite element analysis of the same system. Close approximation is defined here as; within -0/+15% for member loads and reactions and -0/+25% for deflections, of the results from a full structural analysis program, meaning for example, that deflection results or maximum member forces may be understated by 0% and overstated by a maximum of 15% in the case of member forces and reaction loads, and 25% with deflections. As will be seen, the technique developed for open structures is well within these parameters. The simple truss analysis is complicated by the bending moments caused by the distributed loads along the face of the outer truss chords. Further testing of the program and/or fine tuning of the calculation method may make it possible to tighten these parameters for approximation.

Analytical Method for Closed Structures

The following is a simplified method for the analysis of a defined simple truss system. The system is schematically represented in Figure 7.14. Primary input parameters are provided by definition of the glass grid and uniform wind force. Definition of the glass grid includes the vertical and horizontal module as well as the total vertical and horizontal span of the façade. The horizontal grid module defines truss spacing. Steel system options are predefined, and include front and back chord section properties. The user need only define the glass grid, wind speed, and select a system type. The calculation method is to solve for a minimum truss depth.

Compute truss depth;

The minimum depth will be defined by the maximum of one of the following parameters.

$$\text{minimum depth (d)} = \text{the largest value resulting from } d_f\text{, } d_b\text{, or } d_d$$

where;

d_f = depth computed based on the capacity of front chord.

d_b = depth computed based on the capacity of back chord.

d_d = depth computed based on deflection criteria.

1. compute d_f **;**

Calculate moment;

$$M = w(12V_s)^2\,(2H_m) / 8(12{,}000)$$

where;

w = wind load (psi)

V_s = total vertical span of façade (ft)

H_m = horizontal glass grid module (ft)

Calculate depth;

$$d_f = \beta \frac{M}{A_f\,F_{af}}$$

where:

$\beta = 4/3$ compensation factor [12]

A_f = Area of front chord

F_{af} = allowable capacity of front chord

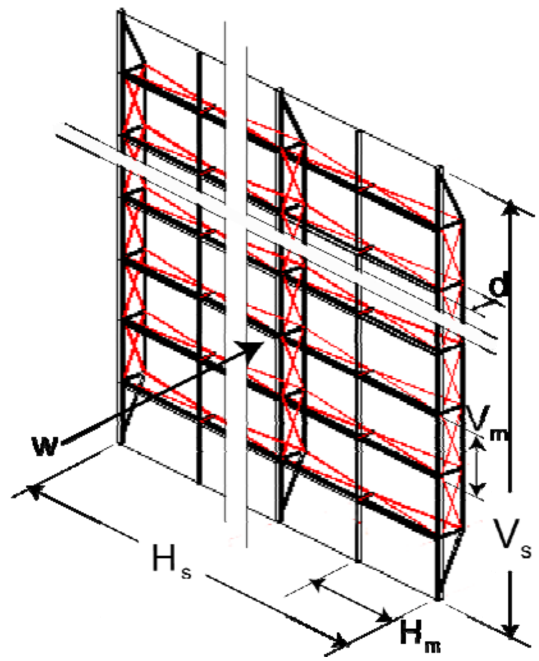


Figure 7.6 Diagram of simple truss with input variables.

Calculate allowable capacity of front chord;

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[12] Compensation factor for the effect of continuously distributed wind load on face of front chord (okay for trusses with bracing at 4 to 5 ft intervals. (T Dehghanyar 2008, per. comm. Mar 12)

$$F_{af} = \left\{ \frac{F_y\left(1 - 0.5\left(\frac{V_m/r_{yf}}{C_c}\right)^2\right)}{\frac{5}{3} + \frac{3}{8}\left(\frac{V_m/r_{yf}}{C_c}\right) - \frac{1}{8}\left(\frac{V_m/r_{yf}}{C_c}\right)^3} \right. \qquad \text{(AISC 1989, p.5-42)}$$

where;

$$C_c = \sqrt{\frac{2\pi^2 E}{F_y}}$$

If $Vmod/r_{yf} > C_c$ then use the following equation:

$$F_{af} = \frac{12\pi^2 E}{23\left(\frac{V_m/r_{yf}}{C_c}\right)^2}$$

where;

V_m = module length in vertical direction (in)
r_{yf} = radius of gyration of front chord in weak direction (in)
F_y = yield stress of steel (46ksi)
E = Young's Modulus (29,000 ksi)

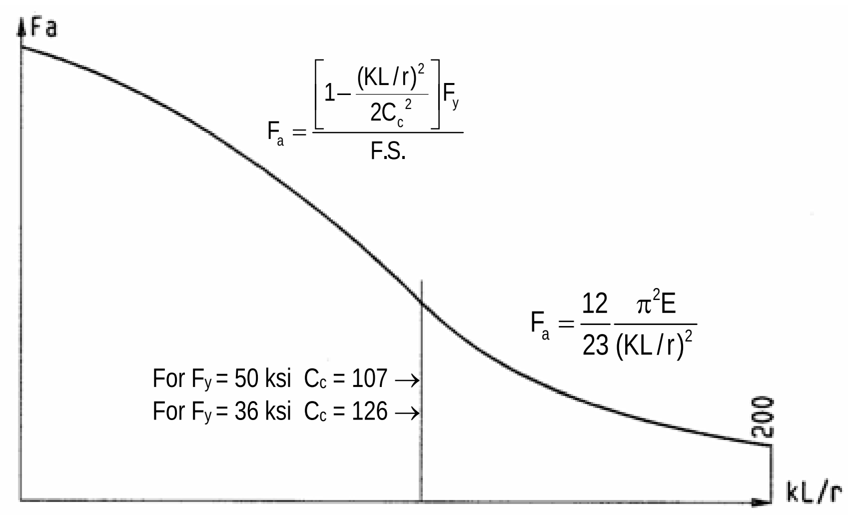


Figure 7.7 Buckling diagram (Schierle 2008, p.134).

2. compute d_b ;

Calculate moment;

$$M = w(12V_s)^2\ (2H_m)\ /\ 8\ (12{,}000)$$

Calculate depth;

$$d_b = \frac{M}{A_b F_{ab}}$$

where:

A_b = Area of back chord
F_{ab} = allowable capacity of back chord

Calculate allowable capacity of back chord;

$$F_{ab} = \left\{ \frac{F_y\left(1-0.5\left(\frac{V_m/r_{yb}}{C_c}\right)^2\right)}{\frac{5}{3}+\frac{3}{8}\left(\frac{V_m/r_{yb}}{C_c}\right)-\frac{1}{8}\left(\frac{V_m/r_{yb}}{C_c}\right)^3} \right. \quad \text{(AISC 1989, p.5-42)}$$

where:

$$C_c = \sqrt{\frac{2\pi^2 E}{F_y}}$$

If $V_m/r_{yb} > C_c$ then use the following equation:

$$F_{af} = \frac{12\pi^2 E}{23\left(\frac{V_m/r_{yb}}{C_c}\right)^2}$$

where;

V_m = module length in vertical direction (in)
r_{yb} = radius of gyration of back chord in weak direction (in)
F_y = yield stress of steel (46ksi)
E = Young's Modulus (29,000 ksi)

3. Compute depth based on deflection criteria:

The following equation calculates the approximate displacement of a truss system (Dehghanyar 2008, per. comm. Mar 12).

$$d_d = \frac{1.414}{\sqrt{\alpha_1 \alpha_2}}$$

where;

1.414 = compensation factor

$$\alpha_1 = \frac{A_f \ A_b}{A_f + A_b}$$

$$\alpha_2 = \frac{384 \ E}{5(\Delta_\rho H_s) \frac{W(12V_s)^3}{144{,}000}}$$

where;

Δ_ρ = deflection ratio (equal 175 for closed system façade structures)

H_s = total horizontal span (ft)

The method then uses the largest resulting value of d_f, d_b, or d_d as the system depth, and proceeds to provide the following output:

4. Calculate remaining output;

truss depth (in) = d

ratio span/depth = $12V_s / d$

Calculate horizontal reaction (kips);

$$R_h = \frac{w2H_m V_s}{2}$$

Calculate front chord stress ratio;

$$sr_f = \frac{M\beta/d}{A_f F_{af}}$$

Calculate back chord stress ratio;

$$sr_b = \frac{M/d}{A_b F_{ab}}$$

Calculate cable force (kips);

$$C = \frac{w'(12V_s) + (V_m - 2)\sqrt{d^2 + V^2}}{2dV_m}$$

where;

$$w' = \frac{2WH_m}{12{,}000}$$

Calculate deflection;

$$y = \frac{5W'(12V_s)^2}{384EI_e}$$

where;

$$I_e = \frac{I_{ef} + I_{eb} + A_f(d-k)^2 + A_b * k^2}{2}$$

$$k = \frac{A_f d}{A_f + A_b}$$

ratio span/deflection = $(12V_s)/y$

end calculation.

Testing of this simplified method in the form of sample calculations is documented in Chapter 10.

Analytical Method for Open Structures

The initial concept was to develop simplified parametric equations for analyzing all the various systems to provide a close approximation of true behavior. This was in fact the method employed on the closed systems (see above). This approach was problematic however, for the highly flexible open systems as identified in Table 6-2 that exhibit significant nonlinear behavior under load. As discussed throughout this thesis, these tension-based structures rely upon prestressing rather than geometric rigidity as the form determinate. Variations in stress distribution under live load conditions directly affect the form; unlike rigid structures, as the loads change the form of the structure changes. These changes are a function of the loads, the geometry of the structure, the material properties of the structural components (most particularly the stiffness), and the stiffness and geometry of the anchor points. (Barnes 1984, p.730)

First developed in the 1960's (Day 1965), dynamic relaxation is a solution method for structural analysis that has been refined and applied to the analysis of tension structures. The technique utilizes standard equations of elasticity in a force displacement method whereby the change in movement is measured in relation to an applied force. The method involves modeling a structure as a series of nodes interconnected by links. The method is an iterative process involving the application of fictitious mass to the nodes of a given structural model, exciting the model through the application of load, and kinetically dampening the oscillations through a series of small steps until a steady-state is achieved. The vector analysis eliminates the formation of an overall stiffness matrix, providing an efficient problem solution. The method is able to accommodate the kind of gross out of balance forces resulting from geometrical inaccuracies and stiffness differences that characterize tension structures. (Wakefield 1984, p.89)

It was initially considered that the use of such a method would be impractical as part of a simplified analysis tool. Dynamic relaxation tools are typically complex computer programs capable of accommodating a wide range of structural models and incorporating form-finding and pattern-making processes (as required for fabric membrane structures).

A dynamic relaxation program called DR was developed by Dr. Tejav Dehghanyar (ca. 1993) and used in the analysis of numerous tension structures since that time (T Dehghanyar 2008, pers. comm., 7 March). DR employs a unique method of applying pulses at key intervals as a means to dampen the oscillations and achieve convergence. The program efficiently and consistently achieves a steady-state; such convergence to a steady-state condition can be a problem with some dynamic relaxation techniques. With his involvement, the viability of adapting DR for use as a simplified analysis tool was explored. The patterning and form-finding components of the program were first removed.

A key opportunity for providing a simplified analysis tool is to reduce the necessary inputs into the system. This simplifies the input process for the user and reduces the demands on the analytical method. Instead of having to accommodate the infinite variations of a custom structure model, a parametric model can be defined and the analysis method simplified and fine-tuned to that model. Here, the requirement for an input model was eliminated entirely, and instead the user merely inputs dimensions for the basic parameters. The flat grid cable net discussed below, for example, solves only flat, rectangular grid two-way cable net structures. Double-curved cable nets will require a new parametric model tuned to the specific minimal input requirements of such a structure, with the analysis fine-tuned to those inputs. Employing this strategy, it was found that the analytical component of DR could be reduced to a very small core easily incorporated into a module of the Visual Basic Program. The strategy thus emerged to develop parametric models tuned to the different system types, and to build these into the StructureDesigner as modules that could be called by the program in response to user inputs.

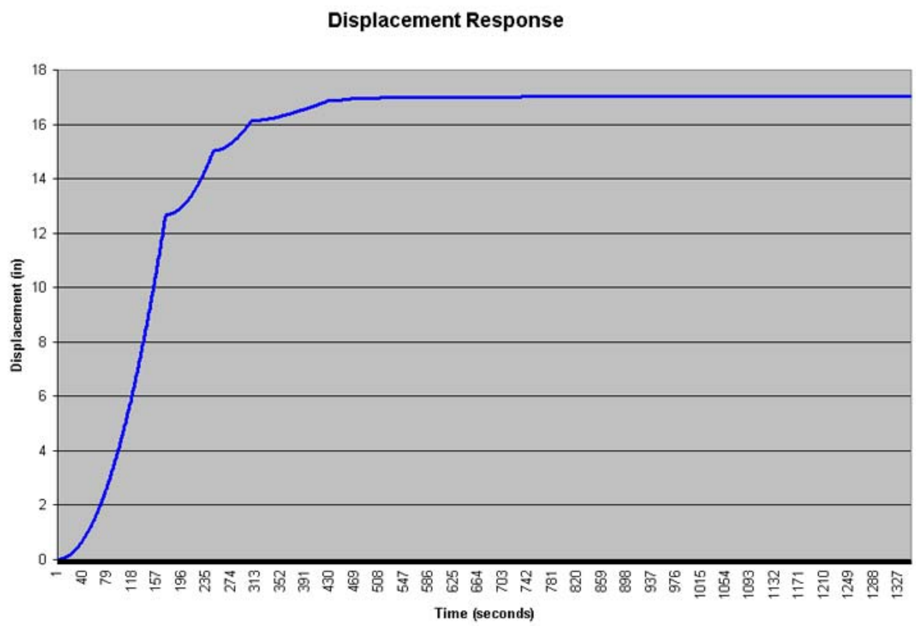


Figure 7.8 Dynamic relaxation displacement response graph.

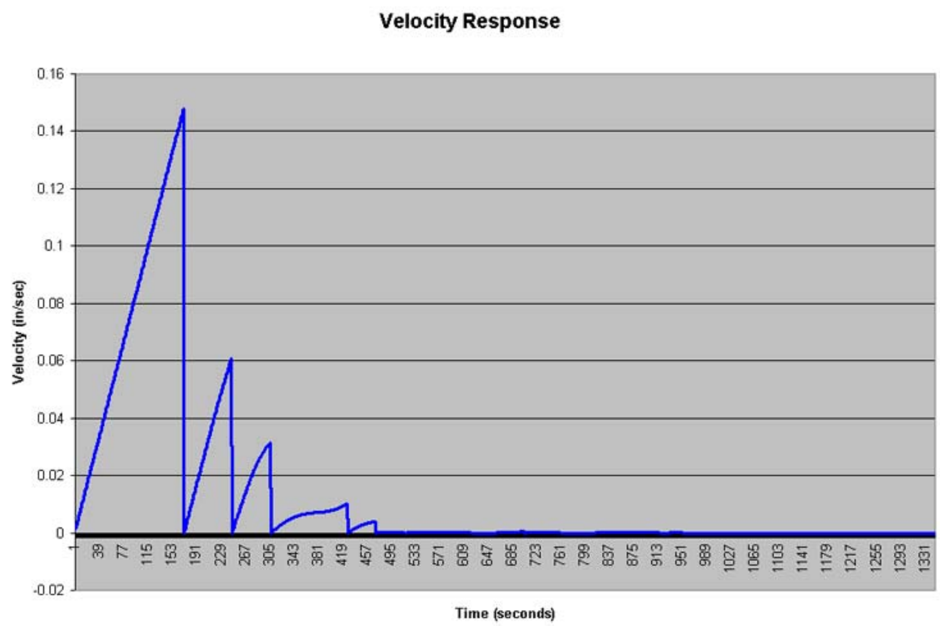


Figure 7.9 Dynamic relaxation velocity response graph.

The characteristic displacement response and corresponding velocity response are charted in Figure 7.8 and Figure 7.9 respectively. The dampening pulses are applied at peak velocity and zero velocity as indicated in the velocity response graph. The discontinuities in the displacement curve correspond to these pulses. Steady-state is achieved in the displacement response graph at 17.02 in (432.3mm), representing the peak displacement under lateral wind load in this analysis.

An interesting aspect of this approach is that an accurate problem solution is provided, not merely an approximation. Given the structural problem as defined by the various input constraints, analysis results match those of the full DR program, or any other dynamic relaxation program. The fundamental calculation method is identical. The limitation comes in the range of structural forms the system is capable of handling. In actual application, few façade structures are comprised of a uniform grid in an overall rectilinear configuration of a single vertical dimension and single horizontal dimension (although this tool could encourage such design simplification by providing for development of the façade design early in the building design process). The perimeter structure may step up or down resulting in different vertical spans. The grid module may change in response to changes in the building grid or for numerous other reasons. Regardless of geometric complexity, the common analytical approach is to model the façade in its entirety incorporating all variations of geometry, and to then analyze this model. Only thus can the behavioral variations resulting from the changing geometry be accurately accounted for. However, this is not required for the preliminary analysis in support of the conceptual design process. Instead, where a vertical dimension or grid change takes place in a façade for instance, the user can quickly and easily model each instance as a separate case. Thus, an approximation of the behavior of complex façade geometry is determined as a function of the exact behavior of similar but not identical structures.

Testing of this method is documented in Chapter 9.

The Systems

The following systems are conceived to be included in this prototype program, however at this time only two of the systems are operational. Customized calculation modules need to be developed for the unsupported systems. All of the systems require further testing.

Strongback: This system was felt to be a lesser priority and left to be completed as future work.

Simple Truss: As the base case in many of the comparative criteria and as the most generally flexible and economical of the systems, this was defined as a priority system. The approach was to define a fixed number of truss configurations comprised of varying member sections for the front and back truss chord members. The user is prompted to select the “system type” as an additional input to the analysis (Figure 7.10 below). Truss depth is an output of the analysis, along with span/depth, horizontal reactions, front chord ratio, back chord ratio, cable (bracing) force, deflection in inches and as L/d. If the truss configuration used is too light, the truss depth will be large and the user is prompted to try a heavier system. Filtering of the truss configuration input with respect to the other inputs could restrict the “system type” selections to those most likely to work.

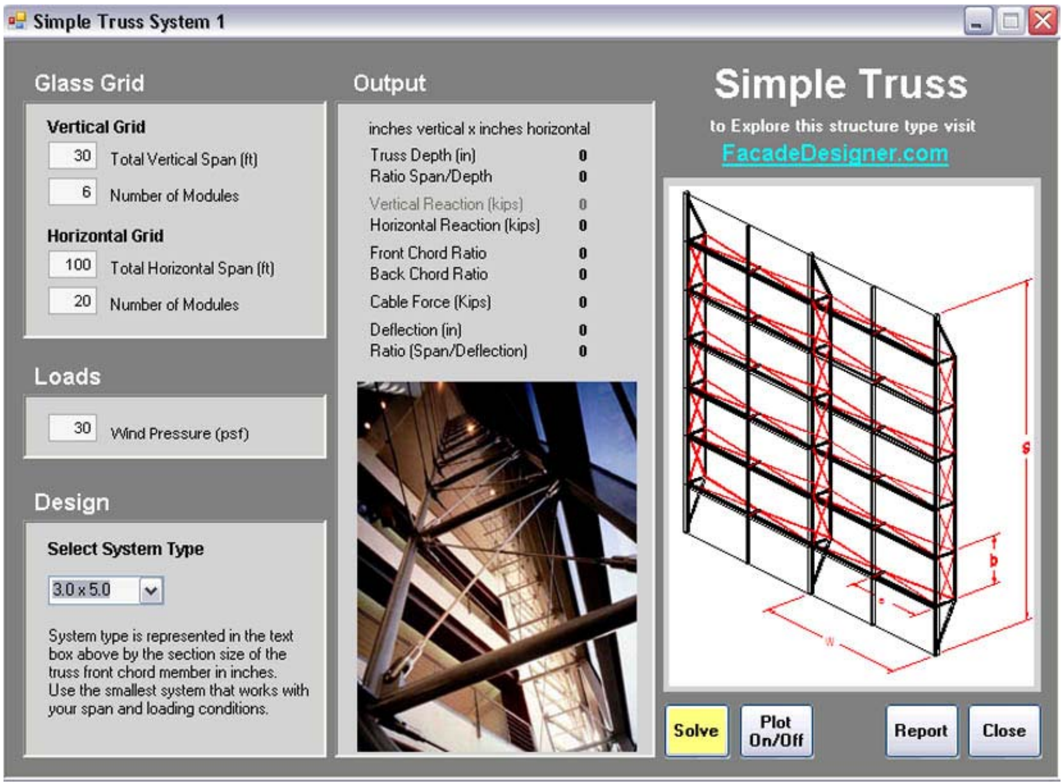


Figure 7.10 StructureDesigner simple truss analysis form.

Mast Truss: The mast truss is a lesser used system type and is left to be completed as future work.

Cable Truss: The cable truss is an interesting and effective structure type. A derivation of the DR program as described above is included in the StructureDesigner module but is not complete.

Glass Fin: There are special considerations for this system type because of the unique structural properties of glass, and was left to be completed as future work.

Grid Shell: The unique geometries of these structures will require some development and experimentation to assure a proper analysis technique. The opportunity of most interest here would be to incorporate the open structure gridshell systems stiffened by the integral cable net bracing. This would require a further adaptation of the modified DR analysis module, and is beyond the scope of this thesis and left for future work.

Cable Net: The flat configuration of this system type is operational in the prototype. The user is given the option of solving for cable force or cable pretension (Figure 7.11).

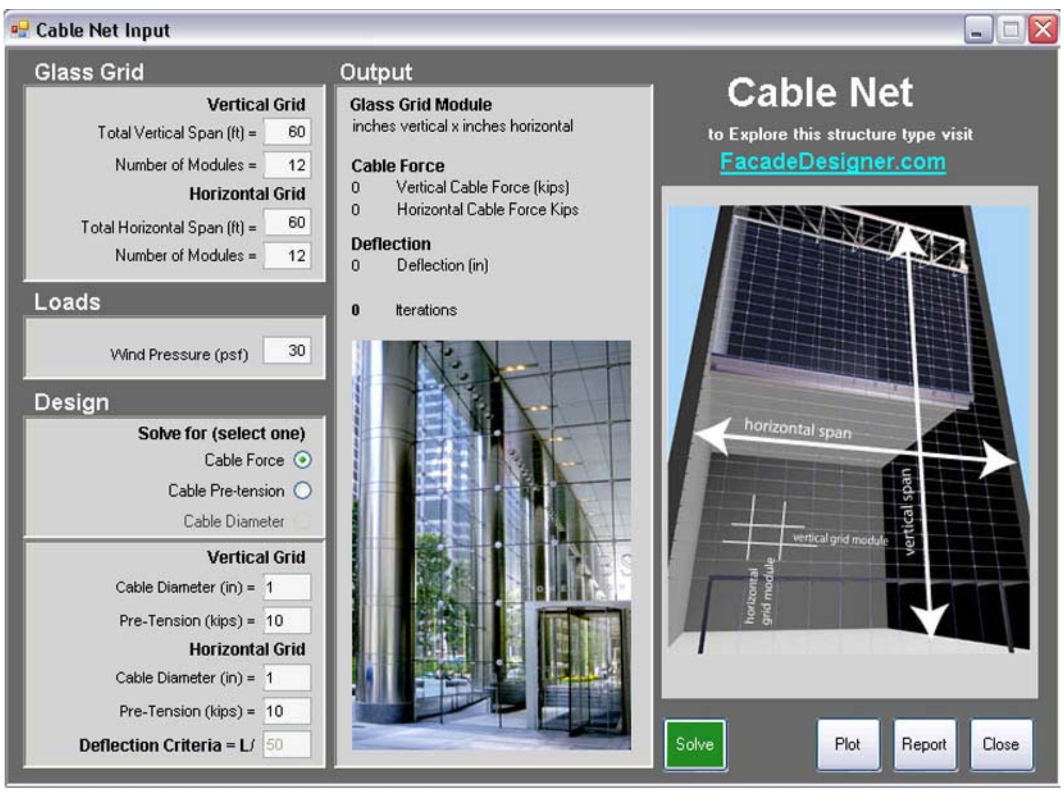


Figure 7.11 StructureDesigner cable net input screen.

Solving for cable force, the additional input variables to those provided through the FacadeDesigner front end (span, grid module, wind load) are cable diameter and pre-tension forces. The output is deflection in inches and as a ratio (L/d), and the maximum cable forces, which represent the reaction loads into the anchoring building structure.

Solving for cable pre-tension forces, the input variables are cable diameter and deflection criteria (L/d). The output is pre-tension cable forces, deflection in inches and maximum cable forces.

Double-curved cable nets will require the additional input of sag as a function of cable curvature. Form-finding will have to be reintroduced to the modified DR module as described above, and the analysis tuned to the new parameters. This will require some significant effort and is left for future work.

Other Structure Types: Chapter 6 discusses structure types not included here such as space frames and tensegrity structures. These may be considered for future work, but there application is currently very limited. There may be some interesting future potential for tensegrity structures; the form-finding and analysis is challenging, but has been the focus of much attention in the engineering community.

7.4.2 GlassDesigner

The GlassDesigner module is intended to provide preliminary analysis of the glass panel to determine deflection and required thickness. The basic calculations required for this are relatively simple. Integrating the user interface into FacadeDesigner.com would be the interesting challenge. The basic structure of the website and modular organization provide a number of opportunities to facilitate this work.

This module is not completed as part of this thesis. Its inclusion in the process mapped in Figure 7.1 is primarily one of convenience; many glass suppliers have online tools available that will calculate preliminary glass thickness (hyperlinks will be included from FacadeDesigner to these Web resources), and relatively inexpensive software programs are also available to facilitate this work. It would however, be of value to have this module integrated into the façade design process.

7.4.3 DetailDesigner

The DetailDesigner module is the sister component to the DetailExplorer discussed previously. DetailExplorer would provide general information related to the available options and a comparative analysis drawn from the related work in Chapter 6. DetailDesigner would potentially draw on the thesis cited earlier (Cheng 2007) to provide a design development guideline or methodology for detailing point-fixed glass system components.

