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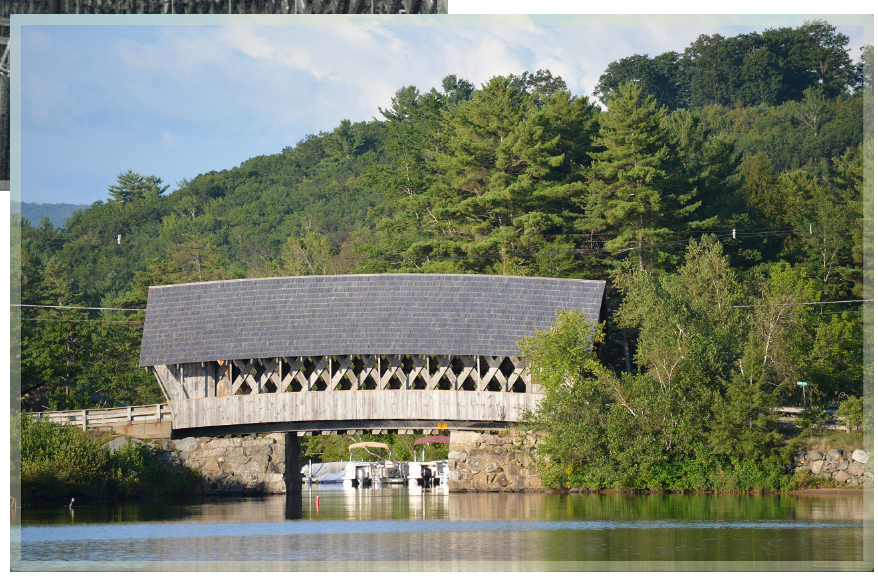
Guidelines to Restoring Structural Integrity of Covered Bridge Members

Ronald W. Anthony



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Abstract

These guidelines are designed for decision makers (selectmen, county commissioners, city planners, preservation officers, etc.) that have responsibility for repairing and maintaining existing covered bridges to help them understand what goes into making effective decisions about how, and when, to repair a covered bridge. The purpose of these guidelines is to present the steps necessary for decision makers to identify effective rehabilitation techniques for restoring the structural integrity of covered bridge members. The intent is to retain the maximum amount of historic fabric while ensuring public safety and minimizing future maintenance requirements. To make informed repair decisions about existing covered bridges, it is important to (1) start with a basic understanding of the type of bridge, (2) know the current condition, (3) be informed of what to consider when conducting an engineering analysis, and (4) be aware of various repair options that can meet the long-term goals for the bridge. Only after the decision maker knows the type of bridge, its condition, and to what loads it is subjected can a repair strategy be developed. How to support the bridge during the repair phase, what repairs are appropriate, and how to maintain the bridge after repairs are implemented are all critical to ensuring a long service life for the covered bridge.

Keywords: covered bridges, historic, guidelines, repair, restore, structural integrity

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This study is part of the Research, Technology, and Education portion of the National Historic Covered Bridge Preservation (NHCBP) Program administered by the Federal Highway Administration. The NHCBP program includes preservation, rehabilitation, and restoration of covered bridges that are listed or are eligible for listing on the National Register of Historic Places; research for better means of restoring and protecting these bridges; development of educational aids; and technology transfer to disseminate information on covered bridges in order to preserve the Nation's cultural heritage.

This study is conducted under a joint agreement between the Federal Highway Administration–Turner Fairbank Highway Research Center and the Forest Service–Forest Products Laboratory.

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English unit	Conversion factor	SI unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
pound (lb), mass	0.45359	kilogram (kg)
ton	0.90718	tonne (t) ($\times 10^3$ kg)

Guidelines to Restoring Structural Integrity of Covered Bridge Members

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Contents

Executive Summary

A covered bridge is a unique structure. Repairing and restoring a covered bridge properly is the primary means of keeping the bridge in service and preserving the craft that went into building the bridge for future generations to appreciate. It is an investment that requires decision makers and contractors to understand the importance of condition assessment and engineering analysis in selecting cost-effective shoring and repair strategies.

Giving strong consideration to repair and/or rehabilitation of original bridge components is a cornerstone of the National Historic Covered Bridge Preservation Program. A covered bridge is a deck for carrying pedestrian and vehicular loads, supported by trusses and protected by the nonstructural roof and cladding. Retaining the maximum amount of historic fabric while ensuring public safety and minimizing future maintenance requirements are key to ensuring that a covered bridge will be there for future generations to appreciate and enjoy.

These guidelines are designed for decision makers (selectmen, county commissioners, city planners, preservation officers, etc.) that have responsibility for maintaining an existing covered bridge to help them understand what goes into making effective decisions about how, and when, to repair a covered bridge. These guidelines present the steps necessary for decision makers to identify effective rehabilitation techniques for restoring the structural integrity of covered bridge members. To make informed repair decisions, it is important to (1) start with a basic understanding of the type of bridge, (2) know the current condition, (3) know what to consider when conducting an engineering analysis, (4) have a basic understanding of how to support the bridge during repairs, and (5) be aware of various repair options that can meet the long-term goals for the bridge.

Prior to conducting any repairs, the historic status of a bridge should be determined and the impacts of the repairs on that status evaluated. But regardless of any formally recognized historic status, covered bridges should be recognized as places of regional, cultural, and personal significance. As such, every effort should be made to adhere to The Secretary of the Interior’s Standards for the Treatment of Historic Properties, which require that the historic character of a property be retained and preserved and prohibit the replacement of intact or repairable historic materials. This includes the character-defining features of a structure, such as the trusses.

Bridge stewards, engineers, and contractors need to know when deterioration has occurred and if the current strength of the structural members is adequate for implementing a repair strategy for the bridge. A condition assessment is a key step to acquire that information. Is deterioration present and, if so, how extensive is it and why did it develop? Are there failed timber members or connections? These are basic questions that need to be asked when establishing the priorities for the condition assessment. It is essential to remember that the purpose of the condition assessment is to provide data that can be used to answer questions about the areas needing repair because of deteriorated conditions or inadequate capacity of the bridge.

In addition to conducting a condition assessment, understanding the structural behavior of the various components of the bridge is essential to making effective repair recommendations. Understanding the structural behavior is achieved when structural engineers conduct an engineering analysis of the entire structure — the trusses, deck, roof, abutments, and piers. A covered bridge performs differently from other structures, and without proper understanding of *how* a bridge behaves, incorrect design and implementation of repairs can be detrimental to the long-term performance of the bridge.

For some bridge repairs, such as those focused on roof covering, siding, or decking, repair work can often be conducted without unloading the trusses or lifting the bridge. Additionally, limited structural repairs can sometimes be undertaken without shoring or extensive rigging on truss types that have many redundant members. Before more extensive repairs can be implemented, however, support of the bridge must be considered. Prior to implementing repairs, properly supporting the bridge, when necessary, is accomplished through cribbing, shoring, staging, and rigging to prevent unnecessary damage to the bridge during the repair phase.

The first question that should be asked when someone suggests that repairs are needed is if the bridge currently provides the required level of safety for its intended use. It may be obvious — a bridge with reverse camber (the bridge is sagging) probably warrants some attention if it is intended to carry vehicular traffic. If it is just a matter of running a computer model and concluding that the bridge is inadequate (and therefore needs reinforcement or replacement), further consideration is warranted. What is the intended use? What did the condition assessment reveal? If the bridge shows no signs of distress, it is possible that repairs may not be necessary.

Based on the condition assessment and engineering analysis, an informed decision about repairs can be made. Perhaps the wood siding or timbers are only weathered, and maintenance is all that is required. Perhaps there is isolated deterioration that should be addressed, but the bridge is able to carry the required loads. If deterioration is more widespread or members have failed, then multiple repairs may be necessary. If there are areas of deterioration severe

enough to require repair or in-kind replacement of a member, the deteriorated material should be replaced with the same species and the original material should be matched in composition, design, color, and texture. Repairing timbers using traditional timber framing techniques and joinery is critical for maintaining the historic character of the bridge. An experienced craftsperson that understands timber joinery can produce tight structural joints that will work and last for decades.

Strength enhancement is considered when load upgrades are needed. Load upgrades are required when the bridge cannot support anticipated loads based on engineering analysis. In cases like these, bridges need to be strengthened. There are several means to increase load capacity. One approach that is often overlooked but can account for slight increases in allowable design values is visual grading of the timber used in the bridge.

Strengthening methods include incorporating mechanically laminated decking or glued-laminated timber beams and deck panels. Post-tensioning, which involves adding steel cables or rods to carry some of the load that the bottom (tension) chord may not be able to carry because of its species, size, or grade, is a viable option for bridges that carry heavy loads. Fully threaded structural screws may allow for repairing damaged connections or members without replacement of the existing materials. There are also means to increase clearance and durability to extend the life of a bridge. A bridge that is properly repaired can provide decades of reliable performance before significant repairs are needed again.

One of the comments made about covered bridges is "This bridge is 150 years old. It had really high quality timber with no knots in it. I can't get that quality of material today." The reality is, you can. There are less than a thousand covered bridges remaining in the United States. They are not all being repaired at the same time, and on any given bridge, a finite volume of timber is needed to do the repairs. Through good specifications, the proper quality of material can be acquired. There may be more expense, but the cost of the material is more than offset by the longevity of the repair.