7.4.4 FaçadeDesigner

The FacadeDesigner module is intended as an overall design guide essentially embodying the process mapped in Figure 7.1. The process incorporates 7-steps, and is linked to the other supporting modules as appropriate. The 7-steps follow.

7.4.4.1 Step 1: Glass Fixing System Selection

The user selects a glass fixing system (Figure 7.12). If the user is unsure what system they want to use, they are provided with a link to the appropriate section of the GlassExplorer module.

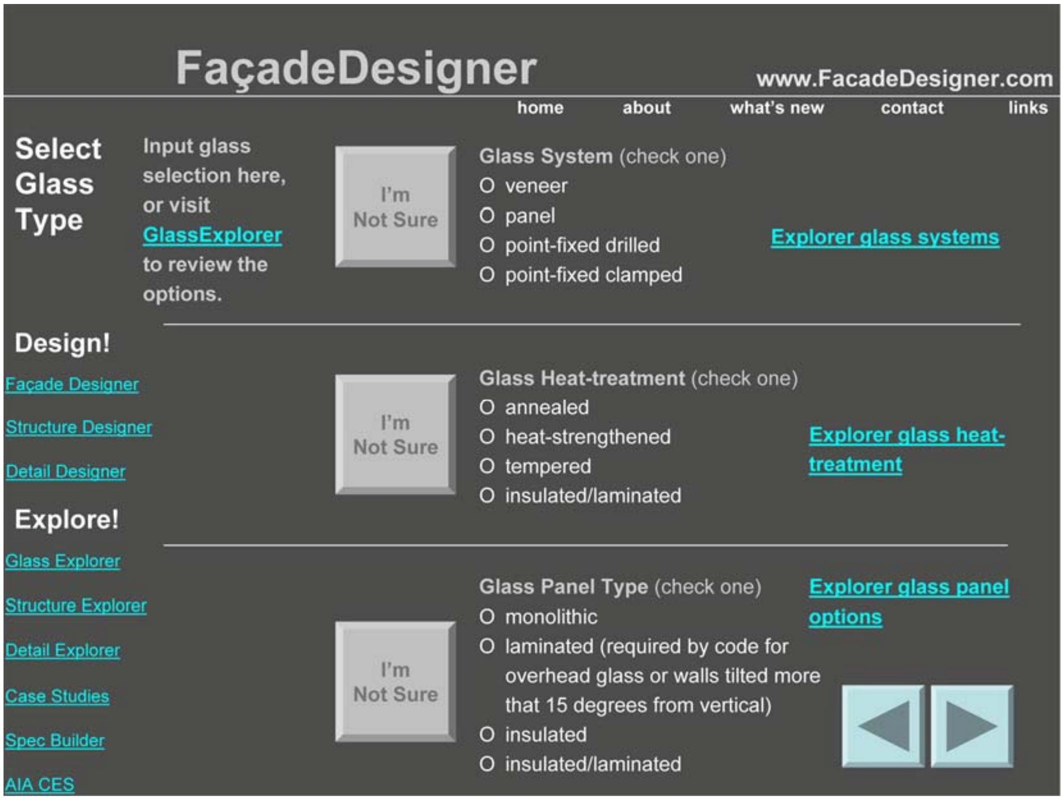


Figure 7.12 FacadeDesigner: select glass makeup.

7.4.4.2 Step 2: Glass Makeup

Glass panel selection is next made as indicated in Figure 7.12 and includes considerations of panel type and heat-treatment. These considerations are relevant to the development of a structural glass façade because these parameters will dictate maximum glass panel size, which may be a factor in the glass grid development (below).

Links are provided to supporting Explorer modules if the user is unfamiliar with the selection options. The categorization, evaluation criteria, comparative analysis and other consideration selections are included in Chapter sections 6.2 – 6.4, and represent the material included in the website.

Considerations relevant to the thermal, acoustical, and other performance aspects of the glass are not considered here as they are not critical items in the structural development of the façade. The system could be expanded to incorporate these important considerations and there would be considerable value in doing so.

7.4.4.3 Step 3: Glass Grid Module

Determination

Definition of the glass grid (or glazing grid) module is a key step in the conceptual design process. The development of the module can be simple or complex depending upon the façade program. Ultimately the designer will develop the grid in elevation drawings. The opportunity exists in a new façade program for the designer to develop a simplified grid as a function of overall vertical and horizontal façade dimensions and to develop the building design around this glass grid. Regardless of grid complexity or variations, a standardized approximation will be used for the preliminary structural analysis provided by the StructureDesigner module as represented in step 5. Wind load is also an input in step 3 that will be used by the StructureDesigner to analyze the structures.

The glass grid is input in this step as represented in Figure 7.13. A link is provided in the program to a section in the GlassExplorer module presenting considerations and strategies in developing the glass grid.

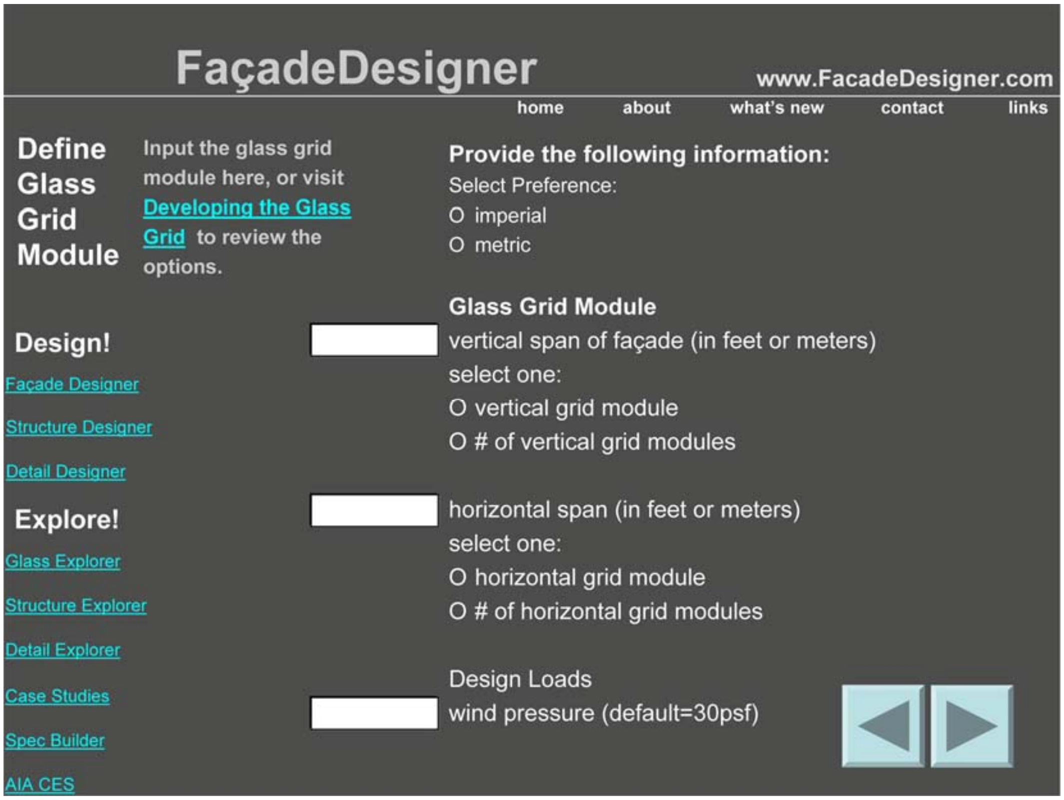


Figure 7.13 FacadeDesigner: glass grid input.

Methods

Depending on the façade program, the grid module can be determined by one of two basic methods.

If global façade dimensions are know, the grid can be generated by dividing the vertical dimension into a number of equal segments, and the horizontal dimension into a number of equal segments. This is the most typical approach.

Alternately, if addressed early enough in the design process, the global façade dimensions can be generated as a multiple of the glazing grid. This method is used when the glass grid is to match a predefined building grid or when the designer wants to use a particular size of glass.

The resulting grid module dimensions need to be checked against maximum available panel sizes and overall panel area limitations.

Example: A 60 ft (18.3m) span divided into 12 equal segments would yield a grid module in one direction of 5 ft (1.52m). A square façade in elevation would yield a 5 ft (1.52m) square grid, well within the size limitations for any glass makeup.

The program provides the user the following options in solving for the glass grid.

Figure 7.14 is a schematic representation of the basic grid dimensions:

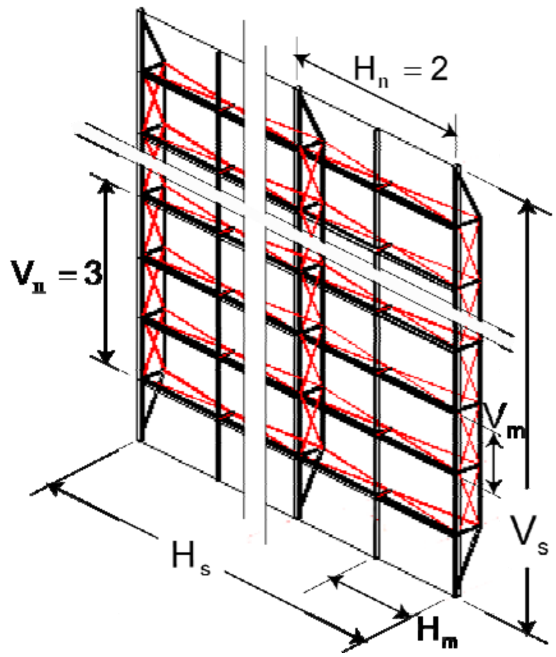


Figure 7.14 Illustration of grid dimension variables.

H_s = full horizontal span of façade

H_m = horizontal grid module

V_s = full vertical span of façade

V_m = vertical grid module

If the user knows the overall horizontal and vertical spans, they can solve for the grid module by subdividing the span by an integer representing the number of grid increments until a suitable dimension is reached:

$H_m = H_s / H_n$

$V_m = V_s / V_n$

Or, if the user knows the grid module and the façade span is not fixed, then they can multiply the grid module by an integer representing the number of grid increments:

$H_s = H_m * H_n$

$V_s = V_m * V_n$

where:

H_n = number of horizontal modules

V_n = number of vertical modules

H_n and V_n are integers

Considerations of and Influences on the Glass Grid

The building grid: The overall building grid is often a determinant of the glass grid, especially with respect to the horizontal grid module. The building grid is not always uniform however, and this may cause variations in the glass grid. This adds somewhat to the complexity of the system, but can certainly be accommodated. The different grids will be analyzed as separate structures when using the StructureDesigner as discussed following.

As the structures are typically free-spanning vertically and do not abut floor slabs, the vertical module is sometimes more flexible. However, the designer sometimes wants the grids at the interface area to align, which can impose a restriction on the vertical module. Other factors unique to the application can also impact glass grid decisions.

Glass grid aesthetics: Another consideration is appearance and the desired aesthetic affect. The glass grid is generally square of rectangular. Sometimes there is a preference to the orientation of the grid, with rectangles arranged either horizontally or vertically. Both grid dimensions can impact the performance of the supporting structure. Primary structural elements such as trusses or cables are typically located at each vertical gridline, so the determination of the horizontal grid dimension will dictate truss spacing, and thus the tributary area of load acting on that member. The vertical module can have similar implications.

Figure 7.15 shows a strong horizontal grid reflecting the relatively short vertical span and long horizontal dimension of this glass wall. Note the widely spaced trusses at each vertical gridline. The glass here is IGU point-fixed drilled. The horizontal glass dimension was too long in this case to span unsupported, and an intermediate support had to be provided at mid-span (Figure 7.16).

Figure 7.15 Example of horizontal glass grid.

Figure 7.16 Mid-span connection of long horizontal IGU.

Figure 7.17 and

show a vertically oriented glass grid with a veneer system and insulated glass fully perimeter supported. Note the horizontal bands created by an alternating shallow horizontal grid module accented by the horizontal capture plates. The trusses in this design fall on each vertical grid module. Note that this is not a uniform grid module, and would thus not be supported by the StructureDesigner analysis tool. The recommended simplified method would be to analyze a uniform larger glass grid with the vertical dimension equal to the vertical dimension of the larger glass pane plus the vertical dimension of the smaller glass pane. This would provide a conservative result appropriate to the conceptual design process.

Figure 7.17 Vertically oriented glass grid with truss at each gridline.

Figure 7.18 Example of vertical glass grid with horizontal module providing visual accent.

Maximum glass size: The maximum allowable, or in many cases the more appropriate term might be practical, glass size is influenced by several factors that are discussed elsewhere herein. Insulated glass in frameless applications may be limited in size by the allowable deflections in a single pane under design loading. Heat-treatment may limit glass size as a function of the producer's tempering furnace; most producers stipulate a maximum width and length for their heat-treated glass. There may also be a limit to the total area of some glass panel types as a function of the weight of the unit. Laminating processes also vary in the maximum width of glass panel they can produce, at the maximum range limited by the width of the interlayer material. Refer to Section 2.4.2.10 for more information.

7.4.4.4 Step 4: Structural System Selection

Supported System Types

Figure 7.19 provides for selection of the structural system type, indicating those that are intended to be supported in the FaçadeDesigner system. The user selects a system type by clicking on one of the system icons or the link directly below. An option is given to exit to the StructureExplorer module to research the options. Once a structure type link is clicked, the user is redirected to the appropriate area of StructureDesigner, with the input screen preconfigured with the information drawn from FacadeDesigner. See Figure 7.11 as an example.

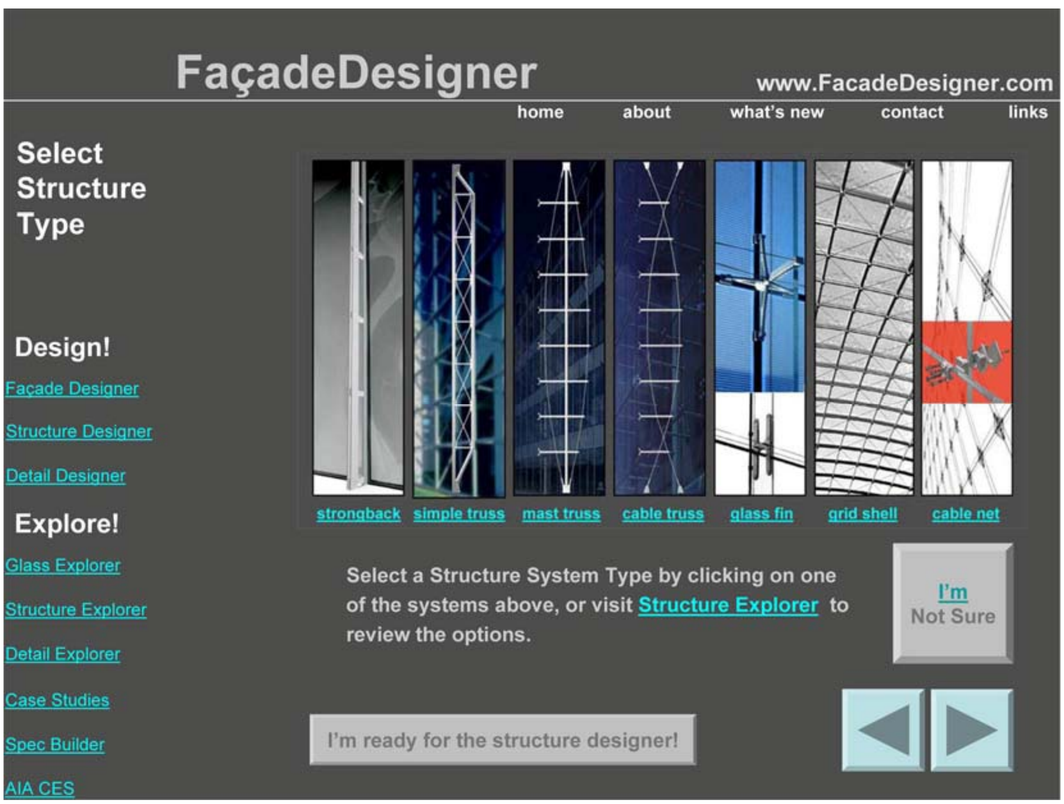


Figure 7.19 FacadeDesigner: select structure type.

FaçadeDesigner is thus linked to StructureDesigner; however, StructureDesigner can be accessed directly without having to go through the FacadeDesigner process. If the user is familiar with the program and simply interested in developing some comparative preliminary performance analysis between systems, simple input data can be quickly entered through this direct method. (See StructureDesigner user interface forms in Figure 7.10 and Figure 7.11 above.)

While the systems included in Figure 7.19 are intended to be fully supported by both FacadeDesigner and StructureDesigner, only two systems are supported in the current beta version; simple truss, cable truss, and flat cable net.

7.4.4.5 Step 5: Simplified Analysis Using StructureDesigner

The input information collected by FaçadeDesigner is fed to StructureDesigner, which presents a user-interface form (see examples Figure 7.10and Figure 7.11) as a function of the system selection. Depending on the system selection, the user may be prompted for some additional input as indicated in Section 7.4.1 above. The user initiates the analysis by clicking on a button, and is provided with virtually instant results depending upon the system (the iterative dynamic relaxation method used on the open systems may take as much as a minute or two depending on the solution option selected and the deflection criterion). Depending on the results of the analysis, the user can modify the inputs from the user-interface and initiate a new analysis, repeating the process until a satisfactory solution is determined. Alternately, the user can close the analysis form, whereby the system-type selection form is presented, providing the opportunity to analyze a different system type. (Refer to the discussion of the various analysis forms in 7.4.1 above.)

7.4.4.6 Step 6: Estimating and Design Development

Figure 7.20 represents the various output from the process. The output is intended to support further design development, the estimating process, and the preparation of a performance-based design/build bid package as discussed in Chapter 3. It is conceivable to develop an estimating template for each façade system type to facilitate the estimating process by the design team as part of future work.

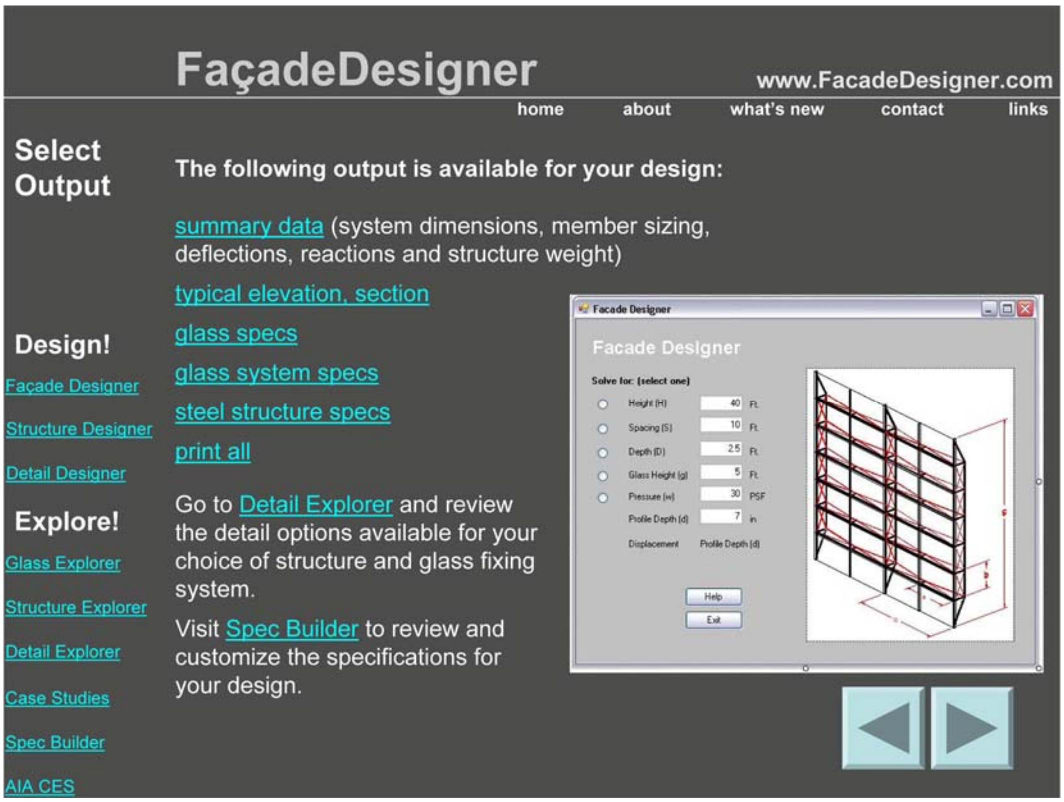


Figure 7.20 FacadeDesigner: select output.

7.4.4.7 Step 7: Design/Build Bid Documents

The final step in the process is the preparation and assembly of design/build bid documents as discussed in Chapter 3.3.2. If the façade system is designed around one of the basic systems included in the FacadeDesigner, the designer will be directed to typical plans, elevations, sections and details. These should provide a useful reference for the designer in adapting these same materials to the specific project needs.

The designer will also be directed to relevant specification information as a result of the glass and structure inputs made in FaçadeDesigner. Sample specifications in standard CSI (Construction Specifications Institute) format would allow for the designer to mix and match according to the project requirements. SpecBuilder is conceived as an expert system capable of automating the assembly of a project specification based on user responses to a series of questions. The information gathered in FaçadeDesigner could be passed to this system as initial input.

7.5 Designing for Simplicity

One of the less apparent potential benefits of the design strategy suggested by the methodology in Figure 7.1 is the opportunity for the architect to design the building and the building interface in a manner that anticipates and accommodates the façade requirements. With the intent of using structural glass façade technology but without early involvement from a specialist consultant, designers often simply leave a "hole" in the design where the façade goes and continue on with the design of the building. A specialty consultant or design/build firm is then later brought in to provide this service. This often leads to unnecessary complexities when the façade system is designed to "fill the hole."

The opportunity here is for more of a "product" approach to the façade system, not in a manner that limits the design, but in the sense that properties of the system defined early in the process can be easily accommodated in the building design. In fact, this is an effective way to manage considerable design complexity while mitigating the associated cost. With a typical standardized window product, the designer just needs to know basic information, like the size and construction of the required opening, to facilitate the installation of the window.

This allows the architect and the building owner to take advantage of the efficiencies of mass production and the economies of scale. There is the potential for a similar advantage with structural glass facades. The biggest opportunity is with the glass grid; to the extent that the glass grid can be made uniform, overall cost will be reduced, sometimes quite significantly. The objective is to minimize geometric complexity that is not integral to the design intent, and thus reduce incidental part differentiation. A large diversity of small quantity components increases complexity, which in turn increases cost. This phenomenon has both overt and subtle aspects; a grid design that generates a large number of one-of-a-kind glass sizes because of a geometrically complex interface will add to the cost of the glass supply, but it will also impact design and installation costs, perhaps more significantly. Automated fabrication processes can do much to mitigate the cost of high component diversity. Design processes can similarly be developed to mitigate design related costs. But this diversity must still be managed, handled, shipped and sorted through the process until each one-off component finds its designated place in the building. The resulting field costs are especially difficult to mitigate.

A reflection of the relevance of this is found in a comment made by Wigginton on Foster's Willis Faber & Dumas Building, a project cited repeatedly in this thesis and in fact representing the birth of structural glass façade technology as defined herein. Wigginton (1996, p.110-115) provides an excellent case study of this suspended glass façade and comments, "…the rigour [*sic*] of the architects required that each panel was the same size, which is something of a challenge in a meandering glass wall without the benefit of cover strips." Even double-curved cable nets, whose geometry will assure a high diversity of glass panel configurations, can benefit from a design emphasis on exploring ways to minimize the occurrence unnecessary component diversity. The diversity is sometimes important to the design and the client is willing to pay for it. Many times however, the complexity is inadvertent and unnecessary, and easily avoidable through the exercise of good problem-solving design process.

Another opportunity lies in understanding the support requirements for the structure; how the trusses or structural components will attach to the anchoring structure, what Cheng (2007, p. 111) refers to in her thesis work as building infrastructure. There will also be important details at the interface of the glass plane at the perimeter. Understanding the underlying technique by which these things are most easily accomplished allows the architect to design the building in informed anticipation of these façade requirements.

Many times, because this kind of information is not available to the design team early in the process, the design of the façade ultimately takes on the nature of a renovation where a new façade design is being constrained by the existing building because so many design commitments have been made by the time the façade design starts. Many accommodations that could have facilitated the façade design, and could easily been made with little or no impact to the building design or cost, were missed resulting in added complexity and cost to the façade.

Structural glass facades are far from being standardized window products. Yet the tools, resources, and perhaps most of all, methods suggested herein could provide the benefit of enabling the architect to best design for the requirements of the façade system, thus simplifying the resulting design and making it not only easier to implement, but reducing the cost.

Chapter 8 - A Learning Program

The FacadeDesigner.com website resource is conceived as a resource incorporating a variety of tutorials and learning programs related to structural glass façade technology, including the structure systems, glass systems, and the primary materials and processes that comprise the technology. A variety of formats are possible to explore, including online video, interactive programs, and downloadable files. As intended, a secondary effect of this thesis is the generation of significant content appropriate for inclusion in a variety of learning programs. One prototype program was developed in support of this thesis as follows.

8.1 Exposed Structural Systems and Long-span Glass Facades

The AIA/CES program is discussed in Chapter 4. It is the continuing education program for the American Institute of Architects. *Exposed Structural Systems and Long-span Glass Facades* is a learning program developed in accordance with the AIA/CES guidelines for adult learning programs reviewed in Chapter 4.

The program is intended as a broad introduction to structural glass façade technology. It covers in broad strokes; glass, glass panels, glass systems, and the structure types that make up the support technology. It is conceived as the focal element of a 60 to 90-minute live interactive presentation by a qualified presenter knowledgeable in the field of structural glass façade technology. The program is developed in Microsoft Powerpoint. The primary audience is design architects. Most architectural firms have a continuing education program in which industry providers of AIA/CES programs are invited in on some regular basis. This most often takes the form of a luncheon presentation typically limited to a 60 to 90-minute maximum timeframe. However, the Exposed Structural Systems program is also well suited for architecture students.