Although these guidelines focus on considerations for making more effective repair decisions, covered bridges often suffer from a lack of regular maintenance that can lead to deterioration and failure of wood roofing and siding that protect the structural timbers and trusses and, in extreme circumstances, to failure of critical structural members. Routine inspection and maintenance can significantly extend the service life of a covered bridge and may require only a day each year to conduct a thorough visual inspection and limited probing to identify potential problem areas. Cleaning and maintaining the painted surfaces are essential maintenance tasks. Decreasing the likelihood of wood decay or insect attack through the use of remedial wood preservative treatments can be very cost effective, and installing fire protection monitoring, alarm, or sprinkler systems can prevent the loss of a bridge from careless acts of vandalism, contributing to the likelihood that the bridge will last for many decades.

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Chapter 1: Introduction

Purpose of the Guidelines

These guidelines are designed for decision makers (selectmen, county commissioners, city planners, preservation officers, etc.) that have responsibility for maintaining an existing covered bridge to help them understand what goes into making effective decisions about how, and when, to repair a covered bridge.

The purpose of these guidelines is to present the steps necessary for decision makers to identify effective rehabilitation techniques for restoring the structural integrity of covered bridge members. The intent is to retain the maximum amount of historic fabric while ensuring public safety and minimizing future maintenance requirements. To make informed repair decisions about existing covered bridges, it is important to (1) start with a basic understanding of the type of bridge, (2) know the current condition of the bridge components, (3) have knowledge of what to consider when conducting an engineering analysis, and (4) be aware of various repair options that can meet the long-term goals for the bridge.

Only after the decision maker knows the type of bridge, its condition, and what loads it must carry can a repair strategy be developed. How to support the bridge during the repair phase, what repairs are appropriate, and how to maintain the bridge after the repairs are all critical to ensuring a long service life for the bridge.

Need for Repairs to Covered Bridges

Giving strong consideration to repair and rehabilitation of original bridge components is a cornerstone of the National Historic Covered Bridge Preservation Program. Maintaining the structural and architectural fabric of these American bridges is critical to historic preservation goals. However, in assessing the condition of these structures, unnecessarily conservative decisions are usually made when replacing members because there is uncertainty about the long-term effectiveness of repair techniques. Decision makers, structural engineers, and contractors need an understanding of bridge conditions and bridge performance to establish sound approaches for implementing effective and durable repairs and to support their replacement and repair decisions. Effective and durable repairs begin with knowing the current condition of the bridge components and the desired use of the bridge, which are often dictated by engineering requirements. The foundation for effective repairs is a proper condition assessment and engineering analysis.

A covered bridge is a unique structure in that it is built primarily to be supported by the trusses. It has a deck for carrying traffic loads and pedestrians. There are nonstructural components, including the roof and cladding. The roof and cladding protect the structural members and consist primarily of the trusses and deck framing.

Covered bridge members are sometimes compromised by decay, insect attack, or a range of nonbiologic factors. Although publications are available describing methods of inspecting covered bridges for degradation, little information is available to guide decisions after a problem is detected. Additionally, assuming the cause of degradation is correctly identified, a decision still must be made as to whether the member can continue to function without corrective action or how it can be repaired, reinforced, or replaced while retaining the maximum amount of historic fabric. Proper repairs can extend the service life of a covered bridge for decades (Fig. 1.1).

There is a need to describe and evaluate repair techniques that are intended to extend the service life of bridge components. Rehabilitation techniques explored in this context include improved traditional timber framing or timber joinery (Fig. 1.2); use of fully threaded structural fasteners; post-tensioning of bottom chords (by adding steel cables or rods); epoxy injections or fiber-reinforced plastic (FRP) plates to reinforce top chords and floor beams; and replacement of members with glued-laminated timber (glulam), engineered wood products, or pressure-treated lumber. In some situations, the in-place application of preservative treatments may be used to decrease the likelihood of future decay or insect attack.

Truss Types

Any discussion of covered bridge repairs must be based on knowledge of the various trusses that are used in the bridges. It is not the purpose of this report to describe each truss type; these are discussed in numerous other publications (see References section and the Bibliography).

Figure 1.1—Replaced diagonal and knee brace that were deteriorated (Taftsville Covered Bridge, 1836, Windsor County, Vermont).

Figure 1.2—A tapered splice common to traditional timber framing ready to receive a wedge or shear key (Used with permission from DCF Engineering, Inc.).

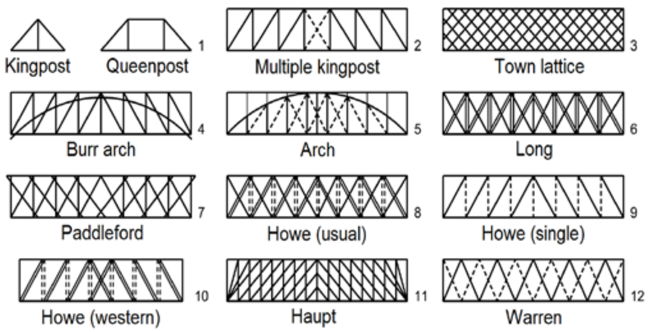

Figure 1.3—Truss types (Used with permission from *World Guide to Covered Bridges*, 2009 edition). The types are identified below (dashed lines typically denote iron rods):

1. **Left, kingpost, right queenpost.**
2. **Multiple kingpost. With odd number of panels, the center panel is open or has crossed braces as shown by dashed lines.**
3. **Town lattice. Disposition illustrated on 1820 patent drawing shown (only two chords indicated thereupon; one at the top and one at the bottom of the truss). For railroads and many highways, two secondary chords were used for additional strength.**
4. **Burr arch. A multiple kingpost truss with one or two arches added on inside and outside. Ends of the arch extend below the lower chord and rest on the abutments.**
5. **Arch (tied (shown) or two hinged (not shown)). The latter is where the ends of the arch are seated on the faces of the abutments. The figure shows various arrangements of suspension: verticals, diagonals, and crossed X-bracing.**
6. **Long. With three wood diagonals and double timber posts in each panel.**
7. **Paddleford. Ends of counterbraces cross both the kingposts and the chords. An inside arch is often added.**
8. **Howe, usual type. Three wood diagonals and two or three iron rod verticals in each panel.**
9. **Howe, single type.**
10. **Howe, western (Oregon?) type. Center panel sometimes open.**
11. **Haupt, 1839 patent. One remaining example is the Bunker Hill Covered Bridge in Catawba County, North Carolina.**
12. **Warren. Single system is in solid lines, double system with added timbers indicated by dashed lines.**

However, repair options depend on the type of truss; therefore, diagrams of typical truss types are given in Figures 1.3 and 1.4.

Some of the most common types of trusses used for covered bridges in the United States are the multiple kingpost, Town lattice, Burr arch, and Howe types (Figs. 1.5 to 1.8).

The Secretary of the Interior's Standards for the Treatment of Historic Properties

The majority of covered bridges are more than 50 years old and are eligible for inclusion in the National Register of Historic Places. Prior to conducting any repairs, the historic status of a bridge should be determined and the impacts of

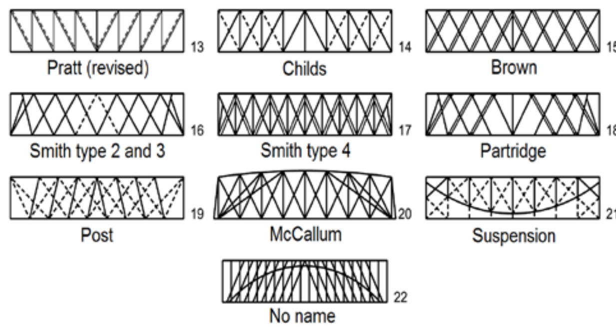

Figure 1.4—Truss types continued (Used with permission from *World Guide to Covered Bridges*, 2009 edition). The types are identified below (dashed lines typically denote iron rods):

13. **Pratt, revised design. Teco-Pratt designs usually have triple timbers. The California design has wooden posts and two iron rods as diagonals, crossed in center panel.**
14. **Childs, 1846 patent. Diagonals are mortised to chords.**
15. **Brown, 1857 patent. Diagonals are mortised to chords.**
16. **Smith, type 2, 1869 patent. Type 3, no patent, reinforced as indicated by dashed center panel timbers.**
17. **Smith, type 4 improved, no patent.**
18. **Partridge, 1872 patent. Note addition of metal footplates. The seven surviving examples are modified designs with reinforcing rods and additional timber diagonals.**
19. **Post, 1863 patent. Iron rods indicated by dashed lines. The only surviving example is the Bell's Ford Bridge (1869), Seymour (Jackson County), Indiana.**
20. **McCallum, 1867 patent. Posts are flared slightly. One example survives, the Powercourt Bridge (1861) Huntington County, Quebec, Canada.**
21. **Suspension of Bowstring. Two examples, both in Ohio.**
22. **No Name Truss (neither a Haupt nor a modified Burr). Two examples are Sayers Bridge (1839), Orange County, Vermont, and Bath Village Bridge (1833) in Grafton County, New Hampshire.**

Figure 1.5—Example of a multiple kingpost truss (Blow-Me-Down Covered Bridge, 1877, Sullivan County, New Hampshire).