A further intent is that this learning program be made available as a website resource from FacadeDesigner.com. The program, and others like it, will be resident on the website as Adobe Acrobat (*.pdf) files. They will download to the user's computer where they will function as a self-paced tutorial. The precedent for this is the *Structures* website (Schierle, n.d.) discussed in Chapter 4.5.4. Professor Schierle's Powerpoint lectures are located on the website in this same format. The lectures are structured to take maximum advantage of this online access as a review method for the students. It is the personal experience of the author that there is significant value in this approach. The value of the online programs to individuals having never received the original lectures is less clear, but through a development and testing program it is a viable consideration that an effective series of tutorials could be developed. While not testing this aspect directly, the testing program outlined in Chapter 10 seems to support this contention.

8.1.1 Program Elements

Select images are included below only as necessary to present the organization of the program and to indicate the elements required for compliance with the AIA/CES program. The program content was derived directly from the material developed for this thesis.

Note: This program has NOT been submitted to the AIA for approval. It is a prototype program developed for testing purposes only. It is believed that this program complies with all AIA/CES requirements and guidelines. The AIA/CES program approves providers of AIA learning programs, and does not approve programs independent of providers. Prospective providers must be practitioners or industry firms, and are required to pay a fee ranging from approximately USD 500 to over USD 3,000 to become an approved provider.

All references to the AIA/CES within the following program are intended only as examples of content preparation in compliance with AIA/CES guidelines. No representation is intended that the author or this learning program as presented here have been submitted or approved in any manner by the AIA/CES. The program may be submitted by an appropriate entity to the AIA/CES at a future date.

8.1.2 Example Content

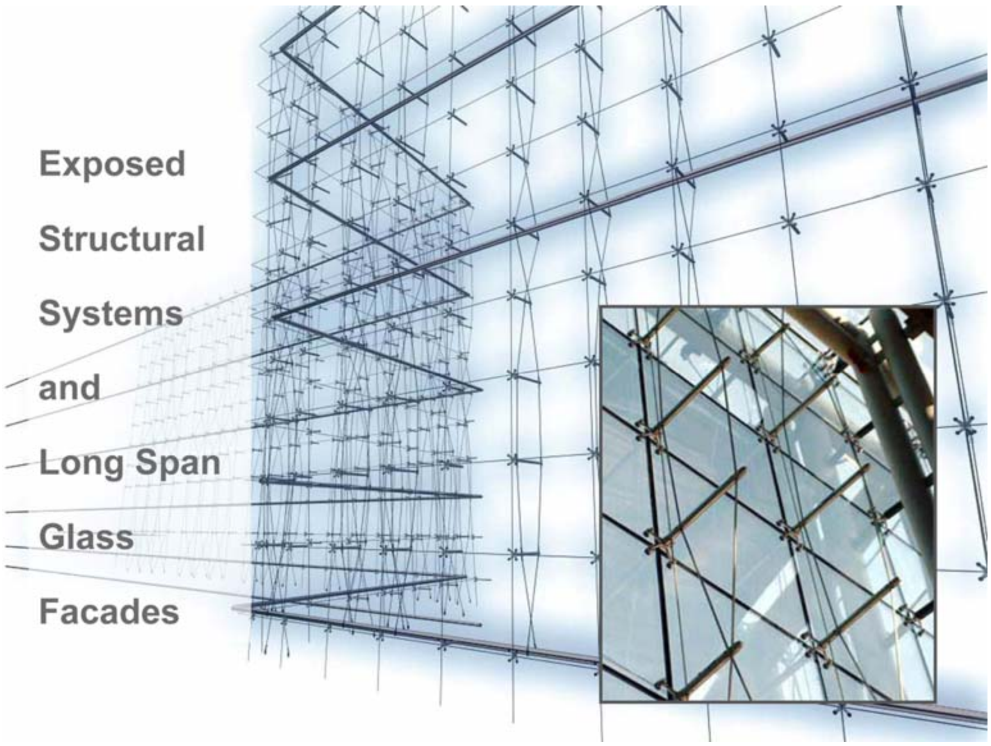


Figure 8.1 Title page.

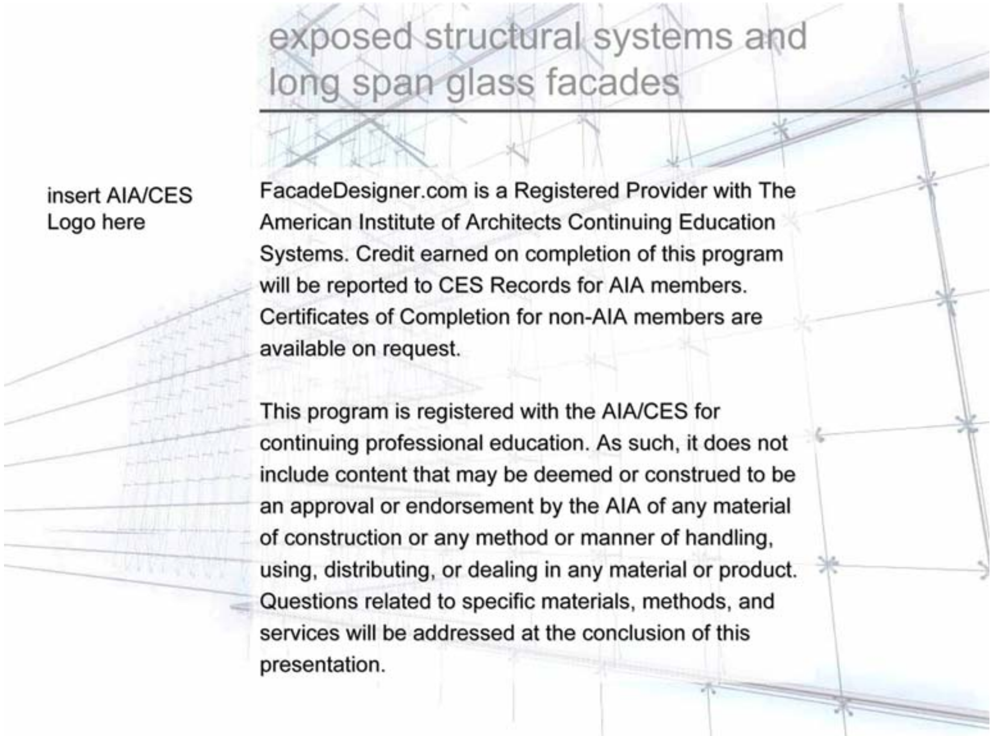


Figure 8.2 Introductory page required by the AIA/CES for each program.

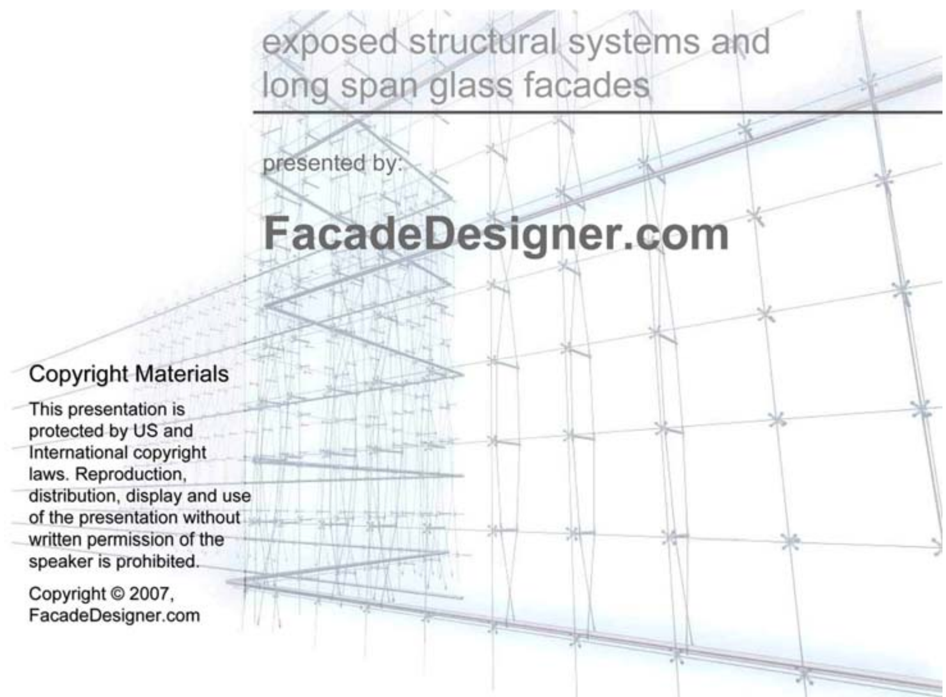


Figure 8.3 Optional page suggested by AIA/CES to protect copyrighted information.

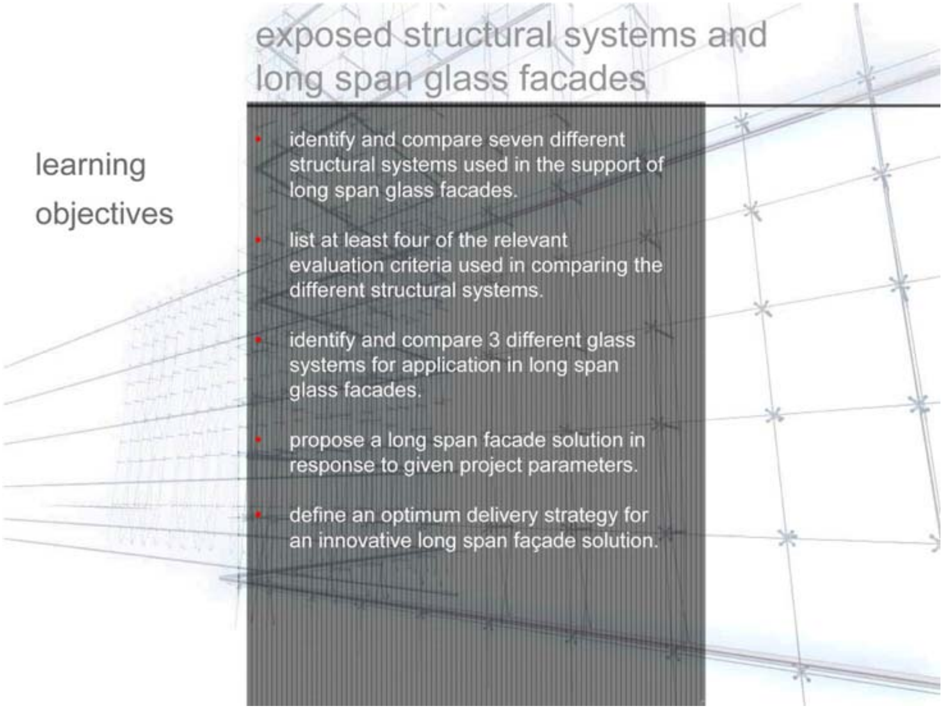


Figure 8.4 Learning objectives required by AIA,CES.

The development of learning objectives is a primary means by which the AIA/CES evaluates the programs submitted by the providers for approval. The AIA/CES has issued guidelines for the development of learning objectives as discussed in Chapter 4.

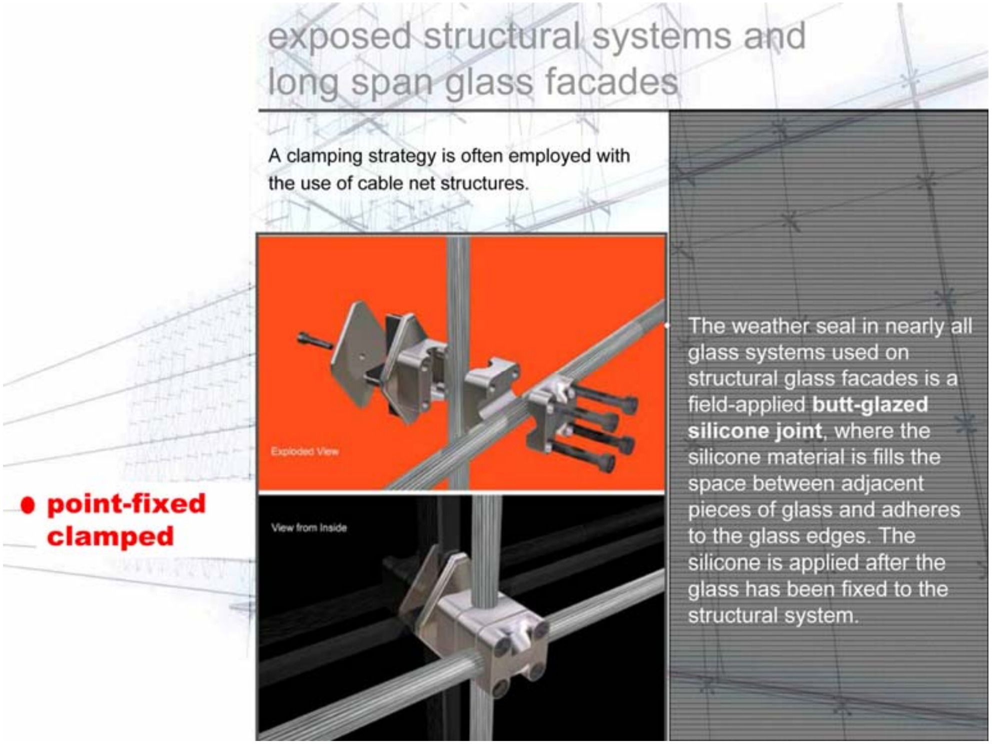


Figure 8.5 Glass system types are introduced.

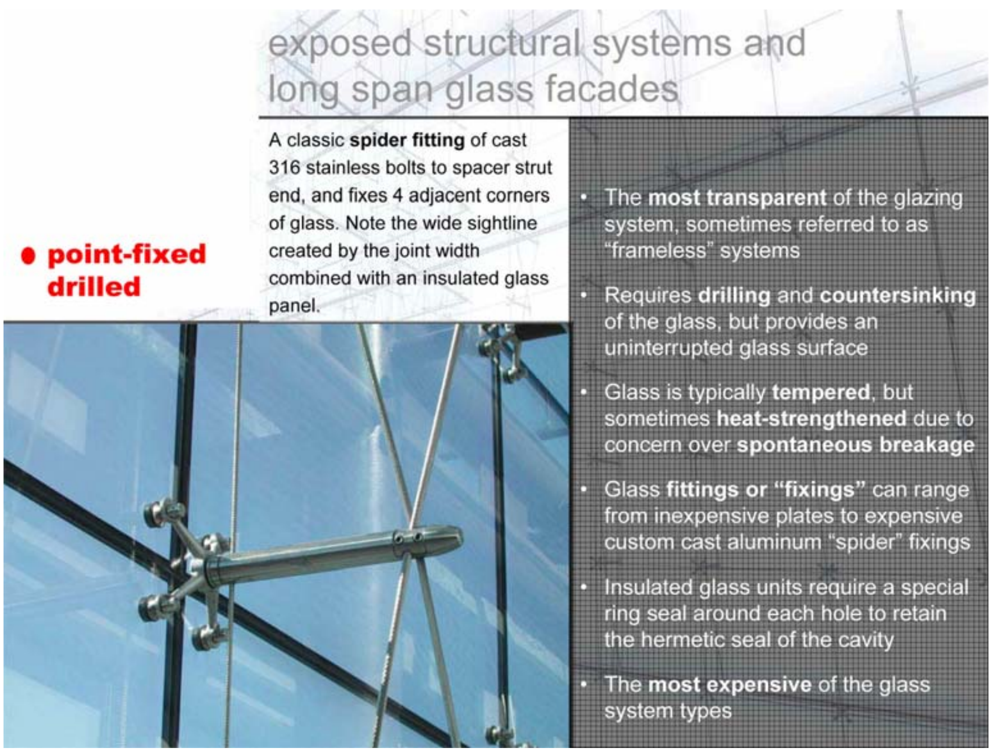


Figure 8.6 Attributes of point-fixed systems.

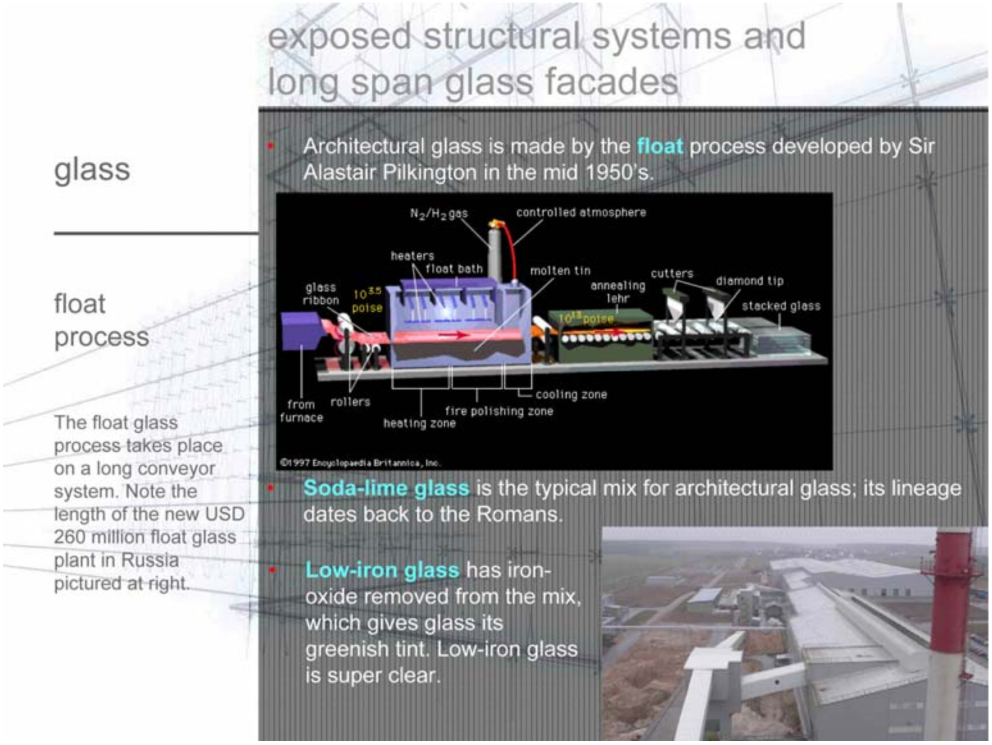


Figure 8.7 Glass and the glass manufacturing process.

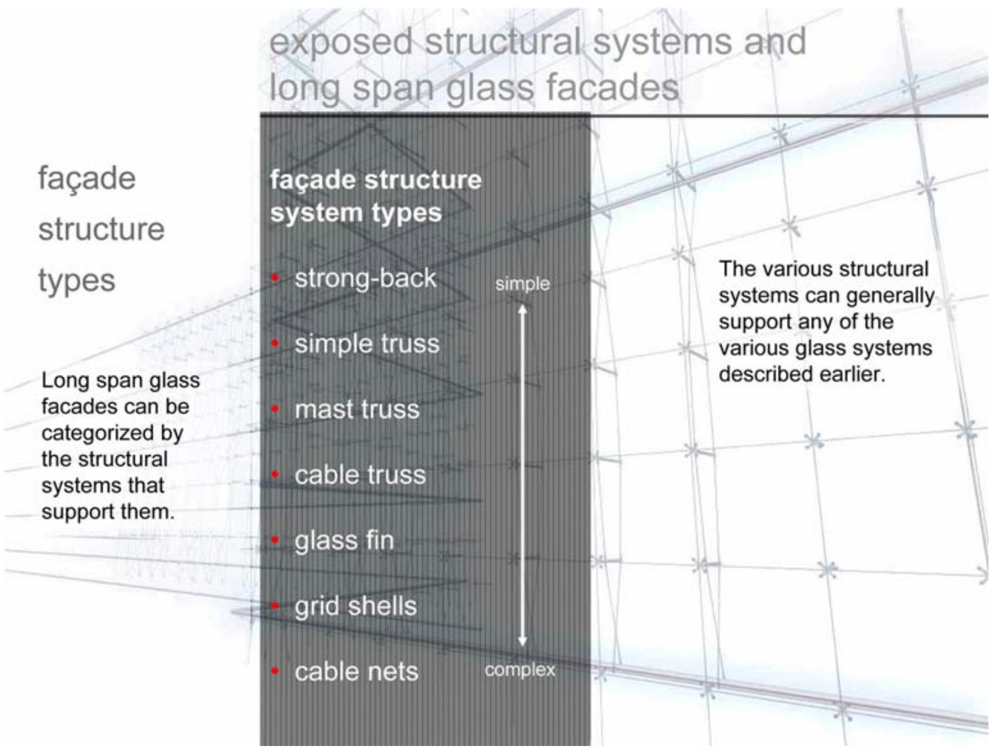


Figure 8.8 Introduction of structural systems.

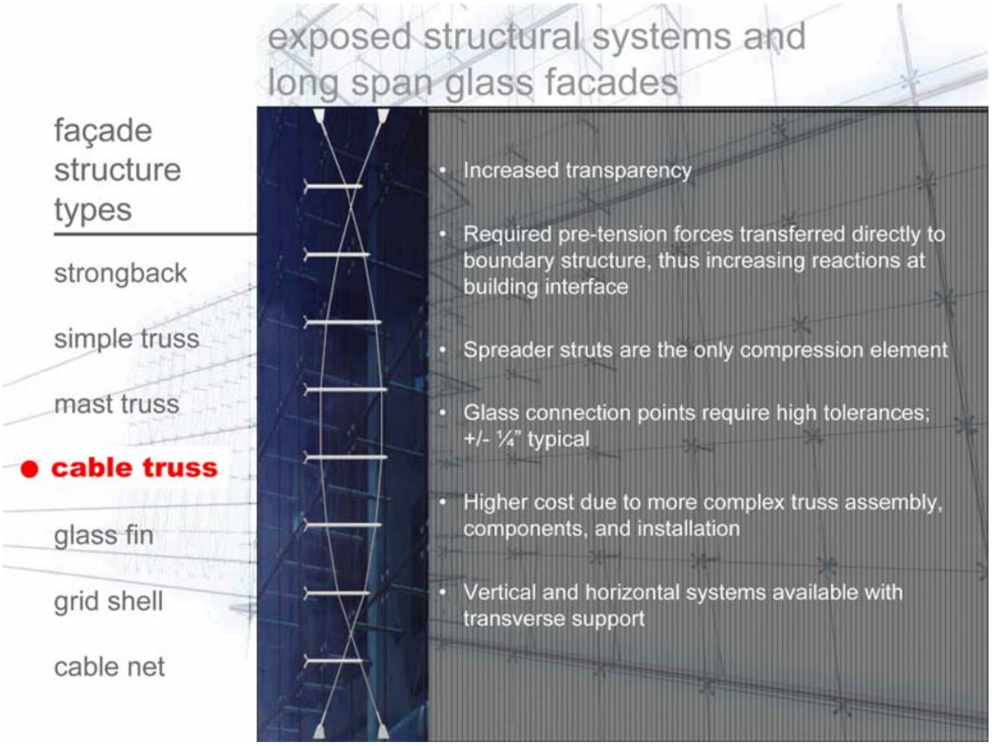


Figure 8.9 Each system type is presented with primary system attributes.

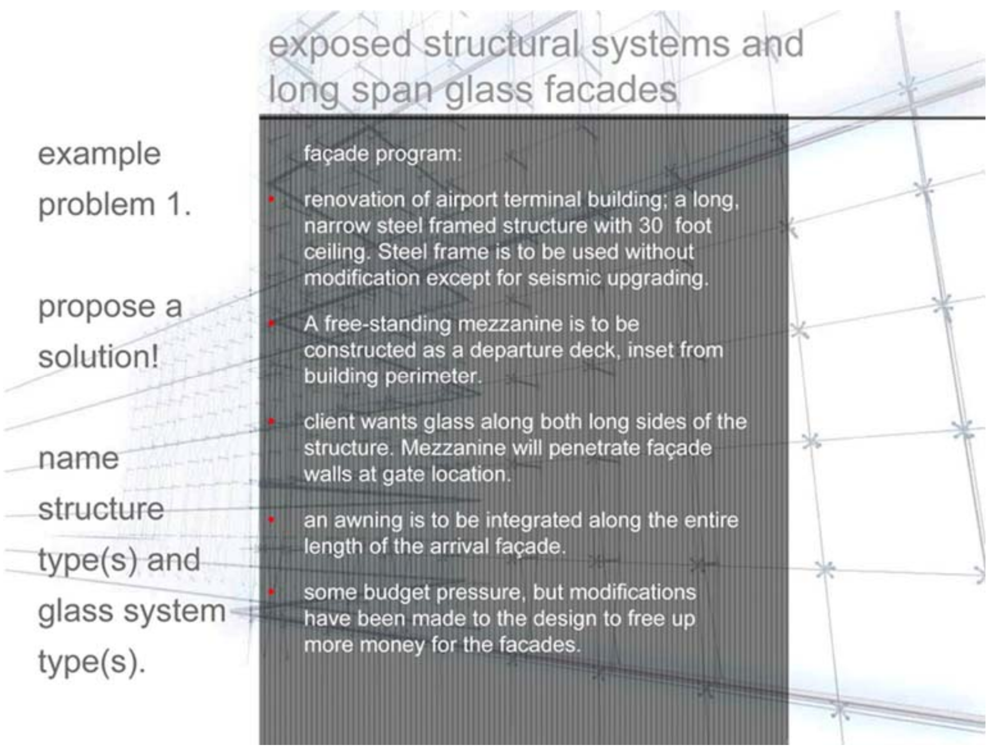


Figure 8.10 Sample problem as interactive content.

Figure 8.11 Required ending slide.

A primary intent of the AIA/CES program is the prevention of blatant self-promotion by the providers. Consequently, providers are instructed to only include company logo, name and contact information on specific introductory pages and this ending page.

8.1.3 Program Evaluation

This program was presented with the AIA/CES references omitted on three separate occasions for testing purposes, as further discussed in Chapter 10.