Figure 1.7—Example of a Burr arch truss (Durgin Covered Bridge, 1869, Carroll County, New Hampshire).

the repairs on that status evaluated. But regardless of any formal recognized historic status, covered bridges should be recognized as places of regional, cultural, and personal significance. As such, every effort should be made to adhere to The Secretary of the Interior's Standards for the Treatment of Historic Properties, which require that the historic character of a property be retained and preserved and prohibit the replacement of intact or repairable historic materials. This includes the character-defining features of a structure, such as the trusses.

All covered bridge work, including repairs, preservative treatments, and the application of protective coatings, should be compatible both physically and visually with the structure and the site as a whole and should be documented and identifiable (upon close inspection) for future research and preservation efforts. Distinctive materials, features, and construction techniques or craftsmanship of the bridge should also be preserved, which may limit some treatment options. If chemical or physical treatments are necessary, those treatments should be applied using the gentlest methods possible. If repairs to wooden elements or timber members are necessary, the existing condition should be evaluated to determine the appropriate level of intervention needed. If there are areas of deterioration severe enough to require repair or replacement of an element, the deteriorated material should be replaced with the same wood species and match the original material in composition, design, color, and texture. Additional information on The Secretary of the Interior's Standards for the Treatment of Historic Properties can be found at the National Park Service's Technical Preservation Services' website (http://www.nps.gov/tps/standards).

Figure 1.6—Example of a Town lattice truss (North Hartland Twin Bridge, 2001, Windsor County, Vermont). There is a twin bridge at this river crossing (the Willard Covered Bridge) that dates from 1871.

Figure 1.8—Example of a Howe truss (Shoreham Bridge, 1897, Addison County, Vermont).

Where Do You Start?

There are several books that the layperson may find helpful in the early stages of bridge research. A series of books by Richard Sanders Allen, including *Covered Bridges of the Middle West* and *Covered Bridges of the South*, identifies locations, truss types, construction dates, brief histories, and general information about covered bridges. But these books do not tell decision makers anything about how to conduct a condition assessment, how to do a structural analysis, or how to support, repair, or maintain a covered bridge. Yet, these are probably the most common references people have readily available to them unless they research the technical literature to understand the issues with covered bridges in greater depth.

A deeper look into covered bridges reveals more technical publications, such as *Timber Bridges: Design, Construction, Inspection, and Maintenance* from the U.S. Department of Agriculture. This publication is not specific to covered bridges, but it does contain a wealth of information about material properties. Wood properties are among the most important topics to consider because timber bridges are made of different wood species, perhaps eastern white pine, hemlock, or spruce in the east and Douglas-fir in the west. For those working on covered bridges, it is critical to have a basic understanding of the material properties of these different species, and that information is available in technical publications on wood properties.

Additional research into the literature on covered bridges will uncover documents such as Phillip C. Pierce's *Covered Bridge Manual* or *Covered Bridges and the Birth of American Engineering* edited by Justine Christianson and Christopher H. Marston, both from the Federal Highway Administration. Similar to the USDA timber bridge publication mentioned, these references have a wealth of information and are dedicated to covered bridges. They discuss the history, inspection, assessment, engineering, and repair of covered bridges. A decision maker consulting any of these references would find enough information to make an informed decision when hiring an engineer or a contractor to repair a covered bridge.

That being said, these publications cover each topic in considerably more detail than most decision makers have time to digest. The role of these guidelines is to condense much of the technical information into a format that identifies the key considerations for establishing a cost-effective repair strategy for a covered bridge.

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Chapter 2: Condition Assessment

Bridge stewards, engineers, and contractors need to know when deterioration has occurred and if the current strength of the structural members (even when they are oversized and provided more strength than required for the original use) is adequate for implementing a repair strategy for the bridge. A condition assessment is a first step to acquire that information.

Wood decay, insect attack, fire, mechanical damage, and vandalism are typical mechanisms of deterioration for covered bridge members. The presence of any of these factors is a primary reason for initiating a condition assessment to determine if repairs are warranted. The role of moisture in wood decay and insect attack are critical to the decision-making process and are subsequently described because they are among the most common reasons that bridge members are replaced or repaired. Fire is not unique to covered bridges and is discussed in a separate publication on fire prevention and alarms for covered bridges, *Evaluating Fire-Damaged Components of Historic Covered Bridges* (Kukay and others 2016). That publication discusses the effects of fire on bridge timbers and how to make informed decisions about when to repair or replace damaged members. Mechanical damage (primarily vehicle impact or overloading) and vandalism (primarily graffiti) are also not discussed in these guidelines.

In addition to wood deterioration, a condition assessment may be warranted because of a change in use of the bridge. Strength requirements may change to carry heavier (or lighter) traffic loads. Proposed changes in load requirements or previous alterations may have unintended consequences (for example, by compromising the ability of the wood to dry quickly or overloading the structural members).

Mechanisms of Deterioration

Wood performs well in covered bridges when it is kept dry and protected from the deleterious effects of prolonged contact with moisture and biological deterioration. The open construction typical of covered bridges, which provides air flow through much of the structure, makes it possible for the wood to dry quickly if it gets wet. However, sometimes moisture is trapped, leading to wood decay or insect attack.

Prolonged exposure to moisture can produce undesirable conditions and long-term maintenance issues for wood in covered bridges, including moisture stains, peeling paint, checking, splitting, and warping of the roofing and siding. Stains can be the result of a single wetting or of periodic wetting and drying. For example, a roof leak that was repaired many years ago may have resulted in a stain that has not affected the wood in any substantive way. Such stains are of no consequence structurally and can be ignored, unless aesthetics warrant a repair.

In other cases, stains may be the result of periodic leaks in roofs or walls, which may lead to more serious problems, such as decay or warping of the protective wood covering, or worse, decay of the trusses and other structural members. Therefore, it is important to determine if a stain is the result of an isolated historical event or the result of active leaks and ongoing moisture intrusion (Fig. 2.1). Decay and insect attack, subsequently discussed in more detail, are also significant problems associated with periodic leaks or moisture intrusion. Measurements of moisture content can identify wood that has moisture levels favorable for the growth of wood-decay fungi. When feasible, moisture measurements should be taken during the season when elevated moisture content is sufficient to support active wood decay.

Most covered bridges were built well over 100 years ago using large-dimension green (wet) timber. The timber was at a moisture content at which it had not yet dried, or at least not dried adequately, when the bridge was built. With time, seasoning checks may have developed in the timbers. Bridge timbers will typically have checks on one or two faces, which were caused by differential shrinkage of the timber and are part of the natural process as the wood dries (Fig. 2.2). A check is a separation of wood fibers in a piece of lumber, post, or timber, typically along the length of the piece, that results from the wood drying after processing or installation in a bridge.

Checks are not a defect and do not decrease the structural performance of a bridge member, except in rare occasions where two checks on opposite faces join to form a through split. However, if the timber has split through the entire thickness, a more detailed investigation is necessary to determine if the split is a failure resulting from overload or mechanical damage or if it is associated with shrinkage around connections. Also, differential shrinkage in mortise-and-tenon joints can result in failure of the joint that is restricted by the treenail (wooden peg).

Figure 2.1—Moisture stain with no wood decay present (Unity Bridge, 1936, Lane County, Oregon).

Figure 2.2—Drying check in a truss diagonal (Cataract Falls Covered Bridge, 1876, Owen County, Indiana).

Figure 2.4—Decay of a timber sill in a bridge pier (Stewart Bridge, 1930, Lane County, Oregon).

Weathering of wood results from cyclic wetting and drying of the wood, exposure to ultraviolet light, and erosion by wind-blown debris, a process similar to sandblasting. Unlike decay or insect attack, weathering is typically not a significant factor in the failure of wood components and the collapse of a structure. Weathering will change the appearance of wood, but the process is so slow that failure of components caused by decay generally occurs long before weathering becomes a major factor in the failure. Weathering seldom damages the wood enough to require replacement, with the exception of shingles and cladding. Weathered wood is often considered aesthetically pleasing (Fig. 2.3).

Biological deterioration is generally caused by fungal or insect attack, as discussed in the Wood Handbook (FPL 2010). Bacteria can degrade wood but are generally not a concern with covered bridges because decay fungi and insects tend to impact material properties more rapidly than bacteria. Thus, the focus of a condition assessment is typically identifying the presence and extent of wood decay or insect activity.

Figure 2.3—Weathered wood resulting in a desirable aesthetic effect. The siding does not require repair or replacement because of weathering (Lincoln Gap Covered Bridge, 1879, Washington County, Vermont).

The most prevalent means of biological deterioration is wood-decay fungi, which can ultimately lead to the inability of structural members in a covered bridge to carry the required loads. Moisture absorption through end grain, checks, or holes in large timbers provides a highly favorable environment for decay fungi to attack the heartwood at the center of a large timber (Fig. 2.4). The heartwood (the inner growth rings of the tree) typically has more decay resistance than the sapwood (the outer growth rings of the tree). However, even the heartwood of naturally durable species such as chestnut will decay when exposed to enough moisture. Deterioration is a particular concern where wood is in contact with the ground or with other materials, such as porous stone abutments, that may allow moisture to be absorbed into the wood.