The first occasion was to a group of executives representing a leading curtain wall firm. No written testing accompanied this presentation. The program was well received with positive and no negative comment. The general consensus was that there would be value in presenting the program to select architectural firms, with the probable result of new project creation. This was evidenced by the subsequent expressed intention by the Firm to make application to the AIA/CES to become a program provider, and to submit a variation of the program presented as their first program for approval.

The second presentation was to the thesis class in the Master of Building Science program at the University of Southern California, of which the author is a participant. This presentation was accompanied by testing as documented in the following chapter.

The third presentation was to a 3rd-year architectural studio class at USC. This presentation was also accompanied by testing documented in the following chapter, along with summary results and conclusions derived from the testing.

The author has the following comments on the presentation itself, independent of the testing results

The program is too long to deliver in a 60-minute timeframe without rushing. The presentation includes 85 slides, and while many of these are primarily images that can be moved through quickly, there are still too many content slides. The content is probably too broad to realistically present in a single program. Ideally, at least two programs could be developed for separate applications, one for glass and glass systems, and the other for structure systems. Each program would still have to be contextualized with inclusion of some of the related content from the other presentation, so there would be some significant overlap between the programs. Content is certainly not the problem; it would be easy to develop a 60-minute program for each of the topics of glass, glass panel fabrications, glass fixing systems, and structural systems, and perhaps this should be considered.

However, a program that integrates the various considerations that comprise structural glass façade technology is undoubtedly of the most general use, and an effort should be made to further refine the current program to improve its efficiency.

The AIA/CES strongly recommends interactive content as opposed to a pure lecture format. The sample problems are included for this purpose as indicated in Figure 8.10 above. The intent is that the information presented in the program be applied to some conceptual design problems. The problems are presented in a purely descriptive manner. It would be far better to develop some simple graphics to communicate the problems. The more difficult issue is time. The program is already pushing a 60-minute timeframe with virtually no time for questions. The inclusion of these problems could easily add 15 to 30 minutes to the program length. In fact, in the three instances of presentation, not once was there adequate time remaining to even consider a superficial presentation of these problems. A better venue for this program would definitely be a 2-hour combination lecture workshop. Such a program is definitely worth doing, although it has less functionality than a more streamlined program.

The presentation is good at getting the viewers excited about the technology. The material in the presentation is so dense and delivered in such a concentrated timeframe, that any significant retention of the information is questionable. A good question is just how important retention is. The objective is to get the designers motivated to use the technology in their projects. Perhaps the most important function of the presentation is an introduction of the broad issues, and assurance that the technical information they need is readily accessible. An opportunity in this regard for strengthening the Exposed Structures program is the development of a handout that documents the program content. The handout could be derived from the presentation with additional explanatory text added. This in fact has been done, albeit in a rudimentary form (essentially a modified Adobe Acrobat printout of the presentation with two slide images to a page) and used as part of the testing program in the following Chapter. Ultimately, the handout is easily envisioned as a visually exciting document in something resembling book-form.

8.2 Summary

The background research and development of this thesis has produced significant content regarding structural glass façade technology appropriate for inclusion in learning programs. In addition to the learning program developed as part of this thesis and described above, other opportunities are discussed following.

The testing results as well as the questions asked during the presentations indicated a general lack of familiarity with the materials and processes involved in structural glass facades. Some of these are somewhat unique; steel cables, fittings, cast and machined components, but these items were not even included in the testing. Glass, one of the most ubiquitous materials in architecture, is a subject of only limited understanding among the students tested. This presents obvious opportunities for a variety of programs related to glass.

FacadeDesigner.com, the pivotal resource as proposed herein, presents a variety of content related to structural glass facades with a primary focus on a select group of items developed in Chapter 6. Using the material from Chapter 1, 2 and 6 as core content with further development as appropriate, there is an opportunity for numerous short, concise, focused learning programs made available in video or downloadable Acrobat format from the website. A few of these possible topics are grouped below.

Steel

- Steel castings
- Steel fabrication of exposed steel structures
- Cable and rod rigging systems

- Protective coatings and finishes for mild-steel structures

Glass

- History of glass
- Safety glass and heat-treated glass
- Laminated glass
- Insulated glass
- Glass as structure
- Glass performance coatings
- Decorative glass treatments
- Float glass manufacturing
- Thermal performance of glass
- Acoustic performance of glass

Glass in Application

- Structural glazing
- Butt-glazing
- History of structural glass facades
- Point-fixed system options

Long-span façade structures

- Simple truss structures

- Cable truss structures

- Cable net structures

Some of these topics would be more appropriate in video format. Others could be effective a simple technical bulletins that could be downloaded as Adobe Acrobat documents.

Chapter 9 - Testing

Testing was conducted with two components of the program developed herein. The focus is on the testing of the learning program presented in Chapter 8, and comprises most of this current Chapter. This is followed by documentation for some limited testing on the StructureDesigner analysis tool.

9.1 Learning Program

Testing was conducted in conjunction with the learning program discussed previously in the previous Chapter. The objectives of the testing are fourfold;

1. to determine the general familiarity with structural glass façade technology, including glass, glass systems and structure systems as employed in the technology.

2. to gauge the general interest level in and perceived relevance of the technology among the target audience.

3. to evaluate a tenant of the hypothesis herein that the diffusion of an innovative technology can be facilitated by enabling a new tier of adopters.

4. to evaluate the effectiveness of the learning program itself.

The learning program was presented three times as discussed in the Chapter 8. Only two of these presentations were accompanied by the testing program as described following.

9.1.1 Test Subjects

Group A is comprised of a 2nd year MBS class including eleven individuals.

Group B is a 3rd year undergraduate studio class taught by Professor Arthur Golding. This Group was tested twice; twelve individuals participated in the first test and nine in a follow-up test. Only seven of those taking the first test participated in the 2nd test; two of those taking the 2nd test did not take the 1st test. Thus inadvertently there ended up being variations of the B Group as explained later in this Chapter.

9.1.2 Testing Method

9.1.2.1..1 Objective Fixed-alternative Questions

A written test was prepared, comprised of 25 quantitative multiple-choice questions followed by some brief subjective survey questions. The multiple-choice questions are divided into five categories of five questions each. The categories are:

- Structure
- Glass
- Glass System
- Performance Criteria
- Project Delivery Method

Five to seven responses are included for each question. "All of the above" and/or "None of the above" responses are included with approximately half of the questions. Each question includes a response of "*I don't know*"**.**" The participants were instructed not to guess if they had no idea of the answer. If they thought they knew but were not entirely sure, they were encouraged to provide the answer they thought correct.

The participants were instructed to put a name on their test for tracking purposes.

9.1.2.1..2 Subjective Questions

The quantitative multiple-choice questions were followed by a series of qualitative subjective questions using an itemized rating scale as follows:

1 = strongly disagree

2 = disagree

3 = ambivalent

4 = agree

5 = strongly agree

9.1.2.2 "A" Group

Monday, 18 February 2008: Group A was given the test prior to the presentation of the learning program described in Chapter 9. The test took approximately 10 minutes to complete. The learning program was then presented, lasting approximately one hour including some questions during and after the presentation. A short break was taken, and the test forms the participants had already completed were returned to them. They had not been told that they would be retaking the test after the program. They were instructed to review the test and modify any answers as they felt appropriate. This took approximately another 10 minutes. The test forms were then collected for analysis.

The testing of Group A was administered in a manner that facilitated participation by the subjects in both tests. Even in this group however, one participant failed to respond to the 2nd test. This was more of a problem with Group B.

9.1.2.3 "B" Groups

Friday, 22 February 2008: The identical test was distributed to Group B before the presentation of the identical leaning program to this group. Again, testing took approximately 10 minutes to complete. The test forms were then collected and the program presented, lasting approximately one hour as before. In contrast with Group A, Group B was not retested until over two weeks later. The participants were not told that they would be retested. On 10 March 2008 the participants were given a nearly identical test (the test included some additional qualitative questions not included on the first test) along with a handout documenting the presentation they were given two weeks earlier. They were instructed to complete the test again, and told that they could use the handout if needed. The handout is intended as a prototype tutorial. The material was left with the subjects, and picked up two days later.

Only seven of the original 12 participants responded to the 2nd test. Two participants of the 2nd test did not participate in the 1st test. These two are excluded from the base B Group used in comparative analysis between Groups A and B, but they are included with the base group in the subjective responses discussed below. As the two participants represent a unique case, they have been designated as Group B3

Another useful differentiation of the B Group is with respect to those who used the tutorial and those who did not. Participants who responded to subjective questioning indicating they did use the tutorial were used to populate a Group B1; those that did not use the tutorial (or indicated that they did not rely on it or use it much) were delegated to a Group B2. Only those who agreed or strongly agreed that they used the tutorial to help answer questions were included in Group B1.

9.1.3 Documentation

The raw test results are tabled following.

Table 9-1 Group A, 1st test results.

Group A; 1st Test Results, 18 February 2008												
	??	A	B	C	D	E	F	G	H	I	J	K
structure	1	x	y	y	o	x	y	x	y	o	y	x
	2	x	o	o	o	y	y	y	x	x	o	o
	3	o	o	y	o	x	o	x	y	y	y	o
	4	y	o	x	o	y	x	x	x	x	x	o
	5	y	o	x	o	y	x	x	o	o	y	o
glass	6	y	y	x	o	x	y	x	x	x	y	x
	7	y	x	o	o	y	y	x	x	y	y	y
	8	o	y	o	o	y	x	o	o	y	o	o
	9	x	o	o	o	y	o	o	o	o	o	x
	10	x	x	x	o	y	y	y	x	o	o	x
glass system	11	x	o	o	o	x	o	o	x	o	o	x
	12	x	o	o	o	y	o	o	x	o	o	o
	13	y	o	o	o	x	x	x	x	o	o	x
	14	y	o	x	o	y	o	y	x	o	o	x
	15	x	o	o	o	y	o	o	y	o	o	x
performance criteria	16	x	o	o	o	x	x	x	y	o	x	y
	17	o	o	o	o	o	o	x	y	o	o	x
	18	y	y	o	o	o	o	y	o	x	o	x
	19	x	o	o	o	y	o	x	x	o	x	x
	20	y	y	y	y	y	x	y	y	y	y	x
project delivery	21	y	y	x	o	y	y	y	x	o	x	x
	22	y	o	y	o	y	y	y	y	o	y	y
	23	x	o	o	o	x	o	x	o	o	x	y
	24	y	y	y	o	x	y	y	y	o	x	y
	25	y	y	x	o	y	y	y	x	o	x	y
subjective questions	1	4	4	5	5	5	4	5	5	5	5	4
	2	3	2	1	1	1	2	4	3	1	2	1
	3	4	2	4	1	5	3	4	3	1	3	2
	4	5	4	3	1	5	4	4	5	5	3	5
	5	4	4	3	5	5	4	4	4	5	4	

- *Multiple-choice questions numbered 1-25 in the 2nd column down, grouped as indicated in column 1.*
- *Participants lettered A-K in 2nd row.*
- *y = correct answer; x = incorrect answer; o = “I don’t know” response*

- *Subjective questions 1-5, column 2, last 5 rows; 1 = strongly disagree to 5 = strongly agree*

Table 9-2 Group A, 2nd test results.

Group A; 2nd Test Results, 18 February 2008												
	??	A	B	C	D	E	F	G	H	I	J	K
structure	1	x	y	y	y		y	y	y	y	y	x
	2	x	o	y	y		y	y	x	x	o	o
	3	y	o	x	o		y	y	y	y	y	o
	4	x	x	x	o		x	x	y	x	x	o
	5	y	o	y	o		x	y	x	o	y	o
glass	6	y	y	x	y		y	y	y	x	y	y
	7	y	x	y	y		y	y	y	y	y	y
	8	y	y	y	y		y	x	y	y	y	x
	9	y	y	x	y		y	y	x	o	y	y
	10	y	x	x	y		x	x	x	o	x	y
glass system	11	x	o	x	o		x	x	x	o	o	x
	12	x	o	y	o		x	y	x	o	o	o
	13	y	o	x	o		x	x	x	y	y	x
	14	y	o	y	o		y	y	x	o	x	x
	15	x	x	y	y		o	y	y	o	o	x
performance criteria	16	x	y	y	o		x	y	y	y	x	y
	17	y	y	o	y		y	y	y	y	y	y
	18	y	y	o	y		y	y	x	x	o	y
	19	y	o	o	o		y	y	y	y	x	x
	20	y	y	y	y		x	y	y	y	y	y
project delivery	21	y	y	x	o		y	y	x	y	x	x
	22	y	y	y	o		y	y	y	o	y	y
	23	x	o	y	o		y	x	y	x	x	y
	24	y	y	y	o		y	y	y	o	x	y
	25	y	y	x	o		y	y	y	o	x	y
subjective questions					5					5		
					4					2		
					4					2		
					4					4		
					5					4		

- *Multiple-choice questions numbered 1-25 in the 2nd column down, grouped as indicated in column 1.*
- *Participants lettered A-K in 2nd row.*
- *y = correct answer; x = incorrect answer; o = "I don't know" response*
- *Subjective questions 1-5, column 2, last 5 rows; 1 = strongly disagree to 5 = strongly agree*

Table 9-3 Group B, 1st test results.

Group B; 1st Test Results, 22 February 2008													
	??	A	B	C	D	E	F	G	H	I	J	K	L
structure	1	o	y	y	x	o	o	x	x	o	o	o	x
	2	o	x	y	x	y	y	o	o	o	y	o	o
	3	x	y	y	y	y	x	y	o	x	o	x	o
	4	o	x	x	o	y	x	x	o	y	x	y	y
	5	y	o	x	y	y	o	x	x	y	y	y	x
glass	6	x	x	y	y	x	y	x	y	y	y	y	x
	7	o	x	y	y	x	x	x	x	o	x	x	x
	8	o	o	x	o	o	y	y	o	o	y	o	y
	9	y	x	x	o	o	o	o	o	o	o	o	o
	10	x	o	y	y	x	x	x	y	x	x	x	x
glass	11	x	o	y	o	y	o	o	o	o	x	o	o
system	12	x	o	o	o	o	x	o	x	o	x	o	o
	13	y	x	y	x	x	y	x	y	y	y	x	o
	14	o	o	o	o	x	y	o	o	o	x	o	o
	15	y	o	o	o	y	o	o	o	y	x	x	o
performance	16	o	x	y	o	x	x	o	x	o	x	o	o
criteria	17	o	o	o	o	o	o	o	o	o	o	o	o
	18	y	o	y	x	x	o	x	y	x	y	x	o
	19	x	x	y	o	x	o	o	x	o	y	x	o
	20	y	x	y	y	y	y	x	y	y	y	y	x
project	21	o	x	x	x	x	x	x	x	x	y	o	o
delivery	22	y	y	y	o	y	y	o	y	o	y	y	o
	23	o	o	y	o	y	o	o	o	x	x	y	o
	24	o	o	y	o	o	x	o	o	o	y	y	o
	25	o	o	y	o	o	o	y	o	o	y	o	o
subjective	1	5	4	4		4	5	5	3	5	5	5	
questions	2	1	4	1		3	4	1	1	2	3	1	
	3	5	4	2		3	1	2	3	4	3	3	
	4	5	5	4		4	4	4	4	5	4	5	
	5	5	5	3		3	5	5	4	5	5	5	

- *Multiple-choice questions numbered 1-25 in the 2nd column down, grouped as indicated in column 1.*
- *Participants lettered A-L in 2nd row.*
- *y = correct answer; x = incorrect answer; o = "I don't know" response*
- *Subjective questions 1-5, column 2, last 5 rows; 1 = strongly disagree to 5 = strongly agree*

Table 9-4 Group B, 2nd test results.

Group B; 2nd Test Results, 10 March 2008													
	??	A	B	C	D	E	F	G	H	I	J	K	L
structure	1	x				y	o		y		y	x	o
	2	y					x		y		y	y	y
	3	x					y		x		y	x	o
	4	x					o		x		x	y	x
	5	y					o		y		y	y	x
glass	6	y				y	y		y		y	x	y
	7	x				y	x		y		y	y	o
	8	y				y	y		y		y	o	y
	9	y				y	o		x		y	x	x
	10	y				y	x		y		y	x	x
glass system	11	y				x	x		x		y	o	x
	12	o				y	o		y		y	x	x
	13	x				y	y		y		y	x	o
	14	y				y	o		y		y	o	o
	15	y				x	o		y		y	x	x
performance criteria	16	y				y	x		x		y	o	o
	17	y				o	o		y		y	x	o
	18	y				y	y		y		y	x	o
	19	x				y	o		x		y	x	y
	20	y				y	y		y		y	y	x
project delivery	21	x				y	y		y		y	x	x
	22	y				y	o		y		y	x	x
	23	o				y	y		y		y	o	x
	24	o				o	y		y		y	x	y
	25	o				o	y		x		y	o	x
subjective questions	1	5				4	5		5		5	5	5
	2	4				4	2		3		3	2	4
	3	5				4	3		3		4	4	4
	4	5				4	4		4		4	5	5
	5	5				4	4		4		5	5	4
	6	4				2	1		3		4	3	1
	7	5				3	1		5		5	4	1
	8	4				3	1		3		4	4	1
	9	5				5	5		5		5	5	3
	10	5				4	1		4		3	4	1
	11	5				5	4		4		5	4	1

- *Multiple-choice questions numbered 1-25 in the 2nd column down, grouped as indicated in column 1.*
- *Participants lettered A-L in 2nd row.*
- *y = correct answer; x = incorrect answer; o = "I don't know" response*
- *Subjective questions 1-5, column 2, last 5 rows; 1 = strongly disagree to 5 = strongly agree*

9.1.4 Summary of Results

9.1.4.1 A Group

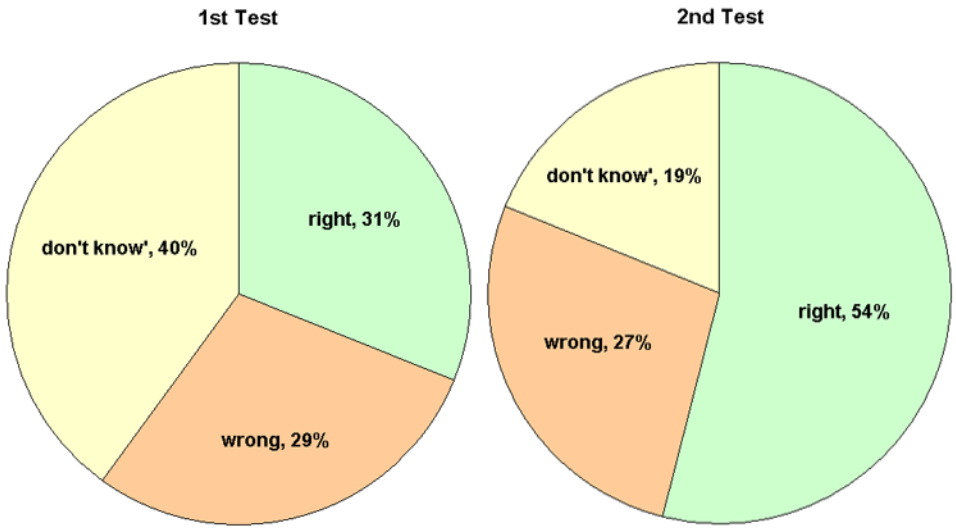
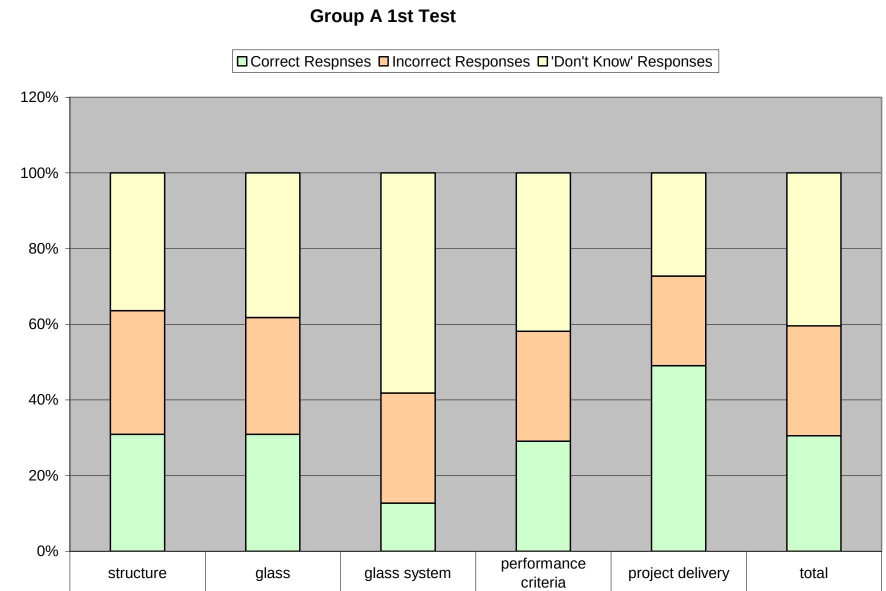


Figure 9.1 Group A, percent right, wrong; 1st and 2nd tests.

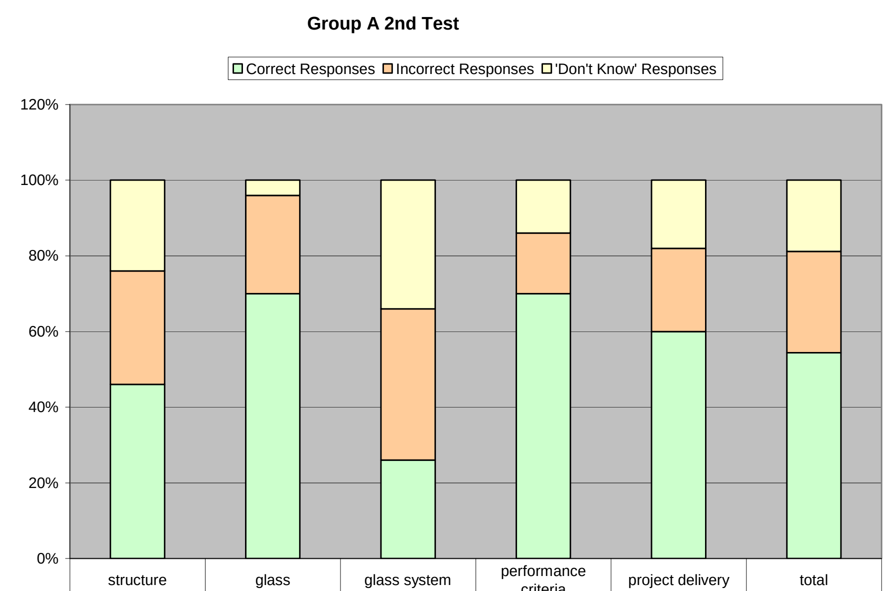
The testing method for Group A is certainly no measure of retention, the test being given the 2nd time immediately after the presentation of the learning program, but a comparison of the pie charts in Figure 9.1 does, as one would expect, reveal an increase in the number of correct responses. It is interesting that the compensating change in the other two categories is almost entirely from the 'don't know' category; the wrong answers stayed nearly the same with only a 2% drop in wrong answers. The likely reasons for this are explored later in this Chapter.

Figure 9.2 and Figure 9.3 show the same test results broken down by question category. Figure 9.4 compares the responses of both tests by category.



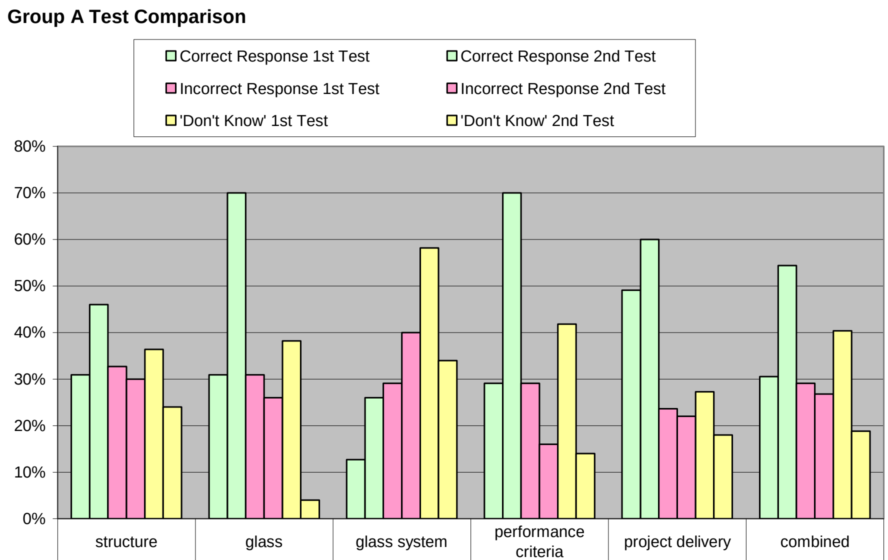
	structure	glass	glass system	performance criteria	project delivery	total
'Don't Know' Responses	36%	38%	58%	42%	27%	40%
Incorrect Responses	33%	31%	29%	29%	24%	29%
Correct Respnses	31%	31%	13%	29%	49%	31%

Figure 9.2 Group A 1st test response by question category.



	structure	glass	glass system	performance criteria	project delivery	total
'Don't Know' Responses	24%	4%	34%	14%	18%	19%
Incorrect Responses	30%	26%	40%	16%	22%	27%
Correct Responses	46%	70%	26%	70%	60%	54%

Figure 9.3 Group A 2nd test response by question category.



	structure	glass	glass system	performance criteria	project delivery	combined
Correct Response 1st Test	31%	31%	13%	29%	49%	31%
Correct Response 2nd Test	46%	70%	26%	70%	60%	54%
Incorrect Response 1st Test	33%	31%	29%	29%	24%	29%
Incorrect Response 2nd Test	30%	26%	40%	16%	22%	27%
'Don't Know' 1st Test	36%	38%	58%	42%	27%	40%
'Don't Know' 2nd Test	24%	4%	34%	14%	18%	19%

Figure 9.4 Group A combined responses by question category.