In addition to decay, fungi associated with wood also include mildew and stain fungi that propagate from spores present in the air. Mildew grows on the surface of wood or the surface of paint and does not affect the strength of the wood. Stain fungi (not to be confused with moisture stains) penetrate the surface of the wood but do not decrease its strength. Decay fungi, however, break down wood components with time. All types of decay fungi — brown rot, white rot, soft rot, and dry rot (which is often mistaken for all decayed wood that is no longer wet) — affect the ability of wood to perform its intended function. Although identifying the specific fungus during wood inspection is not important, identifying the location and extent of deterioration caused by decay fungi is essential.

Generally, if the moisture content of the wood is less than 20%, fungi are unable to grow. Areas with moisture contents between 20% and 30% can support the growth of fungi, but the moisture may not be sufficient to support long-term active decay. Moisture contents between 30% and 40% are highly favorable for active fungal growth and are

Figure 2.5—Evidence of insect attack found below bridge timbers (Belknap Covered Bridge, 1966, Lane County, Oregon).

Figure 2.6—A joist showing fuzzy wood. This joist probably does not need to be replaced. An engineering analysis determined that it should be able to carry the original loads because only the very perimeter of the member was deteriorated (Blair Bridge, 1829, 1869, Grafton County, New Hampshire).

often an indication of advanced decay, with symptoms that may include internal voids and surface deterioration. Insects generally require that moisture be greater than 10% for them to be active and cause deterioration in the wood. Moisture is the controlling factor for active decay in covered bridges.

The early stage of decay, known as incipient decay, is characterized by discoloration and results in an initial loss of integrity of the wood. No voids are present. Probing with an awl or a screwdriver may reveal that the surface of the wood is soft or punky. As the decay progresses, the wood cellular integrity deteriorates until small voids develop. This stage is termed intermediate decay. The small voids continue to extend primarily along the wood grain, where it is easier for moisture to move through the wood, but voids can also extend across the grain. Larger voids develop where the decay originated, and the boundaries of the decay continue to extend, decreasing the integrity of the wood and compromising its structural capacity. At this stage, termed advanced decay, simple probing with an awl or a screwdriver may not detect the hidden deterioration in internal voids. An increment borer or a portable hand drill may be used to examine wood removed from the interior of larger timbers. However, more advanced techniques, such as resistance drilling, are able to quantify the extent of deterioration rather than simply identify its presence.

Termites and wood-boring insects decrease the size of the wood member cross section by either digesting or tunneling through the wood. Subterranean and drywood termites digest the wood as they move below the surface of the wood. Termites can often be detected through the presence of mud tubes on the exterior of either the structure or the individual wood members. The tubes allow the termites to maintain a favorable moisture environment as they move towards a new food source. Wood-boring beetles create holes that are packed with frass (the byproduct of the tunneling process). Carpenter ants and bees leave large clean tunnels in affected wood. Evidence of insect activity is often found in piles of wood substance below affected timbers or on the ground (Fig. 2.5).

With decay, there is a definite progression from sound wood to punky wood to a total loss of wood fiber, that is, a void. Unlike decay, insect damage tends to have an abrupt transition between affected and unaffected areas of the wood. Wood that has not been penetrated by insects retains its structural integrity, although there can be a loss of cross section. The loss of cross section directly relates to the load-carrying capacity of the member by decreasing the volume of wood available to carry loads. The decrease in cross section, if known, can be taken into account by engineers to determine if the affected member can still carry the required loads or if it needs to be reinforced or replaced. For both types of deterioration, moisture is generally required, and the result is a loss of integrity of the wood member, as well as a loss of cross section.

An additional type of wood deterioration that can occur with covered bridges members is called fuzzy wood and is caused by the chemical and physical action of salt breaking down wood fibers (Fig. 2.6). The crystallization of salt in between wood fibers can produce strands of fibers or, if severe enough, a mat of fibers on the surface. Salt damage is typically caused by the de-icing salts used on roadways. In salt environments, fuzzy wood is typically limited to the surface of the timber.

What to Look For

It is not the intent of these guidelines to provide details of how to conduct a wood inspection. Publications listed in the reference sections and the Bibliography provide that information. However, in the context of understanding how a condition assessment helps to make informed repair

Figure 2.7—Crushed timbers at lower chord (West Engle Mill Road Covered Bridge, 1877, Greene County, Ohio).

Figure 2.8—Fire damage of a floor beam (Blair Bridge, 1829, 1869, Grafton County, New Hampshire).

decisions, a summary of basic wood inspection questions and techniques is included here.

Determining the condition of wood components is the most common reason for conducting an inspection. Given the mechanisms of deterioration previously described, what is important to look for when conducting a condition assessment? Although not all inclusive, the following list identifies the primary conditions worth noting that may impact a decision regarding the need for a covered bridge repair:

- Moisture stains (Fig. 2.1)
- Presence of wood decay (Fig. 2.4)
- Insect activity (Fig. 2.5)
- Fuzzy wood (Fig. 2.6)
- Crushing of timbers (Fig. 2.7)
- Moss or lichens growing on wood components
- Peeling or flaking paint
- Fire damage (Fig. 2.8)
- Mechanical damage from vehicle impact (Figs. 2.9 and 2.10)
- Failed or damaged members (Fig. 2.11)
- Missing, loose, or displaced members (Fig. 2.12)
- Loose, missing, corroded, or broken connections (Figs. 2.13 to 2.17)
- Reverse camber (sagging) of the bridge (Fig. 2.18)

Where to Look

When conducting a condition assessment, one needs to know where to look. Knowing what areas of a covered bridge to inspect and what tools to use depends on the goal of the inspection. Where are the typical problems, and how do we go about looking for them? The inspection should begin with looking for problems where they are most likely to occur in a covered bridge. An inspection should focus on likely problem areas, such as the following:

- Wood with moisture stains, visible decay, or insect damage
- Wood in contact with the ground
- Notched or drilled timber connections where moisture can accumulate
- Truss members
- Deck joists, stringers, and girders (Fig. 2.19)
- Openings (for example, portals, frames, and windows; Fig. 2.20)
- Material interfaces (for example, bolster beams on masonry; Figs. 2.21 and 2.22)
- Exterior woodwork, including cladding and shingles (Fig. 2.23)
- Areas where debris can build up (for example, guardrails and bridge approaches; Figs. 2.24 and 2.25)
- Areas of the bridge that have been altered (for example, previous repairs; Fig. 2.26)

What Tools to Use

There are three “tools” for basic wood inspection: visual inspection, a probe, and a moisture meter. An individual experienced in wood inspection may also use a hammer for sounding or a portable hand drill to gain information about the relative condition of the wood, although neither of these methods allows for quantifying the extent of deterioration. They are best suited for identifying locations that warrant further investigation. A probe with a somewhat dull tip will not allow for quantifying the extent of deterioration in larger

Figure 2.9—Damage at portal from vehicular impact (Dunbar Bridge, 1880, Putnam County, Indiana).

Figure 2.12—Displaced top chord members (Dunbar Bridge, 1880, Putnam County, Indiana).

Figure 2.10—Damaged knee brace caused by vehicular impact (Lincoln Gap Covered Bridge, 1879, Washington County, Vermont).

Figure 2.13—Split at bolted connection in a Burr arch truss (Cornstalk Covered Bridge, 1917, Putnam County, Indiana).

Figure 2.11—Compression diagonal notch in timber sheared off in a multiple kingpost truss (Blow-Me-Down Covered Bridge, 1877, Sullivan County, New Hampshire).

Figure 2.14—Loose and missing connections in the arch of a Burr arch truss (Oakalla Covered Bridge, 1898, Putnam County, Indiana).

Figure 2.15—The steel rods, washers, and nuts have surface rust in this Howe truss. This is typically not problematic, but if the connections are loose, that may indicate more serious problems with the bridge (Shoreham Bridge, 1897, Addison County, Vermont).

Figure 2.18—Sagging (reverse camber) (Shoreham Bridge, 1897, Addison County, Vermont).

Figure 2.16—The bolts on the bottom chord of this Burr arch truss have extensive corrosion. This may be superficial, but the efflorescence of salt on the concrete bolster beam below the bottom chord indicates an environment where de-icing salts are used and where corrosion of the fasteners may be a significant problem (Waitsfield Village Bridge (or Big Eddy Bridge), 1833, Washington County, Vermont).

Figure 2.19—Bottom chord of the truss with deck joists above. Gaps can develop in the splices, weakening the bottom chord, especially towards midspan (Shoreham Bridge, 1897, Addison County, Vermont).

Figure 2.17—Close up of a severely corroded bolt (Blair Bridge, 1829, 1869, Grafton County, New Hampshire).

Figure 2.20—Portal opening and window (Lincoln Gap Covered Bridge, 1879, Washington County, Vermont).

Figure 2.21—Material interface at the abutment (Cornish-Windsor Covered Bridge, 1866, Sullivan County, New Hampshire, and Windsor County, Vermont).

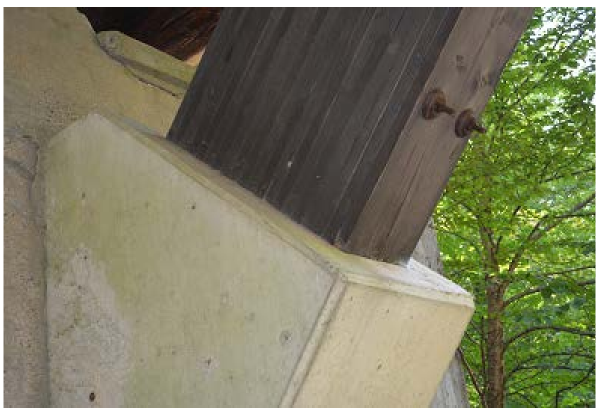

Figure 2.22—Material interface between an arch and abutment (Durgin Covered Bridge, 1869, Carrol County, New Hampshire).

Figure 2.23—Exterior cladding and roof over bearing beam (Blow-Me-Down Covered Bridge, 1877, Sullivan County, New Hampshire).

Figure 2.24—Location along a bottom chord where debris can build up between the diagonals and the vertical post (Pine Bluff Covered Bridge, 1915, Putnam County, Indiana).

Figure 2.25—Debris build up at bridge approach (Oakalla Covered Bridge, 1898, Putnam County, Indiana).

Figure 2.26—Previous repair to a truss post (Baker's Camp Covered Bridge, 1901, Putnam County, Indiana).

Figure 2.27—Resistance drilling of a Howe truss diagonal (Belknap Covered Bridge, 1966, Lane County, Oregon).

members, but it easily detects areas of surface deterioration and should be included in any wood inspection tool kit.

A visual inspection allows for identifying components that are missing, broken, or in an advanced state of deterioration. Missing components are those that have been removed or have fallen away, frequently because of extensive deterioration. If missing components were intended to provide structural support or protection from the elements (for example, to prevent moisture intrusion), their replacement may be essential to prevent long-term damage to the bridge structure. A small mirror with a telescoping handle and a flashlight are useful when inspecting relatively inaccessible areas.

Visual inspection also allows for the detection of past or current moisture problems as evidenced by moisture stains on the exposed surface of the wood.

Further, visual inspection enables detection of external wood-decay fungi or insect activity as determined by the presence of decay fruiting bodies, fungal growth, insect bore holes, mud tubes, or wood removed by wood-destroying insects (frass).

Internal decay and insect damage are often difficult to detect because of the lack of evidence on the exposed surface of the wood. Probing the wood with an awl enables rapid detection of voids in the wood just below the surface that may or may not be visible. It can also indicate the approximate depth of the deterioration. Visual inspection and probing provide a rapid means of identifying areas that may need further investigation or repair.

Moisture measurements can be taken to identify potential sources of moisture intrusion that could result in premature deterioration of the wood and to determine if further investigation of potential areas of decay is warranted. Moisture meters are extremely useful for identifying the current moisture content of wood and can identify problem areas that are not easily seen with the unaided eye. Moisture content measurements identify wood with moisture levels that are favorable for the growth of wood-decay fungi. Specific moisture content ranges that indicate areas of concern were previously discussed in the section "Mechanisms of Deterioration".

In addition to the three basic tools (visual inspection, a probe, and a moisture meter), hand drilling with small-diameter drill bits can be used not only to test the relative difficulty of drilling into wood (resistance) but also to observe the color and integrity of the wood chips extracted by the drill bit. Solid wood chips of light color are indicative of sound wood, whereas dark material with a consistency more like sawdust is indicative of decayed wood.

Nondestructive testing (NDT) equipment can give much more information about wood condition, but the use of such tools is often reserved for situations in which a basic inspection cannot sufficiently answer the questions of the bridgewright, engineer, or owner.

The most useful NDT methods for assessing covered bridges are the following:

- Moisture meters are extremely useful for identifying the current moisture content of wood and can identify problem areas that are not easily seen with the unaided eye.
- Resistance drilling using a calibrated electronic drill is useful to quantify the loss of material caused by decay or insect damage.
- Stress-wave analysis is useful to locate advanced decay.
- Digital radioscopy is useful to view hidden conditions and construction.
- Visual grading is useful for determining the strength of wood members in situ (discussed in Chapter 5).

Resistance drilling using a calibrated electronic drill provides quantified information about the internal, hidden condition of the wood members in a covered bridge (Fig. 2.27). The term resistance drilling has been used to describe any drilling technique intended to measure the ease of drill penetration into wood. Portable drills with standard bits have been used not only to test the relative difficulty of drilling into wood (resistance) but also to observe the color and integrity of the wood chips extracted by the drill bit. However, this type of drilling cannot quantify the loss of material.

Challenges When Assessing Condition

One of the most common issues when assessing a covered bridge is difficult access. Some members may have easy access on only one side (Figs. 2.28 and 2.29), some

Figure 2.28—The siding makes inspection of the treenail connections located on the outside of this Town lattice truss difficult (Cornish-Windsor Covered Bridge, 1866, Sullivan County, New Hampshire, and Windsor County, Vermont).

members may be wholly or partially covered by other members (Fig. 2.30), and some members have excellent accessibility (Fig. 2.31). Other members may have no easy access although they are visible from a distance (Fig. 2.32). The assessment may be limited to visual inspection, perhaps using a mirror or videoscope, or limited to touch to sense loose or missing connections or pockets of deterioration.

On the bridge shown in Figure 2.30, the guardrail is on shims to allow debris to flow underneath the guard rail and off of the deck. The bottom chord of the truss is only accessible from below. However, because of the elevated guardrail, this bridge is more conducive to "natural" cleaning that decreases maintenance requirements.

Contrasted with the hidden bottom chord shown in Figure 2.30, the bottom chord of the truss shown in Figure 2.31 provides nearly ideal access for inspecting the timber. The timbers are visible, and accessible for probing or conducting resistance drilling. It is easy to see if debris is trapped.

Figure 2.29—Top chord of a Town lattice truss that is difficult to inspect on the top and outside surfaces because of the roof pitch (North Hartland Twin Bridge, 2001, Windsor County, Vermont). There is a twin bridge at this river crossing (the Willard Covered Bridge) that dates from 1871.

Figure 2.30—Limited access to bottom chord of the truss for conducting a condition assessment (Willard Covered Bridge, 1871, Windsor County, Vermont).

Although each bridge and bridge type present their own challenges for assessing condition and identifying appropriate repairs, there are generalities that can be made regarding common deficiencies for various bridge truss types. Table 2.1 summarizes common deficiencies for common truss types.

It is essential to remember that the purpose of the inspection is to provide data that can be used to answer questions raised by the architect, engineer, or owner about the condition of the wood in a covered bridge. If the wood has moisture stains, are the stains recent, as indicated by high moisture content readings, or is the wood sufficiently dry that the stain probably occurred long ago? If decay is present, is it active, as indicated by a moisture content reading greater than 20%, or is the decay fungus dormant? Were splits caused by normal drying checks, or are they an indication of failure of that component? If so, was the failure caused by loads exceeding the capacity with time, or could it have been caused by a one-time occurrence? The

Figure 2.31—Excellent access to bottom chord of the truss for conducting a condition assessment (Belknap Covered Bridge, 1966, Lane County, Oregon).

Figure 2.32—Girders and stringers that are visible from below but are difficult to access because of the height above the river (Lincoln Gap Bridge, 1879, Washington County, Vermont).

inspector should ask these types of questions. Sound technical data about the current condition of the wood are necessary for effective repair and replacement decisions to be made. Such data are the result of a thorough wood inspection.

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Table 2.1—Common deficiencies found by bridge type