***I-don't-know* responses**: these dropped across the categories by an average of 21%. The biggest drop of 31% was in the *glass* category, followed by *performance criteria* at 28%. The smallest drop of 9% in the *project delivery* category is due to the highest average of correct responses from the 1st test at 49%.

Correct responses: The general positive pattern to the increase in correct responses is apparent. There is an average 23% increase in correct responses across the categories. The highest increase is in *performance criteria* at 41%, followed by *glass* at 39%.

Incorrect responses: These dropped by only 2% in the 2nd test, the large majority of these the result of the participant not changing their incorrect response from the 1st test, unswayed by the learning program. This may reflect the increased difficulty in learning anything already perceived as known. Alternately, there could be something inadvertently misleading about the questions. The biggest drop in incorrect responses was 13% in the performance criteria category. This was offset by an 11% increase in incorrect responses within a single category as discussed following.

The weakest category is clearly the *glass system*. This presents an opportunity for further investigation. Figure 9.4 makes the problem in the glass system category immediately apparent. While there is an increase in correct responses there is also an increase in incorrect responses. This is the only category in which the incorrect responses actually increased after the presentation of the program (although as noted, the decreases in the number of incorrect responses across all categories were relatively small). This suggests that more people thought they knew the correct answers in this category, but in fact did not. It is important to understand this anomaly, and this question category is analyzed in more detail in Section 9.1.4.4 following.

9.1.4.2 B Groups

Base Group B

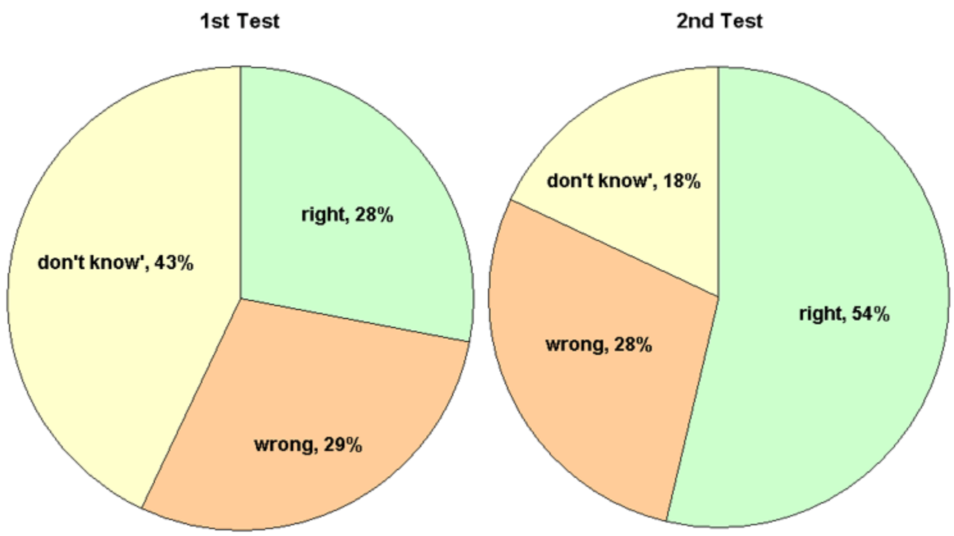


Figure 9.5 Group B, percent right, wrong; 1st and 2nd tests.

Group B was given the 2nd test over 2-weeks after the presentation of the learning program. Again, there was the expected increase in "correct" and decline in "don't know" responses, but with the same lack of decline in "incorrect" responses as resulted with Group A (Figure 9.5). In fact, the overall results are remarkably similar to Group A. This phenomenon is discussed further in the next section of this Chapter.

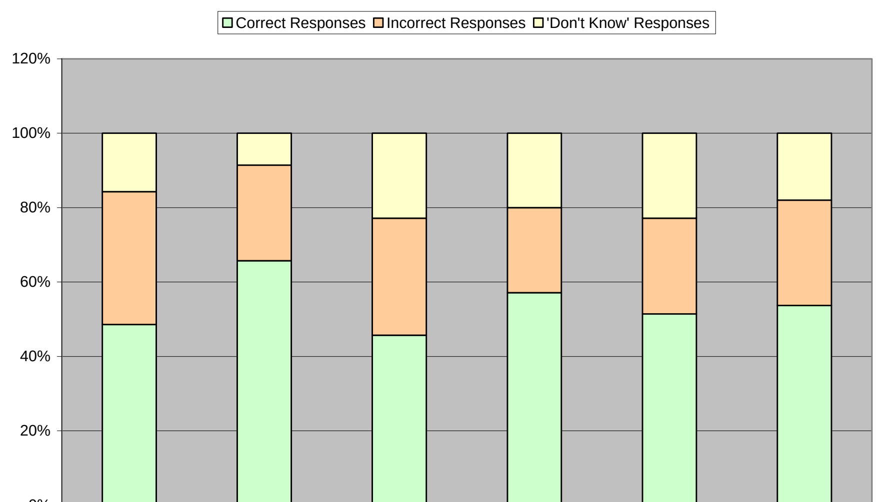
Figure 9.6 and Figure 9.7 show the Group B test results broken down by question category. Figure 9.8 compares the responses of both tests by category.

Group B 1st Test

	structure	glass	glass system	performance criteria	project delivery	total
'Don't Know' Responses	33%	32%	55%	43%	52%	43%
Incorrect Responses	32%	40%	25%	30%	18%	29%
Correct Respnses	35%	28%	20%	27%	30%	28%

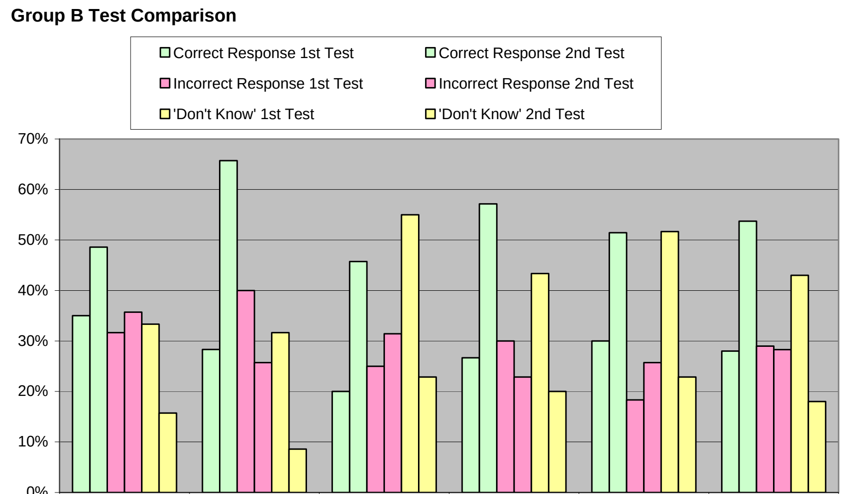
Figure 9.6 Group B 1st test response by question category.

Group B 2nd Test



	structure	glass	glass system	performance criteria	project delivery	total
'Don't Know' Responses	16%	9%	23%	20%	23%	18%
Incorrect Responses	36%	26%	31%	23%	26%	28%
Correct Responses	49%	66%	46%	57%	51%	54%

Figure 9.7 Group B 2nd test response by question category.



	structure	glass	glass system	performance criteria	project delivery	combined
Correct Response 1st Test	35%	28%	20%	27%	30%	28%
Correct Response 2nd Test	49%	66%	46%	57%	51%	54%
Incorrect Response 1st Test	32%	40%	25%	30%	18%	29%
Incorrect Response 2nd Test	36%	26%	31%	23%	26%	28%
'Don't Know' 1st Test	33%	32%	55%	43%	52%	43%
'Don't Know' 2nd Test	16%	9%	23%	20%	23%	18%

Figure 9.8 Group B combined responses by question category.

***I-don't-know* responses**: these dropped across the categories by an average of 25%. The biggest drop of 32% was in the *glass system* category, followed by *project delivery* at 29%. The smallest drop of 18% in the *structure* category is due to the relatively low "don't know" response in the 1st test at 33%.

Correct responses: Again the general positive pattern to the increase in correct responses is apparent. There is an average 26% increase in correct responses across the categories. The highest increase is in *glass* at 37%, followed by *performance criteria* at 30%.

Incorrect responses: In a similar pattern with Group A, these responses dropped by only 1% in the 2nd test, the large majority of the participants not changing their incorrect response from the 1st test, not swayed by the learning program or the handout. Once again, this may reflect the difficulty in learning anything already perceived as known. The biggest drop in incorrect responses was 14% in the *glass* category, followed by 7% in the *performance criteria* category. This was offset by increases in incorrect responses in the other three categories ranging from 4 to 7%, a broader trend than was evident in Group A where the increase in incorrect responses was limited to a single category.

Figure 9.8 reveals the relative responses between the two tests by category. Three categories; *structure, glass system, and project delivery*, while showing an increase in correct responses also reveal an increase in incorrect responses. Once more, this suggests that participants thought they knew the correct answers in these categories, thus the decline in “don’t know” responses, but in fact did not.

Other B Groups

The base B Group is used for the comparative analysis that comprises most of this Chapter, comparing Groups A and B. It is instructive however, to briefly consider three other special Group B constructs as identified above. Figure 9.9 shows simple pie charts comparing the percentages of the three basic response categories. The B chart is the base group 2nd test result, which is nearly identical to the Group A 2nd test results (see Figure 9.10 below).

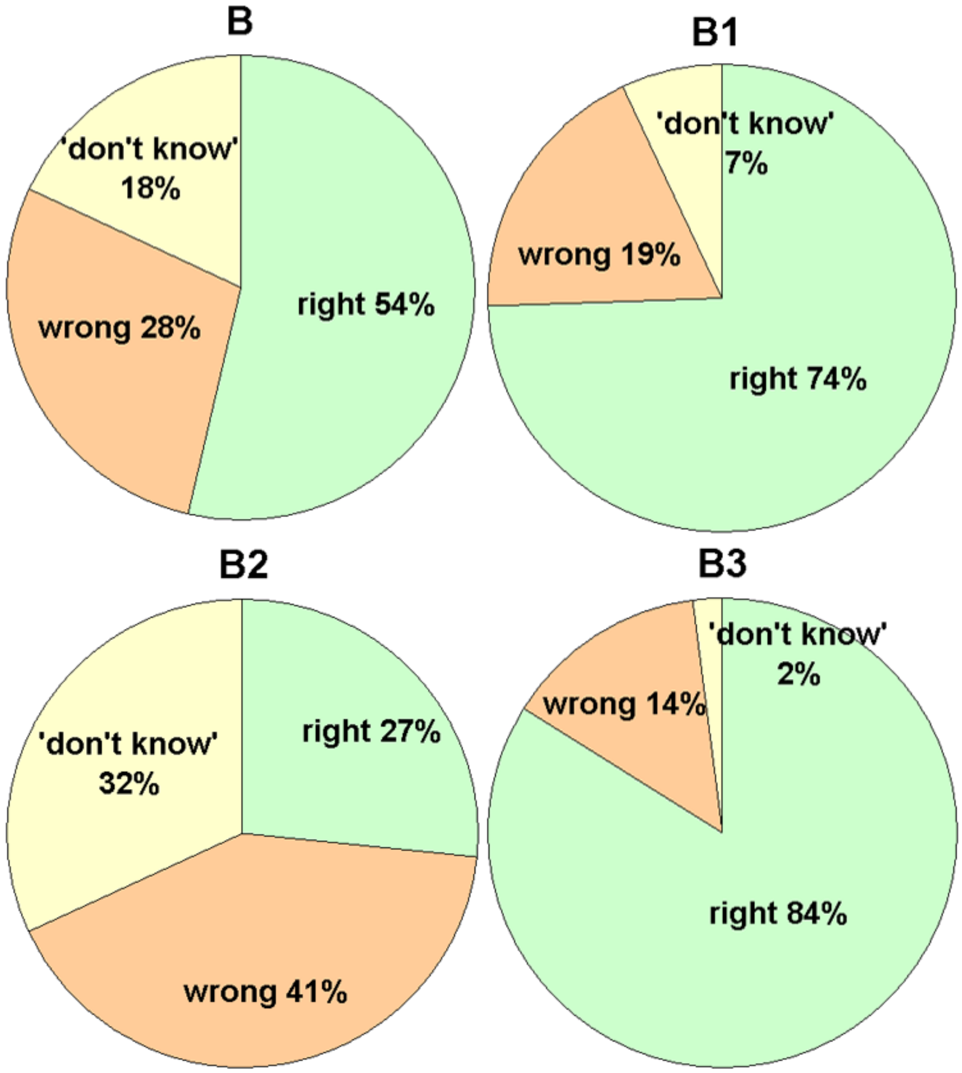


Figure 9.9 Comparative responses of B Groups 2nd test.

Group B1 is comprised of only those participants in the base group who made use of the tutorial. There is a 20% improvement in the correct responses within this group, to 74%. In subjective testing 75% of the Group strongly agreed that the tutorial was helpful in answering the questions. The results here are an indicator that a reference component, as in printed material or a Web access, is an important compliment to the live presentation. The presentation is clearly emboldening the participants to answer the questions, but those using reference materials score significantly better than those who do not.

The results of Group B2 suffered significantly in comparison; “don’t know” responses nearly doubled and incorrect responses rose by 13% in comparison to the base Group 2nd test, resulting in a drop in correct responses to only 27% compared to the 74% of Group B1. This drop is the result of not using the tutorial and indicates a lack of retention of the material presented in the lecture program given 2-weeks prior. Even more interesting is comparing the Group B2 results to Group B 1st test results. The number of correct responses is within 1% of the 1st test given before the program (see Figure 9.5). Incorrect responses however, increased by 12% and “don’t know” responses decreased by a corresponding amount. This group actually seems to have performed worse than on the 1st test. It is difficult with such a small sampling to draw much in the way of meaningful conclusions. A detailed look at the response data of the three individuals that comprise this Group (F, K, L) reveals that; participant F decreased “don’t know” responses resulting in a corresponding increase in correct answers while incorrect responses remained the same; participant K halved “don’t know” responses with corresponding increase in incorrect answers (and a small reduction in even the correct answers); and participant L doubled “don’t know” responses and still managed to drop correct responses to less than half from the 1st test. Evidently the presentation completely confused “L,” who despite this felt no compulsion to utilize the tutorial as an aid in answering the questions. F actually showed improvement, while K’s results perhaps indicate a belief in knowing more answers or at least a willingness to venture more guesses after having participated in the learning program. Fortunately, more favorable results were common in the group at large.

Group B3 is another special and interesting case. The participants here did not attend the lecture program nor did they take the 1st test. Subjective questioning indicated that they strongly agreed that they used the tutorial to answer the question and that it was effective in doing so. Having not attended the lecture, they had no other reference to answer the questions and were more reliant upon the tutorial to provide information. This Group ended up with the best test results, indicating a clear effectiveness to the printed tutorial.

9.1.4.3 Comparison of Groups A and B

There is a remarkable similarity between the results of Group A and B (base group). Figure 9.10 shows that the deviation between groups in the 1st test was within 3% for the "*right*" and "*don't know*" responses, with parity for the "wrong" response. This uniformity is somewhat surprising, but explainable by the similar conditions under which the groups were administered the first test. The 2nd tests however, were administered under quite different conditions between the groups, so the comparative results of this test are considerably more surprising; the correct responses were on par, while the incorrect and "*don't know*" responses were within one percent between Groups A and B.

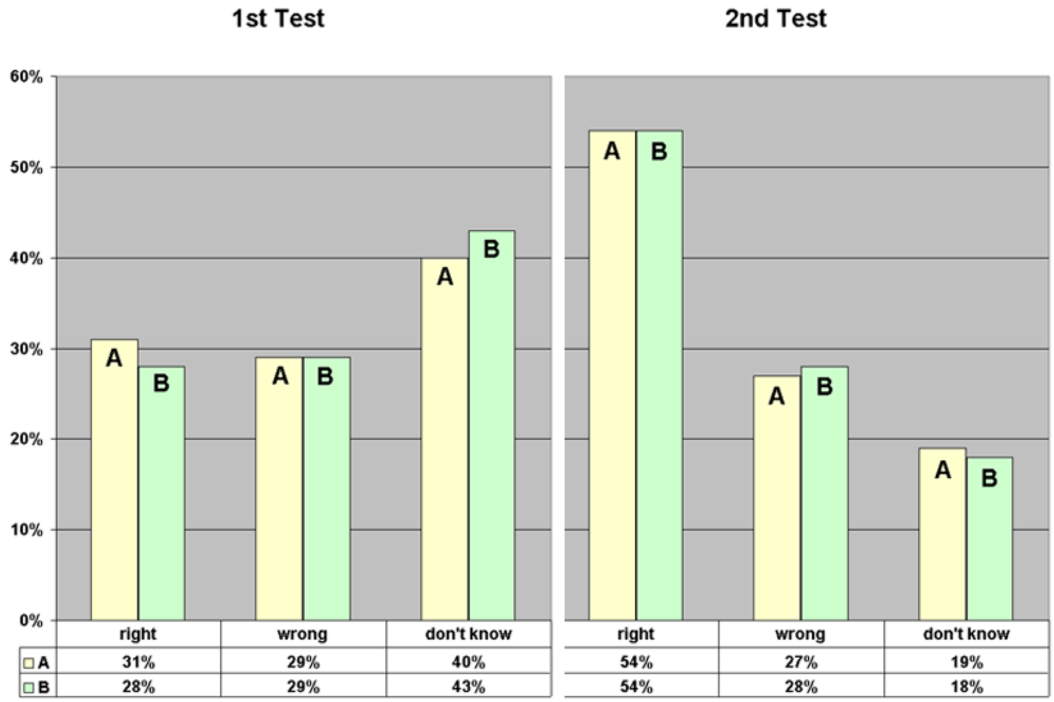
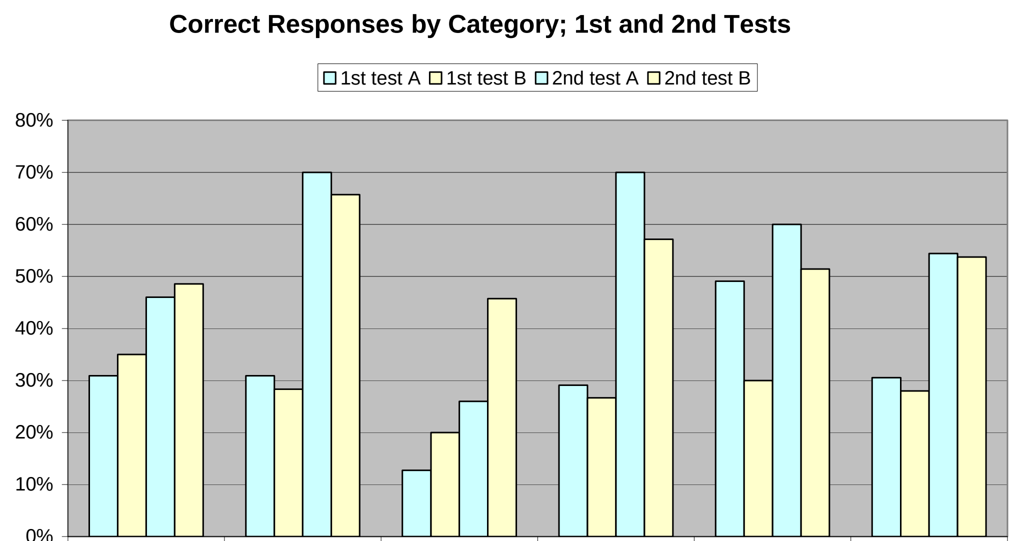


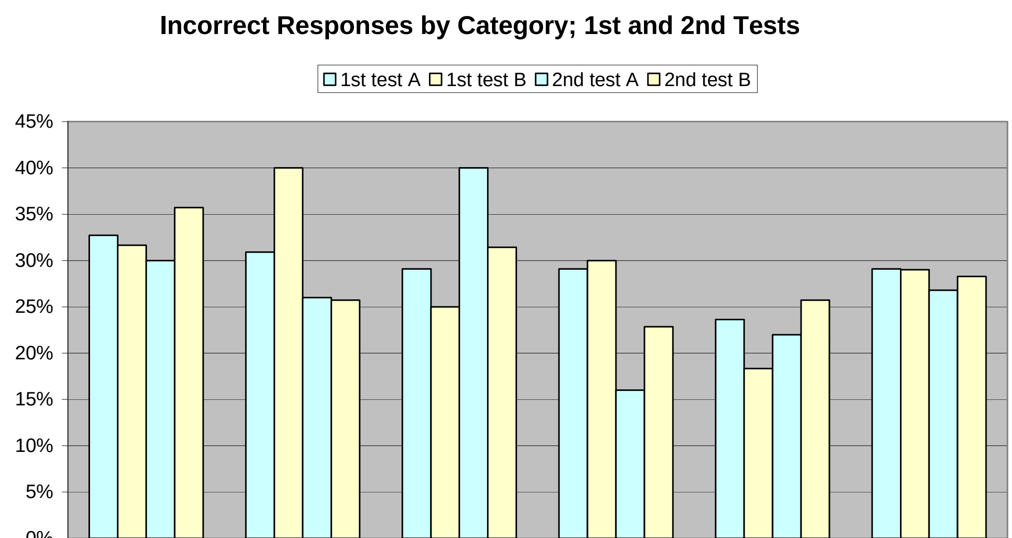
Figure 9.10 Comparison of group A and B, 1st and 2nd tests.

There are some small variations in the categories between the two groups. Figure 9.11 compares the correct responses by category between Groups A and B. The availability of the tutorial handout appears to have presented no significant advantage, except possibly in the category of glass system, where Group A did particularly poorly as discussed previously; Group B did better here, and slightly better in the structure category. Group A scored slightly better than B on the rest of the categories. There were no reversals of which group did best between the 1st and 2nd tests; the group with the highest percentage of correct responses in the 1st test had the highest percentage in the 2nd test across all categories. Incorrect responses are shown in Figure 9.12 and “don’t know” responses in Figure 9.13.



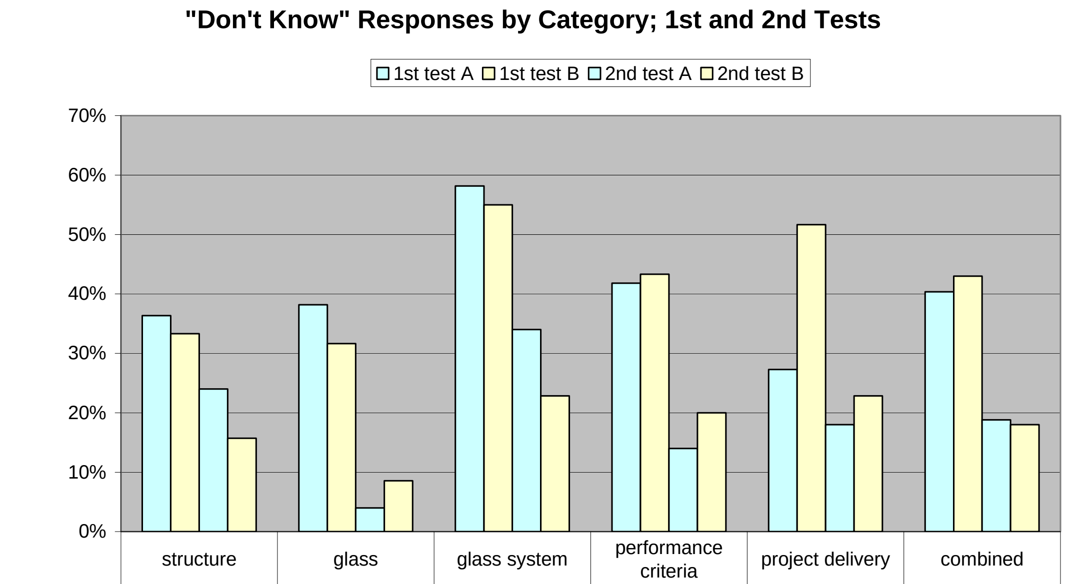
	structure	glass	glass system	performance criteria	project delivery	combined
1st test A	31%	31%	13%	29%	49%	31%
1st test B	35%	28%	20%	27%	30%	28%
2nd test A	46%	70%	26%	70%	60%	54%
2nd test B	49%	66%	46%	57%	51%	54%

Figure 9.11 Comparison of correct responses between Groups A and B.



	structure	glass	glass system	performance criteria	project delivery	combined
1st test A	33%	31%	29%	29%	24%	29%
1st test B	32%	40%	25%	30%	18%	29%
2nd test A	30%	26%	40%	16%	22%	27%
2nd test B	36%	26%	31%	23%	26%	28%

Figure 9.12 Comparison of incorrect responses between Groups A and B.



	structure	glass	glass system	performance criteria	project delivery	combined
1st test A	36%	38%	58%	42%	27%	40%
1st test B	33%	32%	55%	43%	52%	43%
2nd test A	24%	4%	34%	14%	18%	19%
2nd test B	16%	9%	23%	20%	23%	18%

Figure 9.13 Comparison of "don't know" responses between Groups A and B.

Despite the parity of overall results between Groups A and B, differences emerge as the results are analyzed at a higher level of detail. For example, a renewed focus on the incorrect responses shows less consistency between the Groups. Figure 9.14 compares the percentage of incorrect answers on the 2nd test between Groups A and B. Only four questions were answered incorrectly by both groups over 30% of the time; 4, 10, 11 and 21. These questions are discussed following (question 11 is included in the section on the *Glass System* category below).

Question 4

What structure type would likely be best on a renovation project where the client is looking for high transparency?

- *flat cable net.*
- *double-curved cable net.*
- *simple truss system.*
- *cable truss.*
- *I don't know.*

This question was answered incorrectly 55% and 70% of the time on the 1st and 2nd test respectively by Group A, and 42% and 67% of the time on the 1st and 2nd test respectively by Group B. The incorrect answers split between the first and fourth response. This issue of a renovation project was not specifically discussed in the program presentation, but is included in the handout. The final part of the presentation is intended to be a short problem-solving session where this issue would be more directly addressed, but there was inadequate time to do this at both presentations. Question 4 did not have a high percentage of "don't know" responses in the 1st test; most participants appear to have believed they knew the answer on the 1st test and their mind was not changed by either the program presentation or the tutorial handout. The "simple" in the *simple truss* response would seem to be a clue to the correct answer, but apparently not. Perhaps the problem of applying new loading conditions to an as-built structure is not readily perceived as a problem. This aspect of a renovation could easily be added to the program.

Question 10

Tempered glass

- *is 4 times stronger than annealed glass.*
- *qualifies as safety glass.*
- *can spontaneously break if a contaminant is present in the glass.*
- *all of the above.*
- *none of the above.*
- *I don't know.*

This question was answered incorrectly 45% and 60% of the time on the 1st and 2nd test respectively by Group A, and 67% and 43% of the time on the 1st and 2nd test respectively by Group B. The incorrect answers split between the first three responses. The increase in incorrect responses in Group A was a result of two participants changing from a "don't know" response in the 1st test, with one selecting the correct answer and one selecting the incorrect answer.

Question 21

The design/build project delivery strategy

- *prevents the early design participation of the build team.*
- *is good for projects involving innovative technology.*
- *requires the architect to participate in the construction.*
- *is generally slower than the design/bid/build strategy.*
- *I don't know.*

This question was answered incorrectly 36% and 40% of the time on the 1st and 2nd test respectively by Group A, and 67% and 43% of the time on the 1st and 2nd test respectively by Group B. The incorrect answers split between the three alternate responses, with slightly more selecting the third alternative. This increased percentage in Group A in the 2nd test is due to one less participant in the 2nd test that had selected the correct answer in the 1st test; there were the same number of incorrect answers for each test.

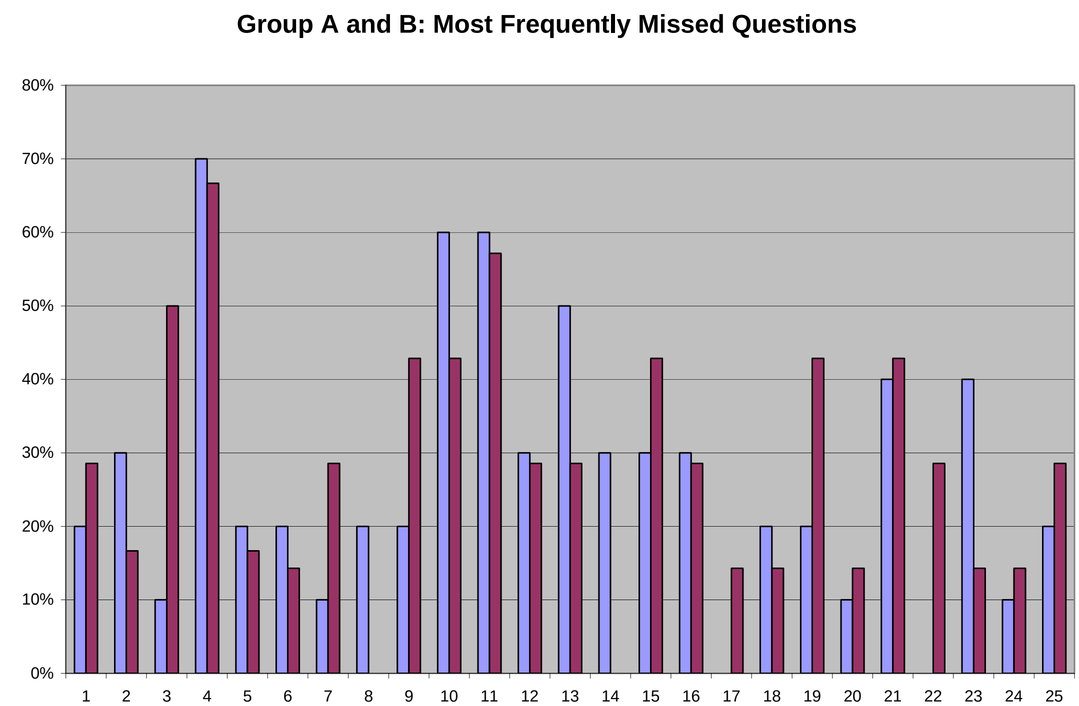


Figure 9.14 Group A and B, 2nd test incorrect responses by question.

Figure 9.16 and Figure 9.16 below graph the *change* in the incorrect responses from the 1st test to the 2nd test for each question. Columns above the 0-line represent an improvement in the number of incorrect responses on the 2nd test, while columns below the line represent a higher percentage of incorrect responses on the 2nd test. While there is much divergence between Group A and B, there are some common trends on both sides of the line with respect to certain questions.

Group A Incorrect Responses: Change from 1st Test to 2nd Test

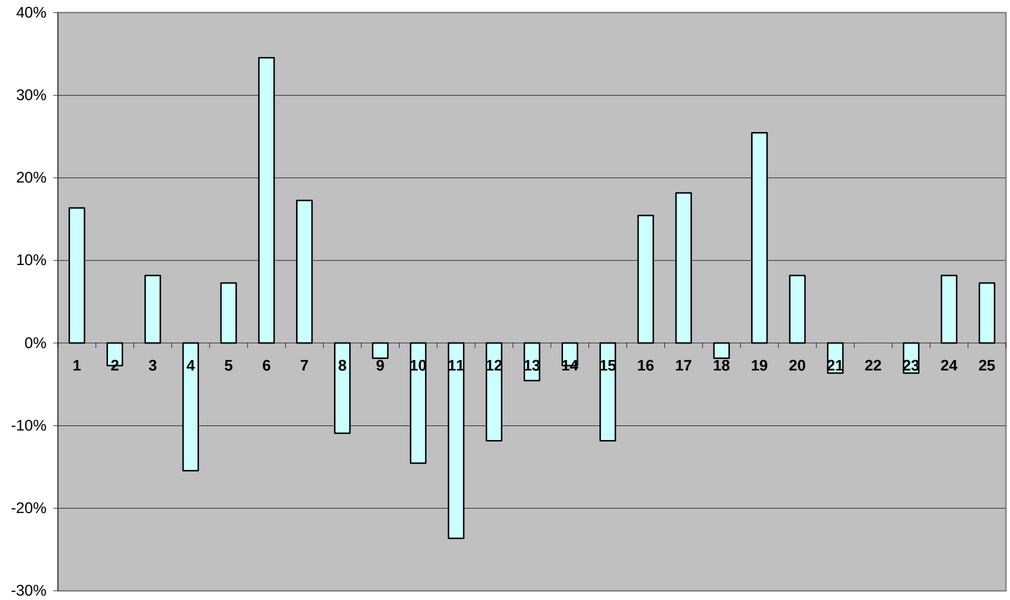


Figure 9.15 Delta incorrect responses Group A.

Group B Incorrect Responses: Change from 1st Test to 2nd Test

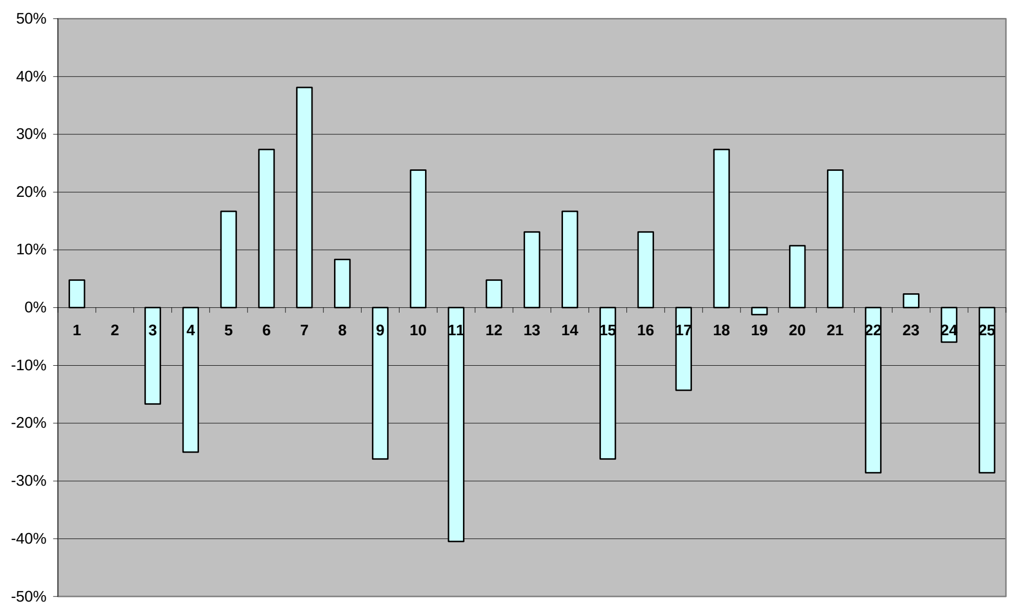


Figure 9.16 Delta incorrect responses Group B.

Positive Delta Questions

Questions 6, 7, and 16 showed the highest likelihood of a correct response in the 2nd test after having been answered incorrectly in the 1st test. Questions 6 and 7 are from the *Glass* category; 16 and 20 are from the *Performance Criteria* category. The questions are reviewed following.

Question 6

Insulated glass is

- *2 or more sheets of glass in a single unit.*
- *heat-treated glass.*
- *sheets of glass with a sealed air space between them.*
- *glass with a special coating that improves thermal performance.*
- *I don't know.*

This question was answered incorrectly 55% and 20% of the time on the 1st and 2nd test respectively by Group A, and 42% and 14% of the time on the 1st and 2nd test respectively by Group B. Incorrect choices varied among the remaining options, with slightly more participants selecting option 1, the next best of the possible answers.

Question 7

Laminated glass

- *has better acoustical properties than monolithic glass of the same thickness.*
- *is a multiple ply panel construction.*
- *is a strategy for improving breaking characteristics of glass.*
- *qualifies as safety glass.*
- *all of the above.*
- *none of the above.*

This question was answered incorrectly 27% and 10% of the time on the 1st and 2nd test respectively by Group A, and 67% and 29% of the time on the 1st and 2nd test respectively by Group B. The incorrect responses were much higher in the 1st test among Group B; most of Group A already knew the answer, most of Group B learned the answer either from the program presentation or the handout.

Question 16

Prestress forces

- *result in large reaction loads to the anchor structure.*
- *are necessary to stabilize cable structures.*
- *can determine the form of a cable net structure.*
- *can be a challenge to the installation team.*
- *all of the above.*
- *none of the above.*
- *I don't know.*

This question was answered incorrectly 45% and 30% of the time on the 1st and 2nd test respectively by Group A, and 42% and 29% of the time on the 1st and 2nd test respectively by Group B. This topic is discussed at length during the presentation. The improvement results from people in the 2nd test selecting the "all of the above" response instead of one of the other correct answers, but no the best answer.

Negative Delta Questions

Questions 4, 11 and 15 showed a trend among both groups to a greater frequency of incorrect response in the 2nd test. Question 4 is from the *Structure* category and has been discussed above. Questions 11 and 15 are from the *Glass Systems* category, which both groups struggled with. The entire group of questions from this category is examined below.

9.1.4.4 The Glass System Category

This category was particularly challenging for both Groups, but especially for Group A. With 3 of the 5 questions in this category, Group A participants provided more incorrect responses during the 2nd test than in the 1st test. The other two questions had the same number of incorrect responses as the 1st test. The questions are presented and discussed below, primarily based upon the Group A results. The correct answer is highlighted in yellow.

Question 11

Point-fixed glass systems

- *provide optimum transparency.*
- *require a spider fitting.*
- *glass with drilled holes.*
- *must have the points securely fixed to the glass with silicone.*
- *I don't know.*

This question was answered incorrectly 36% and 60% of the time on the 1st and 2nd test respectively by Group A, and 17% and 57% of the time on the 1st and 2nd test respectively by Group B.

Group A: Three people changed their answer from *"don't know"*, and all three selected the same wrong answer; *glass with drilled holes*. It is entirely possible that none of these three people had any idea what point-fixed glass systems are when taking the test the first time. The topic was a prominent part of the learning program. The certainly knew *about* point-fixed glass systems by the 2nd test, but what they knew was unclear. The answer they selected was not a bad choice, it just was not the best. Most of the point-fixed systems included in the program were in fact of the drilled type. They were however, presented with point-fixed clamping type systems that do not require drilled holes. One of these participants wrote the word "sometimes" after this answer, which properly qualifies it but still neglects the best and correct response.

Perhaps the shift from *I-don't-know* to the selected incorrect response is not such a bad thing; these participants at least thought they had learned a response, and their selection was close to the mark. Perhaps what is worse is that four of the seven *I-don't-know* responders from the 1st test still did not feel they knew enough to venture a different response after the program presentation. In any case this is a poor result from such a central topic of the program. Two of the three remaining respondents that kept their original answer unchanged also picked a "good" incorrect answer, *require a spider fitting*.

One thing that should be made absolutely clear in the learning program is that point-fixed glazing systems are a strategy to provide optimum transparency in structural glass facades. In fact, an excellent idea would be to feature a slide entitled, "Strategies for Transparence," which could draw from existing elements already included in the program but position them specifically within a context of transparency, which is a central consideration of structural glass façade technology. This slide would feature point-fixed glass systems, low-iron glass, monolithic glass, butt-glazed silicone weather seal, and cable net structural systems, with an example or two, all in the same context instead of from within their segregated categories.

Question 12

Veneer glass systems

- *provide optimum economy.*
- *use a thin wood strip to support the glass.*
- *are maximum transparency glazing systems.*
- *use drilled glass.*
- *all of the above.*
- *I don't know.*

This question was answered incorrectly 9% and 30% of the time on the 1st and 2nd test respectively by Group A, and 33% and 29% of the time on the 1st and 2nd test respectively by Group B.

Group A: This is a tough question. There is no way for the participants to have known this beforehand, and it is only treated in cursory fashion in the learning program. Of the four that ventured and answer in the 1st test, three responded incorrectly. Two of these selected, *are maximum transparency glazing systems*, when in fact the veneer systems are highly efficient but generally the least transparent of the available options. Again, four respondents did not change their *"don't know"* answer.

Question 13

The weather seal

- *is typically a silicone gasket around the perimeter of each glass panel.*
- *is typically a butt-glazed joint made with field applied wet silicone.*
- *is a problem with point-fixed glazing systems.*
- *must be installed before the glass is finally positioned.*
- *I don't know.*

This question was answered incorrectly 45% and 50% of the time on the 1st and 2nd test respectively by Group A, and 42% and 29% of the time on the 1st and 2nd test respectively by Group B.

Group A: This question only had one person go from a "*don't know*" response to the incorrect response of "*is typically a silicone gasket around the perimeter of each glass panel."* This is far and away the 2nd best answer, almost a trick from the best response. In addition, two *"don't know"* responders selected the correct response on the 2nd test. Unhappily, four of the initial responders with incorrect answers were not dissuaded from their answers by the program presentation and stuck with the same wrong answer. In each case however, it was the same 2nd best answer as discussed above. There is an obvious opportunity with the program to clarify the difference between a wet-glazed silicone seal and a silicone gasket.

Question 14

Glass for point-fixed systems

- *is usually tempered.*
- *cannot be insulated.*
- *has a low-E coating.*
- *must be laminated.*
- *I don't know.*

This question was answered incorrectly 27% and 30% of the time on the 1st and 2nd test respectively by Group A, and 17% and 0% of the time on the 1st and 2nd test respectively by Group B.

Group A: One responder switched from an incorrect to the correct response in the 2nd test. The two *"don't know"* responders split, one selecting the correct response and the other the incorrect response. Two of the three incorrect responses on the 2nd test were *must be laminated*, indicating there was some confusion regarding the glass types and their application on structural glass facades. Again, this presents an opportunity to provide focus and clarity in the learning program.

Question 15

Façade structure types

- *must use some type of point-fixed glass.*
- *have only been around a few years.*
- *are usually more expensive than the glass and glass systems they support.*
- *can typically support several variations of glass system types.*
- *all of the above.*
- *I don't know.*

This question was answered incorrectly 18% and 30% of the time on the 1st and 2nd test respectively by Group A, and 17% and 43% of the time on the 1st and 2nd test respectively by Group B.

Group A: The two incorrect responders to this question in the 1st test stuck by their answers in the 2nd test. In addition, one of the "*don't know" responders* selected an incorrect response in the 2nd test. However, three of the *I-don't-know* responders selected the correct response in the 2nd test.

There was a 24% drop overall in this category for the I-don't-know response from the 1st test to the 2nd. This seems to indicate the people thought they knew more about the responses during the second test. What the increase in incorrect responses indicates is that what they learned was not clear enough for them to select the best answer.

The program was seemingly effective in providing information that the users did not know. It was not effective in teaching them things that the thought they new but were wrong about.

9.1.4.5 Subjective Responses

Subjective responses are analyzed separately for Groups A and B following.

Group A

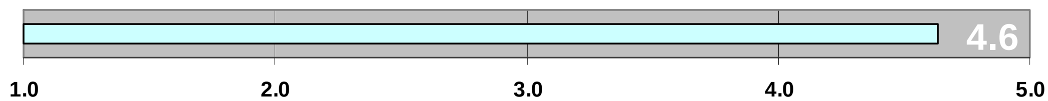
Group A was presented with five subjective questions at the end of their 1st test. Note that Group A answered these questions before presentation of the learning program. They were instructed as follows:

Please circle one number only for each question.

- *1 = strongly disagree*
- *2 = disagree*
- *3 = ambivalent*
- *4 = agree*
- *5 = strongly agree*

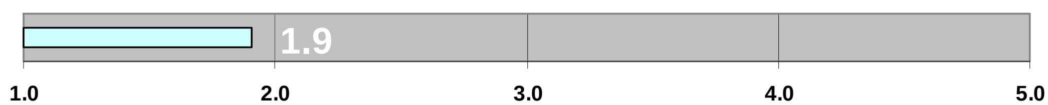
The questions, results and commentary follow:

- *The building skin is a vitally important building system.*



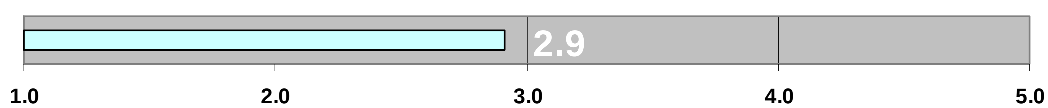
This question was presented to both groups; the majority responded that they strongly agreed with this statement.

- *I am familiar with structural glass facades technology.*



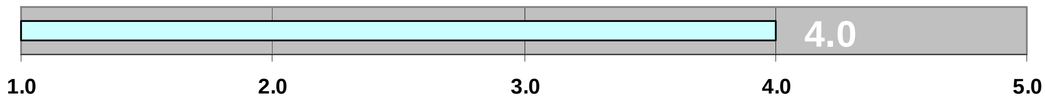
Nearly half the respondents strongly disagreed with this statement.

- *Given what I know, I would be comfortable incorporating a structural glass façade into one of my designs.*



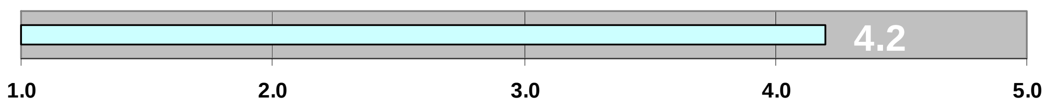
Responses to this question were widely distributed throughout the scale. There was a strong correlation with the prior question, but with most respondents providing a providing a higher score, indicating a general willingness to use the technology in spite of their lack of familiarity with it.

- *I am interested in structural glass facades technology and would like to know more.*



The large majority of responses were 4’s and 5’s, although there was a 1 and a couple of 3’s. This seems a high response for a group that is building science rather than design oriented.

- *If I understood structural glass façade technology better, I would be more likely to include it in my building designs.*



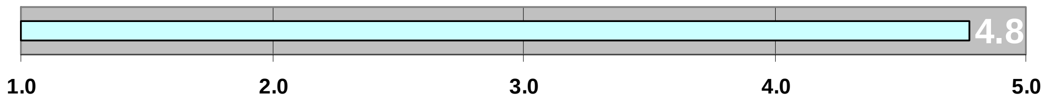
The response here was dominated by 4’s and 5’s.

The above responses are important. Some of this Group are already practicing professionals, and the rest are about to graduate and enter the workplace. If a significant percentage of architectural practitioners responded similarly to these questions, it would provide evidence of the existence of a potential tier of new adopters of structural glass façade technology. This would be a good future testing program that could be administered in conjunction with the AIA CES presentation program represented in Chapter 8.

Group B

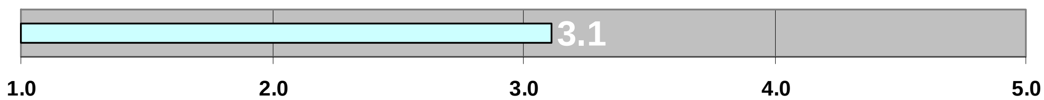
Following are questions, responses and commentary to 11 questions included on the 2^{nd} test of Group B. The first five questions are the same as for Group A above. Group A answered these questions *before* seeing the presentation. Group B answered the questions 2-weeks *after* they were given the presentation. Group B responses are higher than Group A, either reflecting an effect of the presentation or simply the Group's stronger design orientation.

- *The building skin is a vitally important building system.*



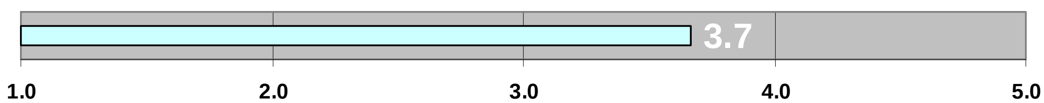
The response here is in general parity with Group A at 4.6

- *I am familiar with structural glass facades technology.*



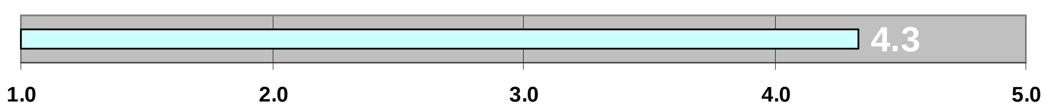
This is a significantly higher response than the 1.9 provided by Group A.

- *Given what I know, I would be comfortable incorporating a structural glass façade into one of my designs.*



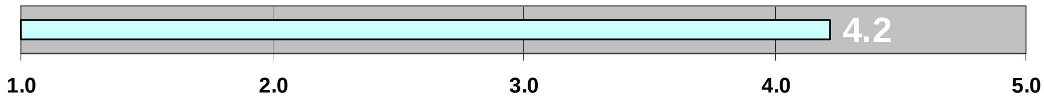
Again, this is nearly a full point higher than Group A at 2.9.

- *I am interested in structural glass facades technology and would like to know more.*



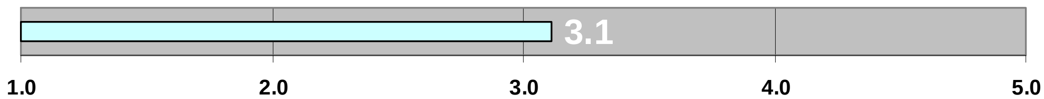
Group B strongly agrees with this statement, and expresses slightly more interest than Group A (4.0) in knowing more about the technology.

- *If I understood structural glass façade technology better, I would be more likely to include it in my building designs.*



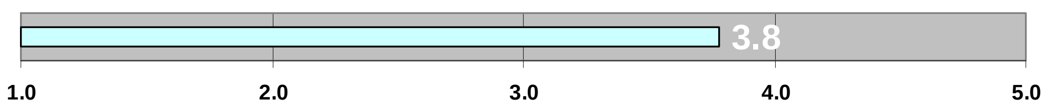
Groups A and B are both in strong agreement with this statement.

- *I used the tutorial to help answer the questions.*



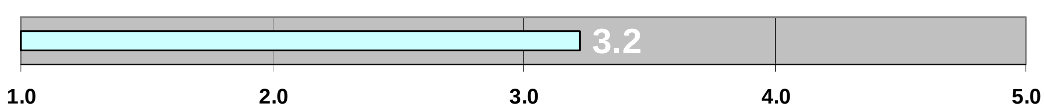
A tutorial was handed out to Group B along with the 2nd test. The tutorial reflected the contents of the lecture presented following the 1st test. They were told they could use the handout to answer the questions on the 2nd test if they needed to. This question is intended to gage the degree of use. The responses were spread across the scale. Two students indicated having not used the tutorial at all because of time pressure.

- *The tutorial was helpful in answering the questions.*



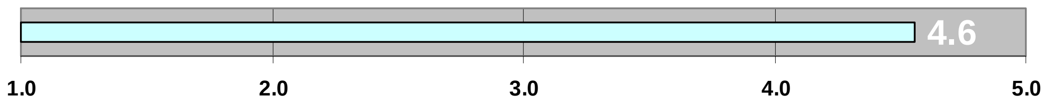
Over half of the participants strongly agreed with this statement. The responses here generally reflected the previous question; the participants that used the tutorial found it effective, those that did not use it strongly disagreed, lowering the average.

- *I could find the answers I was looking for in the tutorial easily.*



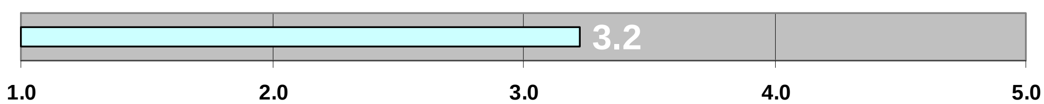
The average response here fell one point from the prior question, indicating that while they found the tutorial effective, it was not necessarily that easy to find the answers they were looking for. The tutorial is a Microsoft Powerpoint document printed in Adobe Acrobat format with 2 slides per sheet, front and back. There is no table of contents or indexing of any kind.