Truss type	Deficiencies
Kingpost	1. Loose diagonals (caused by moving loads) or braces lacking wedges for adjustment. Moving loads cause flexure in the chords. Without counter braces, diagonals become alternately loose and then tight fitting as chords flex and recover. With time, diagonals may fall out of position entirely. 2. Undersized or overly wide spacing of vertical members near abutments or piers, sometimes signaled by crushing of diagonals near abutments, open joints nearer the center of a span, and pronounced deflection of chords in the abutment bays. Strains in the diagonals and ties (vertical members) are greatest near the abutments, although bridge builders did not always adjust panel length and member section to reflect this. 3. Decay in open joinery of the top and/or bottom chords. Both are places where water is apt to get in — at the top primarily as the result of roof leaks and at the bottom as the result of leaks in the siding, water blowing off the river, and water brought onto the roadway by vehicles. Inspection of all four sides of either chord is rarely possible; therefore, decay around joinery often reaches an advanced state before becoming visible.
Town lattice	1. Loss of camber (sag) caused by inadequate stiffness of the truss. This can be the result of having too few pinned connections (that is, having too few lattice members and/or insufficient depth of the truss so that there are too few lattice intersections), lattice members installed at an angle that results in ineffective diagonals, or defects in the pinned connections (too few pegs or splitting of lattice members around pegs because the pins were installed too near the edges of lattice members). Builders occasionally included additional chords (crossing the second intersections of ties and diagonals), but because they are located nearer the neutral axis, these are less efficient than chords at top and bottom. 2. Warping of the trusses. This condition may be especially recognizable as bowing or buckling of the top chord and is caused by insufficient thickness of the chord material and/or insufficient cross bracing. This condition is frequently found in conjunction with loss of camber. Historically, bridge builders sometimes addressed this issue by framing double lattice trusses, trusses with two sets of ties and diagonals sandwiched between three sets of chords. This arrangement stiffened the truss against warping but also doubled the timber devoted to ties and diagonals while only increasing the cross section of the chords by 50%. 3. Decay at chord–lattice and lattice–lattice connections. Because of the tight laps at intersections, these areas are slow to dry and prone to decay. 4. Compression failure in lattice members located near abutments. This is because diagonals and ties are shortest where stresses are highest. Builders frequently avoided the problem by extending the length of abutments by a distance roughly equal to the depth (height) of the truss. In historic bridges, where extending the trusses is no longer an option, trusses may be strengthened by the addition of arch braces (with straining beams) or arches. These can also be used to address insufficient section in the chords. 5. Decay of pegs in lattice–bottom chord connections caused by the high level of exposure to the elements.
Burr arch	1. Loose diagonals (caused by moving loads) or diagonals lacking wedges for adjustment. Moving loads cause flexure in the chords. Without counter braces, diagonals become alternately loose and then tight again as the chords flex and recover. With time, diagonals may fall out of position entirely unless connections are configured to prevent this. 2. Trusses with inadequate stiffness. Where moving loads are heavy, there should be counter diagonals or at least ties parallel to the diagonals to stiffen the trusses (this is also true of kingpost trusses). Counter diagonals fitted with wedges (or threaded connections) allow for preloading, decreasing flexure from moving loads. 3. Insufficient depth of the arch to resist vertical loads. 4. Decay in open joinery of the top or bottom chords. Both are places where water is apt to get in, at the top primarily as the result of roof leaks and at the bottom as the result of leaks in the siding, water blowing off the river, and water brought onto the roadway by vehicles. Inspection of all four sides of either chord is rarely possible; therefore, decay around joinery often reaches an advanced state before becoming visible. 5. Differential settlement of arch and truss, resulting in bolted connections between the two being overstressed.

Table 2.1—Common deficiencies found by bridge type—continued

Truss type	Deficiencies
Howe	1. Loose counter diagonals or counter diagonals lacking wedges for preloading. Moving loads cause flexure in the chords. Without counter diagonals, preloaded against the maximum moving load, the bridge will be prone to excessive vibration as the chords flex and recover. Counter diagonals fitted with wedges (or threaded connections) allow for preloading, decreasing flexure from moving loads.
Long	1. Loose counter diagonals or counter diagonals lacking wedges for preloading. Moving loads cause flexure in the chords. Without counter diagonals preloaded against the maximum moving load, the bridge will be prone to excessive vibration as the chords flex and recover. Counter diagonals fitted with wedges (or threaded connections) allow for preloading, decreasing flexure from moving loads.
	2. Loss of relish in tie–chord connections. The truss relies on vertical wooden ties to connect the chords. Decay or weathering of the ends of the ties can result in failed connections.
All bridges	1. Decay where bottom chords contact abutments and absence of bolster beams or bedding timbers, which are frequently made of denser, naturally decay-resistant wood and support the bottom chords off the surface of the abutment.
	2. Loss of camber in chords, accompanied by buckling of top chords. This can be the result of loss of connection capacity, insufficient depth of the truss, or failing/open splices in the bottom chords in tension.
	3. Damage by cars, trucks, or farm machinery especially at wind braces, siding at openings, abutments, and truss members (where there is no guardrail).
	4. Damage to the upstream side by floating debris (may be accompanied by displacement of lower chords on piers or abutments).
	5. Alteration or removal of wind bracing to accommodate larger vehicles. This can result in buckling of the top chords and/or inclination of the trusses toward the leeward side.

Chapter 3: Engineering Analysis

In addition to conducting a condition assessment, understanding the structural behavior of the various components of the bridge is essential to making effective repair recommendations. Understanding the structural behavior is achieved when structural engineers conduct an engineering analysis of the entire structure — the trusses, deck, roof, abutments, and piers. This chapter is intended to provide the bridge steward or decision maker with a sense of the language and process for properly analyzing a covered bridge, which should contribute to repairs being based on sound technical data and analyses.

A covered bridge behaves as a system different from other structures. Without proper understanding of how a bridge works, the process of designing and implementing repairs can be detrimental to the long-term performance of the bridge. These guidelines are not intended to serve as a primer on the engineering analysis of covered bridges, but a few points for consideration and some examples are provided to illustrate some of the subtleties that are often overlooked when analyzing a covered bridge.

Once condition assessment information is available, an engineering or structural analysis can be conducted. Structures are analyzed by engineers for their behavior under various loading conditions. This is typically accomplished through either structural analysis software or conducting historical analysis. There are several publications and books that discuss design and engineering analysis of timber bridges in general and covered bridges in particular.

Structural engineers that are covered bridge aficionados appreciate the idiosyncrasies and evolution of covered bridge design. The various truss designs shown in Chapter 1 evolved from improvements made by those that designed bridges. There are excellent sources of information, listed in the Bibliography chapter, to gain an understanding of the original design intent and the structural performance of early timber bridges, including covered bridges. Steven H. Long, Squire Whipple, Ithiel Town, and Herman Haupt all produced early treatises on timber trusses. More recent publications serve as useful primers on how a covered bridge works from an engineering perspective, including publications by the Federal Highway Administration, Dario Gasparini (and others), Justine Christianson and Christopher Marston, Jan Lewandoski, David C. Fischetti, and Phillip Pierce.

Most analyses of covered bridges are done using standard structural analysis software. However, covered bridges are somewhat unique and typically do not appear to perform well when analyzed using standard structural analysis programs that may have been developed for concrete, steel, or modern timber construction. There are several reasons for this, a key one being that many covered bridges rely on traditional carpentry joints that are not considered in most structural analysis programs. Covered bridges rely on subtle construction details (such as modeling traditional timber joinery) that are not well suited to most computer modeling software. Additionally, a lack of knowledge about the wood species and structural grade of the timber often results in underestimation of a bridge that may have been performing adequately for decades. Thus, the model inputs for timber-joinery connection details and material properties for analyzing a covered bridge are often unknown, and these inputs may be quite variable.

For new wood construction, structural engineers rely on design values referenced in building codes to determine acceptable species, size, and grade for a particular load condition. For existing covered bridges, engineers often rely on current codes and standards to determine adequacy of the wood members. However, current standards are generally based on lower quality material than what may be found in many historic covered bridges. Because many older bridges were constructed before building codes or design values for wood products were established (and thus before grade stamps were used), engineers inexperienced with historic structures or materials are often in a quandary when determining what design values are appropriate. Frequently, a species and grade are assumed, leading to wood members being declared structurally deficient. The result is often an overly conservative estimate of design values and unnecessary replacement, repair, and retrofit decisions, with the associated unnecessary project costs.

Even for a relatively simple structure, such as a multiple kingpost truss bridge (Fig. 3.1), the results from most commercially available computer modeling software typically show that the bridge is structurally inadequate, when in fact, it has been performing quite well for some time. There is a certain irony in watching a 30-ton truck cross a bridge with a posted 3-ton limit without producing a visible deflection. The bridge is performing well. What is

Figure 3.1—Multiple kingpost truss (Blow-Me-Down Covered Bridge, 1877, Sullivan County, New Hampshire).

Figure 3.2—Check brace (Pulp Mill Covered Bridge, 1820, Addison County, Vermont).

needed is an understanding of why it is performing well. Understanding how a bridge is performing is a goal of the condition assessment and the engineering analysis.

Figure 3.1 shows that how and where the truss members are connected can dramatically impact the structural performance of the truss and bridge, and accurately modeling that performance in a computer model is often very difficult to do. To illustrate some of the peculiarities of covered bridge structural behavior, examples of issues to consider when analyzing simple joints or the composite action of a Burr arch truss are presented later in this chapter.

Construction Details

It is important to understand that there are very few unnecessary components in a covered bridge. If there is something inserted into the structure, no matter how small, there is probably a reason it is there. An example of this is the small check brace shown in Figure 3.2. The truss was constructed with the diagonal web member connecting to the vertical below the panel point. The intent of the design was that the vertical post be axially loaded and the diagonal web member connects to the post below the top chord to simplify the joinery where the vertical post meets the top chord. The diagonal web member induces a bending moment in the vertical post at the connection (remember that the post is designed to carry axial loads, not bending loads). To resist the bending moment and keep it from pushing the vertical post out of plane, the bridge builders inserted a short check brace. Some contractors or structural engineers may not realize the importance of this small detail. If the check brace is removed during repairs, a bending moment is introduced in the vertical post that it was never intended to carry, possibly resulting in unintended consequences.