- *I think a website format will provide an easier way to access this information than the tutorial.*



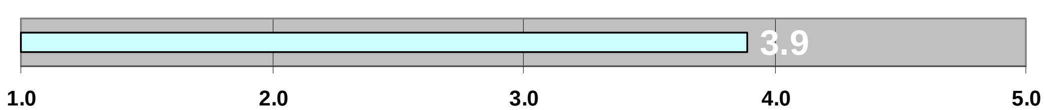
The large majority of participants strongly agreed with this statement. A website format would allow hyperlinks, and thus a quicker and easier access to data. This is the reason that the primary information resource for structural glass façade technology as proposed here in is web-based. It is important to provide information in a variety of formats however, and both online and print tutorials are intended to be available from FacadeDesigner.com.

- *I would be interested in purchasing a book on this subject of structural glass facades.*



The majority of participants agreed or strongly agreed with this statement. Two participants responded with a 1, dragging the average down, one of these indicating that there was no money for books.

- *With resources like FacadDesigner.com and simplified design tools like StructureDesigner available, I would be comfortable including structural glass façade designs in my future projects.*



Here again the large majority responded that they agreed or strongly agreed with this statement. There was one participant who wanted nothing to do with it, and responded with a 1, which dragged the average down.

Summary of Responses to Subjective Questions

There are many interesting nuances to the responses to the above questions. Among these are the responses to the 2nd and 3rd questions. Recall that Group A responded to the subjective questions only before the presentation was given. Their response indicates that they *strongly disagreed* with being familiar with structural glass façade technology, and *disagreed* with being comfortable in using the technology on a project. Group B was tested on the first five subjective questions both before and after the presentation. On the 1st test they indicated disagreement with respect to their familiarity with the technology, and were neutral with respect to being comfortable in using the technology on one of their design projects. After the presentation however, their response to the 2nd question rose by 1.4 points to agreement with being familiar with the topic, and a full point on the 3rd question to strong agreement with comfort in using the technology on a project. One participant in the Group A 2nd test did modify their response to the subjective questions after the presentation, going from a 1 to a 4 for both questions, or from strong disagreement to agreement. These are very positive indicators that a fundamental hypothesis of this thesis, that it is possible to facilitate the diffusion of structural glass façade technology into a broader market by employing the strategies identified herein, has some validity.

9.2 StructureDesigner

Limited testing was done on the simplified structural analysis tool referred to as StructureDesigner described in section 7.4.1. The test is a simple comparison of the results from StructureDesigner to a popular structural analysis program with respect to a simple theoretical case. This approach has been applied to two of the structure types intended for inclusion in StructureDesigner, and the results of this test are summarized below. Other testing is ongoing as the tool is used in a work environment where structural glass facades are designed, bid and built. This testing is also discussed below.

The comparative tool employed in the testing is Space Gass, “a general purpose structural analysis and design program for 2D and 3D frames, trusses, grillages and beams. It comes with a full complement of features that make it suitable for any job from small beams, trusses and portal frames to large high rise buildings, towers, cranes and bridges. Items such as graphical input, polar coordinates, elastic supports, pin-ended members, tension-only members, rigid member offsets, moving loads and non-linear analysis are all standard features.” (Space Gass 2008) It is often used in the nonlinear analysis of cable structures.

9.2.1 Cable Net Comparison

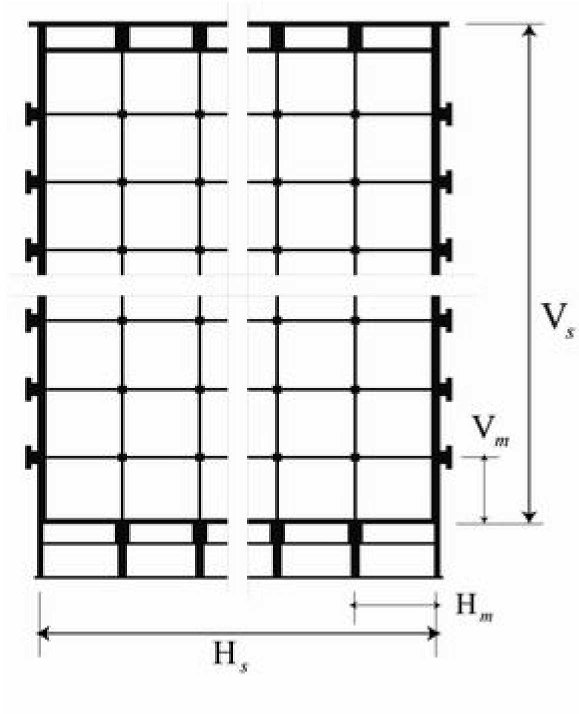


Figure 9.17 Cable net diagram.

Flat Cable Net Test Case

Inputs:

$V_s = 30$

$V_n = 6$

$H_s = 30$

$H_n = 6$

w = 30

D = 1

T = 4.5

Calculate V_m, H_m

$V_m = V_s / V_n = 5$ ft

$H_m = H_s / H_n = 5$ ft

where;

V_s = vertical span (ft)

V_m = vertical module (ft)

V_n = number of vertical grid modules

H_s = horizontal span (ft)

H_m = horizontal module (ft)

H_n = number of horizontal grid modules

w = uniform wind force (psi)

D = cable diameter (in)

T = pretension (kips)

Thus, the glass grid is determined at 60 x 60 in (1524 x 1524mm), a rational glass grid size for any glass makeup.

These parameters were run in StructureDesigner and in Space Gass. The results are compared below. Figure 9.18 and Figure 9.19 document the input screens during the analysis process.

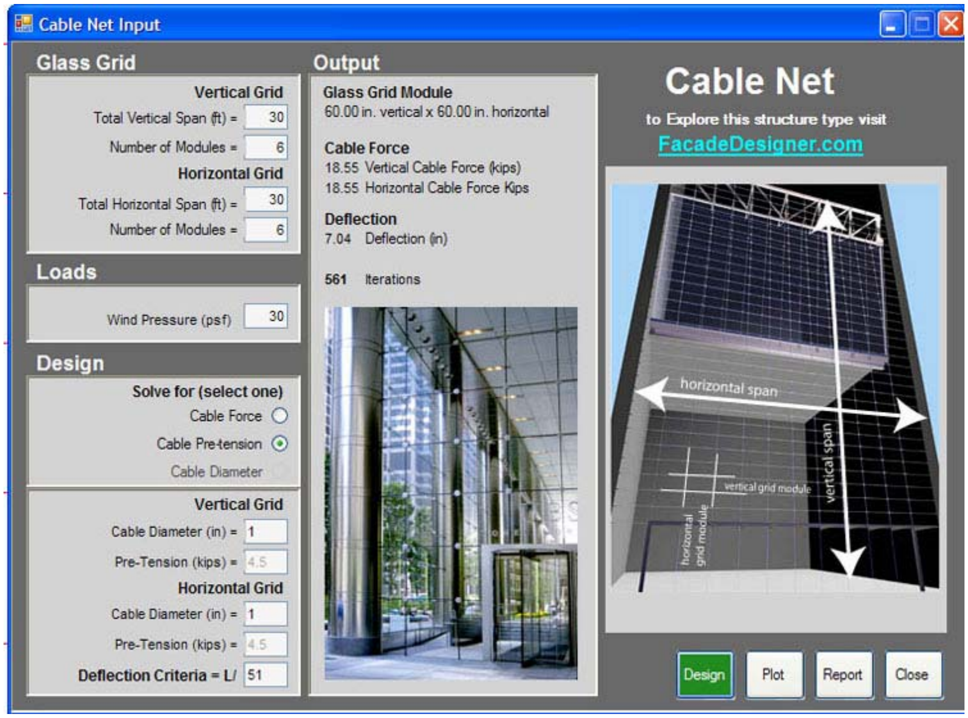


Figure 9.18 StructureDesigner test case.

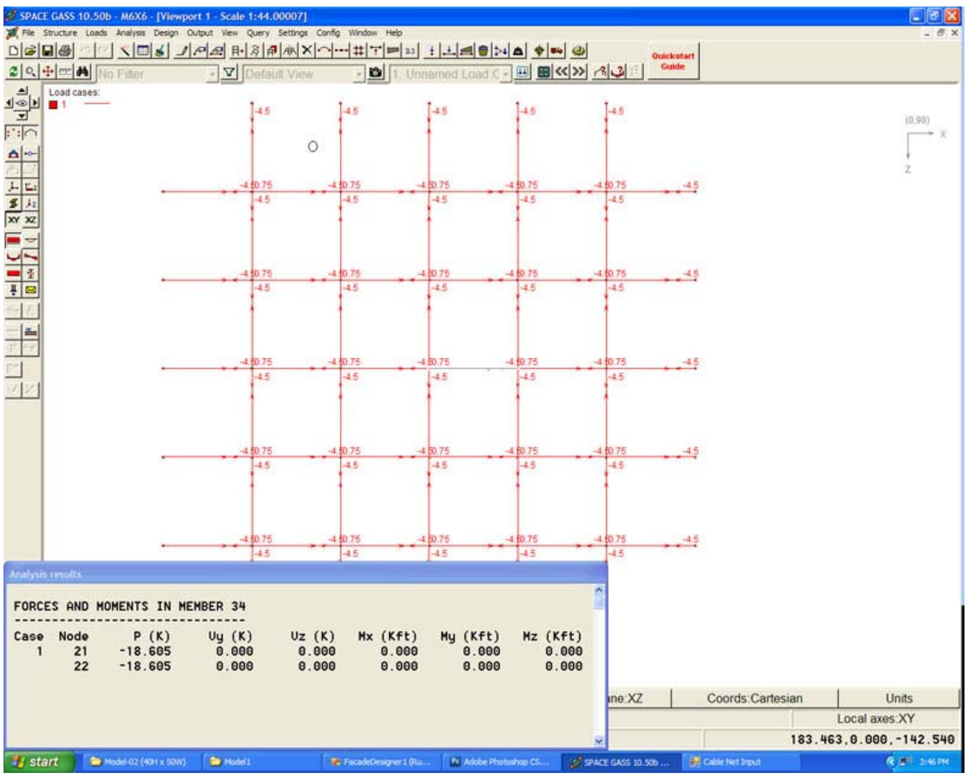


Figure 9.19 Space Gass model and output.

Table 9-5 Cable net; omparison of test case results.

Flat Cable Net Test Case Results		
	StructureDesigner	*Space Gass*
Deflection criteria	*L/51*	*L/50*
Deflection (in)	*7.04*	*7.08*
Max cable force (kips)	*18.55*	*18.61*

As noted in Chapter 7, the analytical engine used in StructureDesigner for cable net structures (DR) is not an approximation method but provides an exact element in the same manner as Space Gass. Thus the results, as can be seen in Table 9-5, are nearly identical. The tool certainly requires additional testing, but the core methodology as derived from DR, a program that has been used by many people on many projects for over a decade, is proven, accurate and reliable.

9.2.2 Simple Truss Comparison

Simple Truss System 1 Test Case

Inputs:

$V_s = 30$

$V_n = 8$

$H_s = 100$

$H_n = 20$

w = 30

Calculate V_m , H_m

$V_m = V_s / V_n = 3.75$ ft

$H_m = H_s / H_n = 5$ ft

where;

V_s = vertical span (ft)

V_m = vertical module (ft)

V_n = number of vertical grid modules

H_s = horizontal span (ft)

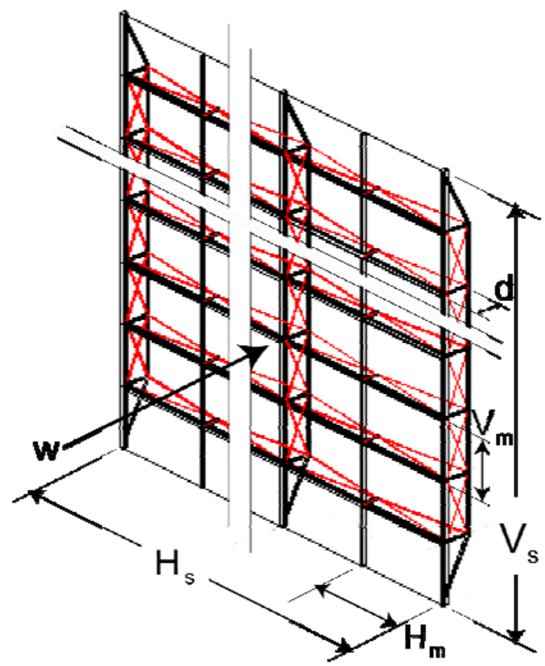


Figure 9.20 Simple truss diagram with input variables.

H_m = horizontal module (ft)

H_n = number of horizontal grid modules

w = uniform wind force (psi)

Thus, the glass grid is determined at 45 x 60 in (1143 x 1524mm), a relatively small glass grid size for any glass makeup.

These parameters were run in StructureDesigner and in Space Gass. The results are compared below. Figure 9.21, Figure 9.22 and Figure 9.23 document the input screens during the analysis process.

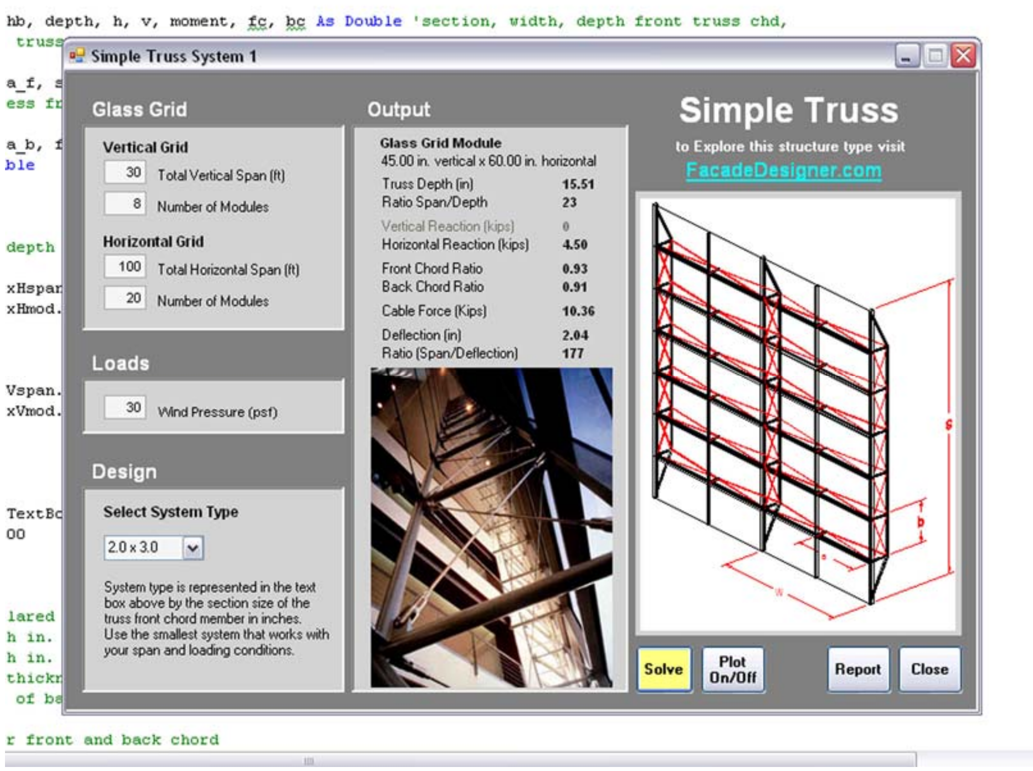


Figure 9.21 StructureDesigner simple truss test case.

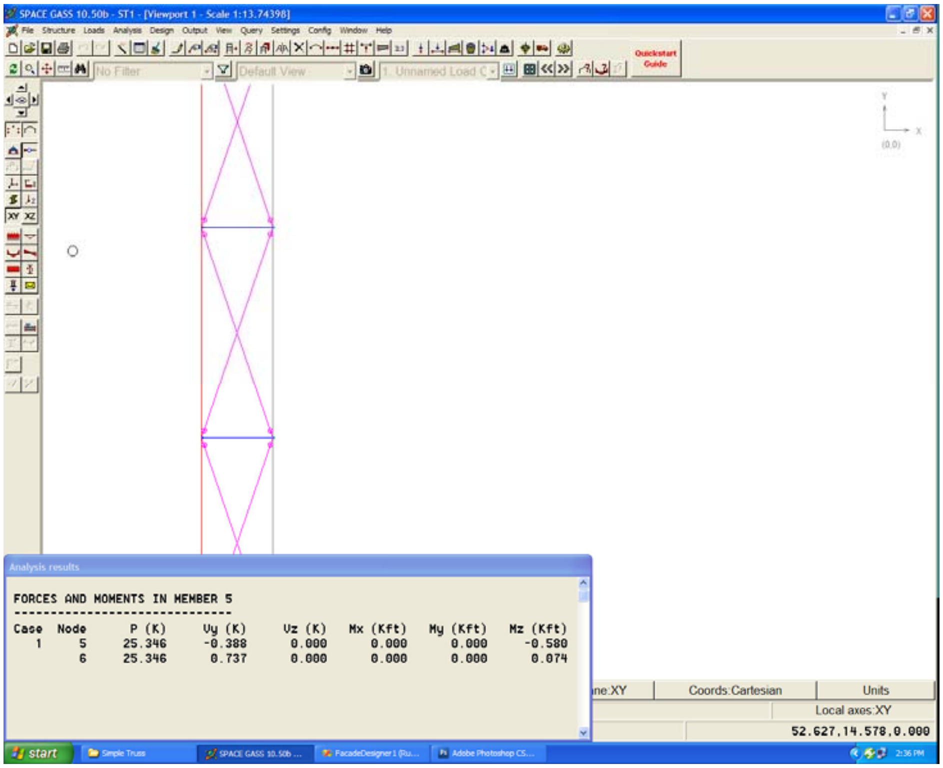


Figure 9.22 Simple truss, Space Gass model and output.

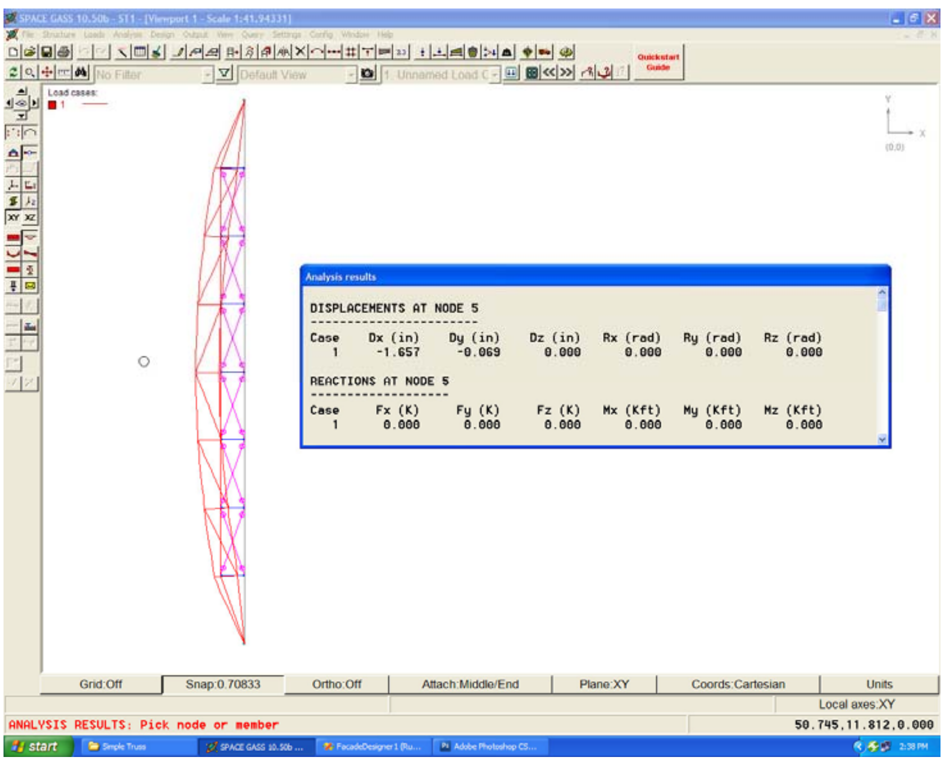


Figure 9.23 Simple truss, Space Gass deflection output.

Table 9-6 Simple truss; comparison of test case results.

Simple Truss Test Case Results		
	StructureDesigner	*Space Gass*
Max member force (kips)	*26.13*	*25.346*
Deflection (in)	*2.04*	*1.657*
Horizontal reaction (kips)	*4.5*	*4.5*

Table 9-6 compares the output between StructureDesigner and Space Gass. The simplified method easily accommodates an exact match for the horizontal reaction load. The maximum member force in StructureDesigner is within 3% of the Space Gass result, and on the high side of the Space Gass number as desired. The deflection in StructureDesigner is within 22% of the Space Gass result, and again on the high side. The results fall within the parameters established in 7.4.1.

9.2.3 Ongoing Testing

The StructureDesigner tool is currently being tested by a small team of designers and engineers, part of a design/build company providing structural glass facades. The program is being used in parallel with conventional analysis programs as part of the conceptual development process, which in this context functions primarily as a technical sales support function. The tool appears to be effective in providing quick approximations of loads that allow for member sizing as required in support of budget development activities. If it proves effective in this environment, it should have potential value to an architectural firm. An important difference is in the users; the current users are technically trained and proficient with more complex programs, so the training component for competency with the tool is virtually nothing. The user-interface is currently very minimal and will require improvement and further testing before it can efficiently be handed off to an untrained user group. This is discussed further in the final Chapter.

Chapter 10 - Summary and Conclusions

10.1 Thesis Summary

A primary intent of this thesis has been to identify, define, and categorize a unique building technology labeled herein structural glass facades. The technology is considered across the full range of the building process from conceptual design through fabrication, erection and lifecycle maintenance. The materials, processes, glass and structural systems that comprise this technology have been dealt with at some length.

Structural glass façades have been characterized herein by certain attributes ranging from performance and appearance to cost. Two of the more frequent adjectives to be used in reference to this technology have been “emergent” and “innovative.” Certain other market related attributes led to a conclusion that while emergent, the technology is mature and potentially poised for broader application. A hypothesis was then developed that it was possible to facilitate the diffusion of this innovative technology to a broader market by enabling designers aspiring to utilize this technology, these designers representing new tiers of adopters as discussed by Rogers (2003, p. 263). On page-1 of *Diffusion of Innovations* Rogers points out that the adoption of the new and innovative, even when possessed with obvious advantages, is no sure thing. Sometimes adoption fails; other times it takes a very long time for the adoption process to unfold.

The beginning of structural glass façade technology is identified here as being in the early 1970’s in Europe. The innovators and early adopters were European engineers and architects that began shaping this technology over the ensuing decades in a series of innovative glass façade and building enclosures. This technology was not adopted at all in

North America until the early to mid 1990's. The reasons for this are many and complex, among them with respect to the North American marketplace; restrictive building codes, cheap energy, varying architectural styles[13], risk aversion in an increasingly litigious environment, a culture that was still learning to value quality architecture, relatively meager project budgets, and a general lack of the technical capability required to design with the technology.

Much has changed. Many structural glass facades have been built in North America over the past 15-years.[14] A review of these projects however, shows that these facades have been produced by relatively few architectural firms; large, successful firms with prized commissions characterized by relatively large budgets. These firms typically use structural glass façade technology as a feature element in the architecture, such as with a long-span glass façade enclosing a lobby area. A proportionally larger budget is reserved for this area with the intent of creating a dramatic focal element. A high level of custom design is generally involved, and occasionally the stated intent is to surpass the prior art. For these reasons structural glass façade technology has produced a high yield of innovative designs, making a dramatic and exciting contribution to the built environment.

Trickle-down of the technology into the less refined airs of the broader building marketplace however, has not happened to any significant degree. A review of Chapter 6 reveals useful attributes for many architectural applications. The technology is capable of producing less stunning but more practical and economical façade solutions. Most technologies reveal a

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[13] A review of the architectural journals in the late 1980's and early 1990's reveals a largely postmodern style with punched openings in opaque facades or a predominance of strip window-wall systems. Large areas of glass and transparency were not common feature elements in North American architecture of the time. Architecture journals today of course, are filled cover to cover with projects featuring an extensive use of glass.

[14] Many of these with the involvement of European architects and/or engineers.

pyramid structure when the distribution of project applications is studied as a function of cost. The less expensive applications make up the base of the pyramid with the highly customized and complex applications at the peak. Structural glass façade technology seems to comprise an inverted pyramid in this respect, with new applications vying for top, or at least the top tier. Budget is often not the dominant consideration. Budgets for other building areas are raided to build up the façade budget. This is not to say that there are no aspiring users of the technology interested in less aggressive applications at a more reasonable cost.

The author's own experience confirms beyond doubt that there are many practicing architects that would like to use the technology. This group is in fact identified herein as the key to unlocking this diffusion potential; the source of the built work of structural glass façades can be traced to the design architect. If the design architect undertakes the conceptual design of a structural glass façade as part of a building project, there is a high probability that the façade will emerge as a building opportunity and ultimately be realized as a completed work. The most direct method to grow the market is to get more design architect producing more façade concepts. The hypothesis is that this group is effectively prevented from including structural glass facades in their designs by a lack of know-how in the use of the technology, and access to the technical capability required to exercise the technology. The focal area identified herein is the conceptual design process within the broader context of a design/build or design/assist project delivery strategy. The hypothesis is that if the design architect can be provided a methodology that facilitates the conceptual design process, if they can be thus enabled and assured of the resources necessary to support the façade implementation process, they will make use of the technology. In this context structural glass façade technology is very new. Designs to date have been produced virtually exclusively by highly skilled specialists, and each design has been highly customized to the individual project. Nothing exists in the way of standardized methodologies, tools, or leaning resources in support of structural glass façade technology. This represents an opportunity.

The intent here is not to standardize the façade designs themselves, producing a uniformity that would have little appeal to the majority of design architects. The intent is rather to develop a generalized, robust methodology, supported by resources in the form of learning programs, technical information and automated design tools that accommodate a wide diversity of design and design complexity as part of an efficient implementation process. The work of this thesis has been to map a comprehensive methodology rather than to focus on any single element that would comprise it. Certain elements of the methodology however have been developed as prototypes to further articulate the functioning of the proposed design method and test its viability. These elements are discussed following.

10.2 Evaluation and Recommended Improvements

The elements of the FacadeDesigner methodology that have been developed as part of this thesis are in prototype form only. The scope of work involved for completion of these various items lies considerably beyond the scope of this thesis. Some of these elements, such as the SpecBuilder module, are untouched. The following discusses the current state of the various prototypes and identifies the work needed to complete them as envisioned within the context of the fully developed FacadeDesigner methodology.

10.2.1 FaçadeDesigner.com; the Web Resource

There is no question that a resource such as described herein should be Web-based. The World Wide Web provides unparalleled access to information. This does not mean that the Web should be the only resource; print media is still an important form of communication with many technology users. Even here, much of print media is most conveniently accessed from the internet and downloaded for local printing.

The author is not a Web designer or Webmaster. A rudimentary website has however, been produced as part of this thesis work. The basic structure of the website is in place, although most require further development.

A great advantage of structural glass façade technology is the compelling visual imagery of the built work. While a focus of this thesis is the development of technical resources to support the FacadeDesigner methodology, an equally important aspect is inspiring interest in the potential user; people learn best when they desire knowledge of a subject. The website attempts to take maximum advantage of this attribute of the technology through the prominent display of visually exciting material as a primary communication strategy. The problem with this is collecting the necessary approvals to prevent copyright infringement. This process is not complete for the FacadeDesigner.com website, so the site has not yet been published to the Web.

Remaining Work

The homepage main menu bar at the top of the page is not completely functional, although the primary functions are working. Modules such as the library do not yet exist and thus cannot be linked.

The StructureExplorer module is active, but only two of the structural systems are supported, mirroring the two active systems of the StructureDesigner module.

The Designer modules are not active from the website. StructureDesigner was originally envisioned to be operable from the website. This was found to be beyond the scope of this thesis, but is an area for potential future development as discussed following.

The Case Studies and Library modules are not active. Both are envisioned as web pages where documents in Adobe Acrobat (*.pdf) format will be posted.

Testing

The site has only been tested on Foxfire and Microsoft Internet Explorer web browsers, and only on two different PC computer systems. The site has not been completely tested for dead links.

Opportunities for Future Development

Interactive Online Accessibility

As discussed above, it may be advantageous to have FacadeDesigner and StructureDesigner operable interactively from the website. Currently they are embodied in a visual basic program that is intended to be downloaded from the website and run from the user’s computer. Interactive operation will require writing Java Script code and integrating it into the website HTML code. A server-side database may be required. This is beyond the current expertise of the author.

Interactive learning programs would be appropriate for including on the website. Again, these are beyond the current skills of the author. AIA/CES learning programs as discussed in Chapter 4 could be developed for interactive website access, but would require user registration and access to a password protected area of the website, as well as the collection of test results and personal user information. This would require a database driven website.

A Structural Glass Façade Community Website

There currently are no websites focused on structural glass facades. There are several good websites focused on glass. A goal of FacadeDesigner.com is to inspire interest in the technology as well as to act as a resource for all aspects of structural glass façade technology, from glass to castings. The homepage is conceived as a posting place for topical content that is changed on a relatively frequent and regular basis. A web blog could be incorporated into this area as well.

10.2.2 FaçadeDesigner; the Methodology

FacadeDesigner is the focal methodology developed from this thesis with the intent of diffusing structural glass façade technology into a broader market. It is conceived as a comprehensive method for the implementation of structural glass façade technology. The primary intent was to map the process. The implementation of the process itself is beyond the scope of this thesis. Instead, certain key aspects of the method have been developed as prototypes to demonstrate viability. The method attempts to simplify a complex process of design and construction. It thus embodies a full range of process considerations from concept development through construction and lifecycle maintenance.

Remaining Work

FacadeDesigner as presented in Chapter 7 is only partially complete. Only the StructureDesigner, StructureExplorer, and GlassExplorer modules have been prototyped. Much of FacadeDesigner will act as a front and back end for the Microsoft Visual Basic program of which StructureDesigner is a part. The glass elements of the module are incomplete. Output is currently limited to what is available from the StructureDesigner analysis form. The output for FacadeDesigner requires the development SpecBuilder, left for future work.

A help system needs to be built for the entire system.

Testing

Limited testing was undertaken only on the active systems within the StructureDesigner module and with a learning program documented in Chapter 9. A testing program should be developed and testing commenced when the whole system prototype is complete. Beta testers could be identified from FacadeDesigner.com, and especially from the live presentation programs to select architectural offices as part of the AIA/CES program. An interesting experiment would be to sponsor a 2-hour workshop comprised of a 30-minute introduction and a 90-minute work session. The program would be passed out and two or three exercises worked through with the group working on notebook computers.

Opportunities for Future Development

GlassDesigner Module

A tool for calculating glass stress could be integrated into FacadeDesigner. While not a requirement of the design method, it would be very convenient to have this capacity integral to the process. Simplified tools for calculating glass capacity are available online from various sources as noted in Chapter 4. The tool as developed for FacadeDesigner should be fine tuned to accommodate the special requirements of point-fixed glazing systems.

Facilitating the Budgeting Process

Estimating is an important part of the conceptual design process as discussed in Chapter 3. Estimating templates could be developed for each of the system types to facilitate the development of façade budgets. The templates could include the typical parts and pieces found in the various systems, with links to appropriate materials suppliers and subcontractors.

Case Studies

The effectiveness of case studies is discussed in Chapter 4. Case studies of completed structural glass facades could be organized according to the basic steps identified in Chapter 7 for the FacadeDesigner process. This would present the completed work to aspiring users in a highly practical and informative manner. The case studies in Cheng's (2007, p. 136-268) thesis work could provide a good start. Four relevant structural glass façade structures are represented in some detail. Some modification would be required.

Tutorials

An objective of FacadeDesigner is the provision of a method for developing appropriate façade concepts that brings the user to a level of competency quickly and efficiently. A tutorial or tutorials in support of the program could be very effective in facilitating the use of the system. The tutorials should present the basic system functionality and then work though a series of example problems. This could be done in conjunction with relevant case studies.

10.2.3 StructureDesigner; the Tool

StructureDesigner is an integral process within the FacadeDesigner methodology. It resolves one of the biggest hurdles to the implementation of structural glass facades; the need for preliminary, close-approximation structural behavior early in the design process. This is needed to validate the façade concept, to provide reaction loads into the supporting structure to the building engineer, and for budget development purposes. Of the seven initial structural system types conceived for this tool, two have been developed as part of this thesis. More systems are possible, both as new system types and as subsets of the various existing system types. Not all of the systems represented in Table 6-2 have been included in StructureDesigner. Tensegrity structures are not included at all, nor are space frames. Seven systems were selected for inclusion on the basis of their frequent use in currently completed work and because of the range of attributes they provide the façade designer.

Structure types like the simple truss system present the potential for other variations. The included system is referred to as Systems 1. It features a particular truss style and an alternating pattern of primary truss and secondary tensile truss supported by a vertical and lateral tension system. Many variations are possible; primary trusses can be spaced by two secondary trusses, or a primary truss can be used at each gridline with no secondary trusses. Varying truss styles can be used. Another included structural system type, cable net, currently only supports the analysis of flat cable nets. It could be developed to accommodate the analysis of double-curved cable nets also. The utilization of the simplified analytical processes requires that an analysis module be developed and fine-tuned for each included system type; it is this approach that provides for the speed and simplicity of the process.

Remaining Work

The initial system types require completion. Much of the program infrastructure is present, but the analysis modules are incomplete. The following systems are incomplete; strongback, mast truss, cable truss, and grid shell. There are opportunities for additional systems also, as discussed below under opportunities for future development.

A help system needs to be developed for all programs.

The interface with FacadeDesigner needs to be developed.

The user interface can be refined. Input filtering needs to be implemented before the program is presented to untrained users.

An output form needs to be developed for printing. Guidelines on the use of the output form may also be useful or necessary.

The tool currently operates in English units and needs to be adapted to support the metric system. This will require the creation of a parallel set of input and output forms, and either the modification of the analysis modules to a metric format, or a conversion process of the input and output data from the modules.

Testing

Preliminary testing for the two completed modules is included in Chapter 9. Further testing is required on these modules with a broader range of problem types involving varying spanning and load conditions. A testing methodology should be developed that each newly defined system type could be subjected to upon completion.

Opportunities for Future Development

Additional System Types

As discussed above, there is great opportunity in additional system types. Tensegrity type structures have been explored to only a very limited extent as façade structures. Grid shells and hybrid structures offer other interesting possibilities.

Building Enclosures

This thesis has been broad enough in scope just in consideration of structural glass facades in relatively conventional form; in vertical applications as part of a larger building. In fact, the technology is capable of accommodating overhead applications and even complete building enclosures in a remarkable diversity of form. It is entirely conceivable that such systems could be developed and included in the FacadeDesigner and StructureDesigner programs. Although this would represent a considerable undertaking, it would dramatically broaden the functionality and potential application of the programs.

Development of the DR Technique

In conversations with Dr. Dehghanyar, author of the DR program, it has been determined that there is some possibility of applying a modification of the DR method as discussed in Chapter 7 to a broader range of structure types, including the simple truss system as a replacement to the method described in 7.4.1. The potential advantage is for a closer approximation to the results of a full structural analysis[15], especially with respect to the system deflections.

FaçadeDesigner as a Simplified Drawing Program

There may be some value in developing a simplified drawing method for integration in the FacadeDesigner program. The approach would be to fine-tune a draw program for each of the various system types, thus minimizing the input required by the user. A system type graphic representation may be possible through the definition of relatively few parameters. A very preliminary experiment with this provided some interesting and promising results.

Tutorials

A tutorial or tutorials for StructureDesigner could prove very useful, and could be developed as part of a tutorial series for the FacadeDesigner system. The tutorials should cover a variety of sample problems covering all the various system types.

10.2.4 Learning Programs

Marketing is not simply about advertising and public relations. Marketing is much more about communication and education, especially when it comes to new and/or innovative technology. In this sense, this thesis is as much about marketing as it is about building science, as much about media communication as about structure analysis. Education can propagate the adoption of new and innovative technology by facilitating technical competency in a new group of potential users.

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[15] The DR technique provides an exact solution, as can be seen in the testing results in 9.2.1. See also the discussion in 7.4.1.

The need is for education and resources. The FacadeDesigner methodology and program is intended to provide the resources; the design tools, techniques and guidelines. Equally important are the learning programs and tutorials to support FacadeDesigner.

One such program was developed as part of this thesis as presented in Chapter 8 -A Learning Program. The program was developed as a live Powerpoint presentation and tested in three presentations as documented in the Chapter. The presentation was presented in conjunction with testing as documented in 9.1 Learning Program.

Summary Conclusions of Learning Program: Exposed Structural Systems and Long Span Glass Facades

The program tries to communicate too much; it is too dense with detailed information. This is appropriate for a reference type resource, such as a printed document or a webpage. Architects, as much as any profession, have too much to know to carry all of the information in their heads. Rather, they learn what information is relevant and how and where to access it when needed. The opportunity is to demonstrate the dominate issues and point to where the answers can be found; FacadeDesigner.com.

It is also important to recognize that there are two distinct but related objectives of value in this communication; one is to excite and the other is to inform. Each component of the learning system will embody these objectives differently. A technical bulletin in print form or as a webpage may have the sole purpose of informing. The live presentation on the other hand, is much more about exciting a potential user group.

The program was effective in both regards. Test scores did improve after the programming, although retention of detailed information over time is questionable. The test scores however, suggest that the most improved response resulted from the use of a printed version of the presentation that was provided to one of the tested groups as a reference. All groups presented with the material, including the industry group, expressed positive feedback regarding the presentation. Perhaps most significant of the test results was the response to qualitative questioning indicating a measurable increase in the participant's perception of their familiarity with the subject of structural glass façade technology, and their willingness to use the technology in a project. This supports the hypothesis developed herein that the diffusion of an innovative technology, such as with structural glass facades, can be accelerated through the methods discussed herein. Similar results from the program presentation to a group of practicing design architects would provide even greater validation.

The value and significance of the testing is obviously limited by the small sample size. Other conclusions can be ventured however, even based on this small sample size. The very large majority of both groups strongly agreed that the building skin was a vitally important building system and expressed interest in learning more about the subject. The high percentage of "don't know" responses in the 1st test and significant overall improvement in the 2nd test reflects a lack of formal training in glass and glazing systems in the architecture curriculums at USC. This represents an opportunity. Glass is a ubiquitous material in the building arts, one that plays both a significant performance and aesthetic role in architecture. A solid foundation of knowledge regarding this material, and related systems and materials as used in building facades, is imperative for the architecture student.

Remaining Work

The *Exposed Structural Systems and Long Span Glass Facades* learning program requires another round of modifications in two areas. First, the presentation needs to be refined with somewhat less detail, fewer slides, and a reliance upon largely visual communication; a minimum of text. Secondly, the handout needs to be further developed as a reference document with more information and greater detail, and most of all, easier access to the information. Better organization of the material with a table of contents and indexing will provide significant improvement.

Testing

The next level of relevant testing would be to get the program qualified for AIA/CES credit, and to present the material to practicing architects.

Opportunities for Future Development

Structural glass façade technology ranges across structures, glass, glass system types, and other specialized materials and process with respect to the full spectrum of the building process, from concept design through installation and lifecycle maintenance. This is a huge and dynamic playing field for learning programs, with new opportunities materializing daily as a result of emergent technology, increasingly demanding performance requirements, and burgeoning interest in the design community.

10.2.5 Other Considerations

A brief version of the FacadeDesigner program was presented to Chris Luebkeman, Director of Global Foresight for Ove Arup.[16] His first comment following the presentation regarded concern over the potential liability of providing preliminary structural information that could possibly be misused resulting in damage to property, life, or both. This concern is an unfortunate but necessary reality of an increasingly litigious society, especially in North America, and especially in the construction industry. An increasingly common practice seems to be that if a project turns bad, if any kind of difficulties are encountered that result in schedule delays and cost overruns, everyone involved gets sued regardless of fault. The attorneys and insurance agents are called to the table and, only as the case nears trial and

[16] Chris Luebkeman attended the Wednesday Building Science Thesis class and presented a lecture that evening at the School of Architecture; 7 November 2007.

after a great deal of expense in legal fees has been incurred, a settlement is reached that typically involves a contribution by all of the insurance companies, again regardless of fault.

Legal consultation will be required to develop appropriate disclaimers and indemnification agreements to accompany all program components of the FacadeDesigner methodology. Legal council has advised against publishing the website or distributing the StructureDesigner program until these elements are in place.

10.3 Opportunities for Future Research

10.3.1 A Building Skins Program at USC

The testing that was undertaken as part of the learning program developed for this thesis revealed a weakness in the familiarity with glass and glazing systems by the students in the architecture program at USC. This is discussed briefly in 10.2.4 above, but the results of the testing indicated an understanding of the importance of the building skin and strong interest knowing more about this subject, at the same time indicating a lack of basic knowledge that was favorably affected by even a brief learning program. This indicates both a need and an opportunity.

The introduction to this thesis comments that no building system impacts both the performance and the aesthetic of a building as does the building skin. Escalating concerns of environment and energy have resulted in a renewed focus on the energy performance of buildings. The building skin plays a dominant role in such consideration. In addition, the majority of multi-story buildings are clad in curtain wall, most making a predominant, if not exclusive use of glass. Many of these buildings feature custom curtain wall designs, which play a very large role in defining the aesthetic of the building.

As little as 8 to 10-years ago there were virtually no major learning institutions in North America offering programs in façade design or technology. This is changing rapidly;

institutions such as the Massachusetts Institute of Technology, the University of Illinois, the University of Texas-Austin, and many others are offering coursework and programs in façade design and technology. It is vital that USC integrate priority aspects of the building skin into the architecture program. Beyond that, there is the opportunity for USC to lead the way in this most important area of building design and technology. The School of Architecture is optimally positioned to develop such a program, already having a building science department where such technology oriented programs can reside.

The opportunity is to research what other schools are doing, evaluate the educational needs and opportunities with respect to building skins, and to further gage student interest if required. A program could then be developed for consideration by the administration of the USC School of Architecture. An approach might be to develop a single 2 to 4 unit semester course that could be adopted on a trial basis to determine interest and effectiveness.

10.3.2 Performance Issues: Strategies for Sustainability

This is a very significant opportunity. Although structural glass façade technology has been used since the early days of its development in innovative façade applications with energy performance as a predominant consideration, such applications have been rare until relatively recently. The unfortunate reality is that most applications of this technology as used to enclose large, sun drenched public spaces, have ignored the realities of climate, thermal and energy performance of the facades, dealing with the environmental control issues through the sizing of the HVAC equipment. This has finally started to change in recent years.

Structural glass façade technology is being used for example, in long-span dual-skin applications where an outer cable net supported glass membrane is separated from a more conventional interior glazing system creating a thermally treated cavity between the systems, similar to some of the dual-skin curtain wall systems that have emerged in recent years. The cable net provides important flexibility needed to respond to changing pressure differentials between the cavity and the inside and outside air pressures.

In another example, the terminal building for the new Bangkok Airport designed by Murphy/Jahn Architects is the 2^{nd} largest building enclosure in the world, and is essentially a glass box with 120 ft (36.6m) vertical glass walls and a largely glass roof spanning overhead. The project involved Werner Sobek as engineer and Mattias Schuler, a climate consultant. The design incorporates many interesting features aimed at improving the energy performance and comfort provided by the enclosure, including deep overhangs around the perimeter, an exterior louvered canopy cladding to encourage ventilation, an exterior trellis structure over the roof glass to restrict direct solar penetration, and an in-floor radiant cooling system. (Mukerji 2007)

This is an exciting area for future research. Designers, building owners, even the public, have become accustomed to large glass-clad light-filled architectural spaces and are reluctant to give them up in spite of the potential for increased security threats and poor energy performance. It is up to the design community in close collaboration with industry suppliers to develop high performance solutions to these problems. The pressure for performance is already yielding innovative new materials and design techniques.

There is also an educational component to this aspect of the technology. Many of the design techniques being applied to improve performance are not new, especially the passive design strategies such as the use of deep overhangs as noted above. These techniques were articulated in the 1970's and earlier (indeed, this was part of the vernacular of indigenous architecture in many hot climates), but are being rediscovered by a new generation of designers looking for solutions to energy performance issues.

The important issue of sustainability with respect to structural glass façade technology has been ignored in this thesis not because of a lack of relevance, but simply because it represents a thesis topic in itself. It does belong however, as an integral component of the FacadeDesigner program. This is recommended for future research below.

10.3.3 Structures

This thesis focuses on structures as the primary means of categorizing the body of structural glass façade technology. Opportunities for additional structure types and structural systems have been discussed above, and represent significant opportunities for the further evolution of this technology.

Highly Flexible Structures

Opportunities can be found not just in the potential for new structural system types, but in the *application* of the technology. For example, many unique attributes of the structural systems that populate structural glass façade technology are cataloged in Chapter 6. Prominent among these attributes is that of flexibility; cable nets in particular belong to a class of tensile structures characterized by high flexibility. This flexibility is a functional attribute in the context of dual-skin facades as discussed above. Other applications where high-flexibility is a desirable attribute are sure to exist.

Blast Glass

Highly flexible, lightweight structural systems such as cable nets have seen increasing use as feature elements in contemporary commercial architecture. These systems are designed for relatively large movements, as these structure types typically deflect much more than conventional structures. Rather than being a problem, this phenomenon represents an opportunity. Like a tennis racket, cable nets absorb energy as they deflect and return to normal position. Hypothetically, these structures could provide optimal performance under bomb blast conditions. Testing this hypothesis would require developing a system and a design application of the system for testing purposes. In combination with other design strategies consistent with security concerns, such research could be of some significant value.

10.3.4 Productization of Structural Glass Façade System Types

What Is a Product

It is no coincidence that the often referenced Willis Faber & Dumas building, designated herein as the birth-point of structural glass façade technology, is the first application of a suspended glass façade product brought to market by Pilkington, a prominent global glass supplier. Pilkington has led the market in the development of structural glass façade products and technology, and in so doing has arguably done more than anyone or anything else in diffusing the technology into a broader market. The single-glazed suspended system used in the Willis Faber building has evolved into today's Pilkington Planar system, arguably the leading structural glass system in the marketplace. The Planar system is supported by product samples, connection details, product specifications, technical support, case studies, design guidelines, test reports, installation guides and an industry leading 12-year warranty; everything required to address the full building process from concept design through installation. This is what defines a product. Yet this product has been used to produce repeated innovation in structural glass facades including designs of incredible diversity and range. However, in many applications designers are able to take the Planar product and apply it to an evolving design, essentially designing around the product requirements, with little industry support and no requirement for a specialty consultant.

The potential is to develop product systems out of the various structural types, "standardized" products able to accommodate significant design diversity in their application. This is not simply a matter of providing a stainless steel cable net vertex clamp. This level of product is already available. The opportunity is for robust product systems that accommodate application needs from concept design through installation. Using the cable net example, a cable net product in this sense would include design tools, guidelines and tutorials, samples, images, connection and interface details for a range of applications, technical information and support, product specifications, installation equipment, methods and support, and a system warranty, and of course cables and all components, all available as a single package with or without glass. No one in the market is doing this with the structural systems that make up structural glass façade technology. The key to unlocking this potential is the same dynamic as with the Willis Faber building; a partnership between industry and the designer whereby the designer is provided with the tools, information and know-how required to design with the product.

10.3.5 Applications to Multi-story and High-rise Structures

Little has changed in the curtain wall technology used to clad high-rise buildings since its widespread adoption in the mid 20th century. If there is to be any radical innovation in the manner in which such structures are clad, it is very likely to emerge from the cutting-edge of structural glass façade technology.

A Cable Supported Curtain Wall System

Conventional curtain walls are constructed from aluminum extrusions that act as a structural framing system for the glass or other panel cladding material. An alternative worthy of exploration would be a cable based system. Steel cables running vertically on the glazing grid could be attached at each floor slab. A variety of glass systems are already designed for attachment to a cable system. Fire-safing and spandrel panels of various configurations could be designed as part of the system. Dual-skin glass panel types could also be developed.

Alternate weather seal strategies could also be explored. Conventional curtain wall systems use extrusions with complex section configurations designed to provide pressure equalization and air and water barriers. Great complexity has evolved in these designs in an effort to control water and air penetration. These systems typically use pressure gaskets to seal aluminum to aluminum and aluminum to glass. The problem is that when these systems leak, the leaks often propagate along the extrusions and may penetrate the building interior a great distance from the actual source of the leak.

An alternative technique used in specialized circumstances is a weather seal comprised of field applied wet silicone, most often in the form of a butt joint (see Figure 2.40) between adjacent panels of glass. The advantage to this technique is that, if properly applied, the seals have a track record of being leak free indefinitely. Leaks in the system are easily identified and repaired. The downside is the requirement for field application of the silicone, requiring site labor which is both expensive and prone to quality problems; the application of a silicone seal is more easily accomplished in the factory than in the field. The silicone seal is typically applied from the exterior. It may be possible to develop a hybrid system that includes a pressure gasket seal in the floor slab area with butt-glazed silicone elsewhere. If the cables were exterior to the glass plane, the silicone could be installed from the inside.

Site labor in the US construction market is extremely expensive, resulting in an effort to design building systems in a manner to minimize the site labor requirements. For the cable supported curtain wall system to be viable, two problems must be solved; 1. getting individual glass panels into place quickly and easily, and 2. facilitating the application of the silicone weather seal. The potential exists for the development of an automated material delivery system for the glass panels, and the development of a robotic tool to apply of the weather seal. Both systems could be designed to work off the parallel tracks of vertical cables. The entire integrated cladding system could represent a patentable new cladding technology.

10.3.6 Diffusion of Innovation in Architecture and Construction

Another area of interesting research that was touched upon in this thesis is the manner in which new and innovative technology is diffused into the marketplace. Rogers (2003) has done significant work in this field, but there may be unique relevance in such study within the construction industry and the practice of architecture.

It has already been discussed here that education is a primary strategy for the diffusion of an innovative technology. The effectiveness of various learning programs could be tested in these specific market sectors.

This could have particular relevance when it comes to the new sustainable and green materials and technologies being introduced into the marketplace daily. As Rogers (2003, p.1) points out, merit does not equate to usage, good products often fail to be adopted. Strategies for deploying these technologies are as important as the products themselves. It would be an unfortunate waste to have effective green technology go unused. What are the metrics that equate to adoption in the complex environment of the building process?

Examples include waterless urinals and building integrated daylight harvesting systems. The issue is not with the technology itself, it is with how the technology is perceived and responded to by the various stakeholders. Integrated building systems are an obviously important concept, but when automated systems for light level control are installed they are invariably compromised by the user response. What measures might be effective in anticipating and mitigating these problems? This is an interesting area that bridges building science, marketing, and innovation theory.

10.3.7 Material, Process, and Design Innovation in Architecture

Another profound dynamic that becomes apparent in the study of glass and architecture is the complex relationship between material, process and design innovation. Do advances in materials science and new fabrication processes lead to design innovations, or does demand for certain attributes of material or form issuing from the design offices prompt an industry response leading to material innovations. Amato (1997) explores this in his book *Stuff*; *The Materials the World is Made Of*. Certainly both take place in an ongoing interplay between industry and the building arts. There is a great richness of this interplay in the history of the evolution of architectural glass that one senses would be enlightening to unravel in some detail, and from there to identify and explore other relationships of material and form in architecture, looking for patterns and trends. Success could provide insight into the process of innovation and into methods to facilitate the process, yielding some additional predictability to the outcome of product development while mitigating the elements of risk that always accompany innovation; this being yet another aspect of implementing innovative building technology.

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