The repair detail shown in Figure 3.3a and b is a round shear pin, designed to transfer shear loads between adjacent members of a Town lattice truss. To the untrained individual, it may look like a plug with no structural role. The shim in Figure 3.4 was inserted during previous repairs to ensure that the compression load in the diagonal was transferred adequately. Sometimes these small construction details seem like an afterthought, and people want to pull them out (sometimes as a souvenir). If a shim needs to be removed during repairs because of deterioration or damage, a new one should be installed using one made of the same wood species. If it is not replaced, leaving a gap, the

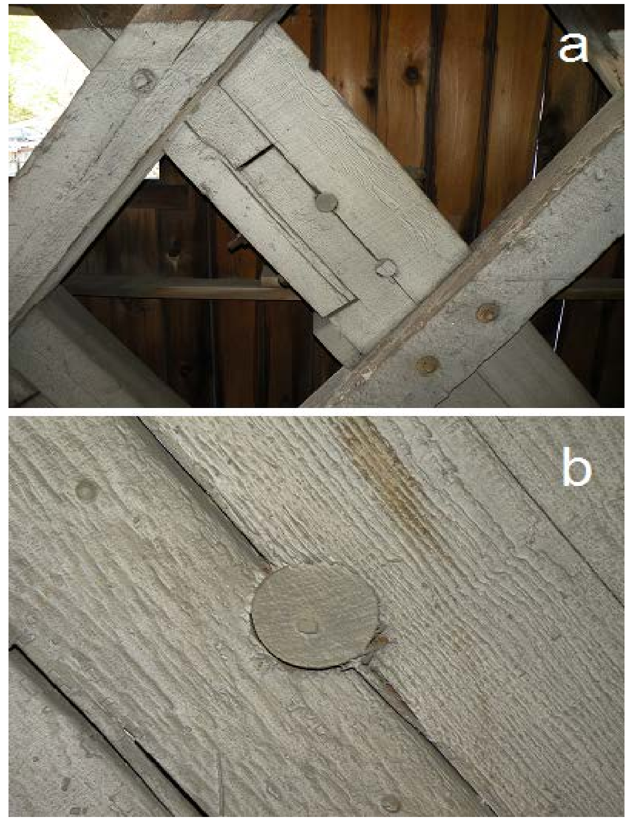

Figure 3.3—Round shear pin between diagonal truss members (a) with close up (b) (Cornish-Windsor Covered Bridge, 1866, Sullivan County, New Hampshire, and Windsor County, Vermont).

Figure 3.4—Shim in a compression diagonal of a Town lattice truss (Cornish-Windsor Covered Bridge, 1866, Sullivan County, New Hampshire, and Windsor County, Vermont). The shim should not be removed.

diagonal will no longer have full contact in bearing and the compression load will not be transferred as originally intended.

Timber Joinery and Connections

Structural analysis of a traditional covered bridge will provide information on the internal forces in the framing members and estimates of the deformations (deflections) that the bridge will experience under various loads, such as those caused by structure self-weight, vehicular traffic, pedestrians, snow, and wind. The analysis models also report the forces acting at connections (also referred to as joints) between members. Resolution of the member forces at a connection, such that they are effectively transferred through the connection, is critical to the performance and long-term durability of the structure. Hence, special consideration must be given to connection design and also to repair of distressed or failed connections. The critical role of connections is easily overlooked relative to the overall configuration and condition of the structure, probably because the load-transfer mechanisms in a traditional timber connection are typically not accurately characterized by the structural analysis model. Thus, professionals with experience in covered bridge evaluation and repair must be engaged early in the project to perform the required assessment, analysis, design, and repair.

Traditional joinery used in historic structures, including mortise and tenon joints, notched heel joints in trusses, scarf joints, and others have performed well in hundreds of bridges for centuries and are effective solutions for repair situations. An uninformed rush to use nontraditional methods, such as steel side plates, gussets, weldments, etc., demonstrates a lack of understanding on the part of the engineer or contractor and can actually compromise the integrity of the repair. Rather, an understanding of the load-transfer mechanisms in traditional joinery and a sensitivity to the properties of timber used in these structures can yield a repair that possesses structural integrity along with the aesthetic qualities of the original construction.

For example, consider the roof-truss heel joint shown in Figure 3.5 (this type of joint can be found elsewhere in covered bridges but is often used in the roof trusses). Under normal circumstances, the rafter load thrusts into the notch, producing a tension force in the tie. The post supports the truss by applying compression to the bottom of the tie at the joint. Aside from selection of the members themselves, designers of such a connection must consider at least the following load-transfer mechanisms:

1. The tension force in the horizontal tie is resisted across the net cross-sectional area of the tie at the root of the notch, where stress concentrations act.

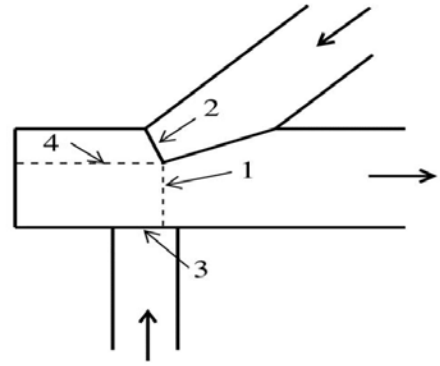

Figure 3.5—Roof-truss heel joint (Used with permission from Dick Schmidt, Fire Tower Engineered Timber).

2. Thrust in the rafter is transferred into the tie without crushing wood fibers at an angle to the grain of either the rafter or the tie.
3. The post provides vertical support to the truss without crushing the wood fibers of the tie perpendicular to the grain.
4. The horizontal component of the rafter thrust must be carried into the tie without causing shear failure of the tie. Stress concentrations act at the root of the notch as well.

In addition to understanding the basic load-transfer mechanisms in traditional joinery, professionals engaged in repair of covered bridges must understand the properties of wood sufficiently to make wise design decisions. Some factors that a design professional should allow for when designing the repair of a connection include but are not limited to the following:

- Repair in-kind, that is, match the wood species, structural grade, surface texture, and moisture content of the original members with the replacements. Timbers salvaged from other structures (mill buildings, mines, trestles, etc.) might be preferred to freshly cut and dried stock.
- Consider partial replacement of decayed or damaged members by removing only the decayed or damaged portions of a member and scarfing in a replacement section.
- Design joinery that effectively sheds water or can be protected from rain and runoff. Notches, pockets, or other depressions that can hold water must be protected by siding, flashing, or other means.
- Avoid using steel side plates or knife plates. They constrain the connected timber from its natural tendency to shrink and swell with changes in moisture content that occur naturally throughout the year. They also hold moisture against the

timber, preventing it from drying (which can lead to decay), and possibly prevent detection of decay during maintenance inspections.

- If necessary, connect steel rods (which can be effective tension members) to the timber members by fully penetrating the member so that load is transferred by direct bearing on the opposite side of the member using a nut and washer.
- Minimize eccentricity in joints, that is, the centerlines of all members that frame into a joint should meet at a common working point. For example, the heel joint of the roof truss in Figure 3.6 should have its support post at position A rather than at position B. An exception to this approach is to use a check brace as was previously discussed if the eccentricity cannot be avoided.
- Attempt to transfer load through contact by wood-on-wood bearing surfaces rather than through lateral load in bolts. For example, case C in Figure 3.7 shows that a keyed scarf joint with a table is preferred to case D with the simple half-lap joint. The "table" is the offset portions between the two pieces of timber that bear against the shear key, which is indicated by the X in Figure 3.7C.

To illustrate the unique structural performance of covered bridges and the issues to consider when developing a structural model, two examples are given below that represent typical questions and considerations that should be asked by the structural engineering firm as part of their analysis. The first example addresses general considerations in the analysis of timber joinery, and the second example poses questions about the composite behavior of a more complex Burr arch truss.

Considerations for Engineering Analysis of Timber Joinery and Connections

As was previously mentioned, joint design and structural evaluation begins with an analysis of the structural system to determine member forces acting on the joints. This analysis includes a number of considerations that can have a significant impact on the results. Looking a bit closer at a particular joint or connection, the following questions might be asked:

- Is the joint pinned, fixed (rigid), or somewhere in between?
- Are there loading conditions that cause the reversal of member forces?
- When there is more than one possible load path through the structure, how much load is resisted by each path?

Often member forces are bounded by analyzing multiple conditions and assumptions and then considering the maximum of each. These forces and stresses can be compared with field observations in an attempt to more closely reflect past performance. Components of the structural system that are working well and others that show signs of distress should be identified because this information can help guide the analysis to some degree. The result of this process is a set of member forces that can be used in the analysis of the joints.

At first glance, joint analysis can appear quite simple. Free-body diagrams of the joint are created for each controlling load combination, including all of the member forces. Each of these forces must be transferred through the joint using a calculated structural approach. Usually, bearing or fasteners are used to resist the loads.

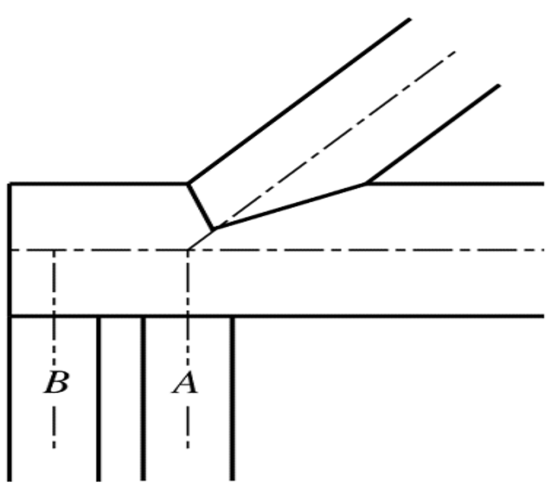

Figure 3.6—Heel joint of a roof truss (Used with permission from Dick Schmidt, Fire Tower Engineered Timber).

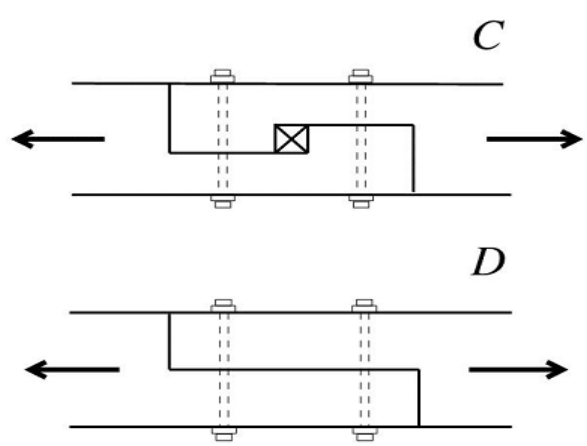

Figure 3.7—Wood joints using bolts (Used with permission from Dick Schmidt, Fire Tower Engineered Timber).

There are a number of subtle yet important considerations that can add to the complexity of joint analysis. For joints that involve a mixture of existing timbers and new timbers, it is often important that new timbers are dried to a moisture content that closely matches the existing timbers. If not, there will be shrinkage of new timbers that could affect the structural capacity of the joint:

- Shrinkage rates vary with orientation to the growth rings. Typically, shrinkage in the direction tangential to the rings is greater than radial shrinkage, and longitudinal shrinkage is negligible. This variability can affect bearing areas.
- Bearing lengths can be affected as a supporting member shrinks away from the supported member.
- Bearing areas can be affected by changes in the angles of bearing surfaces as new members come to equilibrium.
- The capacity of connections involving fasteners can be drastically affected by moisture content. The National Design Specification for Wood Construction includes strength reduction factors to account for the use of unseasoned timbers and for timbers used in high moisture conditions. For instance, when multiple rows of bolts are used to connect steel plates to timbers with a moisture content greater than 19%, the capacity of each bolt can be decreased to 40% of that with dry timbers (less than 19% moisture content). This is caused by the steel plates, in conjunction with the bolts, restraining the natural shrinkage of the wood, causing splits at the bolts.

Other considerations:

- Ideally, the structural capacity of a joint will be governed by a nonbrittle failure mode. It is preferable for joint capacities to be limited by bending or bearing rather than tension or relish (material between the bolt and the end of the timber) strengths. This helps to ensure that there will be a visual indication of joint overstress before complete failure occurs.
- Friction is typically neglected; therefore, bearing surfaces can only resist components of loads that are perpendicular to the surface.
- In mortise and tenon joints, how much tenon bearing should be included? This can be affected by swelling and shrinking and by the tightness of fit of the mortise with respect to the tenon.
- How will member rotation affect joints with longer bearing lengths?
- What are the tolerances and how will they affect bearing areas?
- Consideration needs to be given for reduced member strength at connections because of mortises, housings, etc.
- It is generally not recommended to combine multiple load resistance methods (peg shear with bearing for instance) because of differing stiffnesses.
- Is the joint configured in an eccentric way, and has this been accounted for?

Considerations for Engineering Analysis of a Burr Arch

A Burr arch is a combination of a truss, typically a multiple kingpost truss, and an arch (Fig. 3.8). The truss and arch are intended to work together to share the loads acting on the bridge. To assess the structural adequacy of the existing members and their connections, one must first establish how much of the applied load is resisted by the truss and how much is resisted by the arch.

This question is more nuanced than it may initially appear and has been a topic of spirited debate among bridge builders, bridge engineers, and bridge lovers since the time the first Burr arch was constructed. Contemporary structural analysis software can quickly do the calculations, but the analysis results are only as good as the assumptions made. There are so many variables at play in a Burr arch that it is not feasible to model the system with enough accuracy to provide a definitive answer about load sharing between truss and arch and the resulting forces in each member and connection. The engineer must use a healthy dose of engineering judgment to decide how a particular Burr arch bridge is behaving based on field observations, to decide how best to model it within the constraints of the available analysis software and project budget, and then to attempt to bracket that solution to account for the various uncertainties that were not explicitly included in the analysis model.

What follows is a discussion of some of the engineering issues and uncertainties to be considered when embarking on an analysis of a Burr arch.

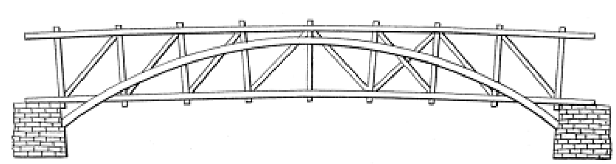

Figure 3.8—A Burr arch, constructed using a multiple kingpost truss and an arch (Image from Theodore Burr's 1817 patent).

1. How does the geometry of arch versus truss affect the distribution of load between the two?

When more than one load path is available, load will be distributed based on the relative stiffness of the competing load paths. The arch and the truss are two different load paths with different behaviors. An arch is very stiff under uniform loading — much stiffer than a truss of comparable span and depth; therefore, there is a tendency for more of the dead load to be resisted by the arch. The truss is stiffer and thus more effective for unbalanced (off-center) live loads because an arch with an unbalanced load tends to sway to the side in-plane of the arch. Connecting the arch to the truss to prevent this side sway stiffens the arch and allows it to carry more of the live load.

Structural analysis software does a reasonably good job of resolving the load distribution issues that are based purely on the geometry of arch and truss. However, there are many other factors that are difficult to quantify or model that affect the relative stiffness of arch versus truss and thus alter the resulting member design forces.

2. How does the nature of the connections affect load sharing between arch and truss?

The notched timber joinery used between truss members relies on side-grain or angle-to-grain bearing, which compresses more when loaded than the end-grain bearing at the ends of the arch segments. In addition, it is more difficult to cut the truss joinery to fit with perfect bearing on all surfaces, leaving more potential gaps in the truss joints than in the arch connections. When the Burr arch is initially loaded, the truss connections will have more "give" than the arch connections as everything compresses into tight bearing. Because tightening of joints is not considered in the computer analysis model, the model will overestimate the stiffness of the truss and underestimate the forces in the arch.

3. How is the end of the arch supported?

The most common detail is for the arch to pass by the truss bottom chord to bear directly against the abutment, as shown in Figure 3.8. The arch is only effective if the abutments prevent spreading at the arch supports. Poor quality construction at the abutments, particularly if the arch was a later addition and there is little behind the abutment wall to resist the thrust, can lead to abutment spread, decreasing the effectiveness of the arch and increasing the load carried by the truss.

Arches that project below the deck to bear against the abutment are prone to decay where in contact with the abutment; significant rot can cause the arch to settle downward with respect to the truss supports, completely changing the distribution of forces between arch and truss and potentially damaging members and connections.

Some Burr arches use a tied-arch detail instead (Fig. 3.9). In this case, the bottom end of the arch is notched directly into the truss bottom chord near the end of the chord. This has the advantage of better protecting the end of the arch from the elements and eliminating the possibility of differential settlement between arch and truss supports. However, the thrusting force of the arch is now resisted by the truss bottom chord rather than the abutments, significantly increasing the tension force on the bottom chord splices — the connection that typically limits the overall load capacity of the bridge. The arch-to-bottom-chord connection is prone to shear failure because the notch is close to the end of the chord; failure of this connection can produce distress in the truss as it results in complete loss of the arch action.

4. Are the arches connected to the trusses? If so, how rigid is the connection?

Most of the previous discussion has assumed that the arches are connected to the truss in a manner that prevents relative horizontal or vertical displacement between arch and truss at their connection point (rigid or fixed connection). Reality is more complicated.

In some cases, there are no connections between arch and truss; the arch is free to move in-plane under unbalanced loads and there is no way to share vertical loads between arch and truss. Thus, load will stay where it is applied, either to the truss or to the arch. Of more concern in these cases is the possibility that the arch will buckle out-of-plane, which has been observed in cases where an arch was added after the original construction to help support the floor but was not tied back to the truss.

Details vary for those cases in which the arch is connected to the trusses. A single iron through-bolt is a common detail, typically grossly undersized by today's design standards and often decreased in cross section because of corrosion (Fig. 3.10). If the bolt is undersized, does the engineer want to rely on that existing bolted connection as a load-transfer

Figure 3.9—A Burr arch using a tied-arch detail (Quinlan Covered Bridge, 1849, Chittendon County, Vermont. Used with permission from Katherine Hill PE, The Structures Studio – Structural Engineers).

mechanism? Some of these bolts show visible signs of distress when removed, including bending of the bolt and crushing of the surrounding wood; such a bolt cannot be assumed to provide a rigid connection from arch to truss. In theory, one could treat the bolt as a spring and continue on with the computer analysis; in reality, it is difficult to estimate the spring stiffness of the bolt with sufficient accuracy to justify the increased time and complexity to include this spring behavior in the computer model.

Other Burr arches have the arch notched slightly into the truss verticals. This increases the reliability of the connection compared with a bolt alone, but gaps will develop with time as the arch shrinks; therefore, this is not a truly rigid or fixed connection either.

5. Does the construction sequence affect member forces?

Distribution of dead loads between the arch and the truss can be significantly altered by the chosen repair sequence. If the whole system is shored until arch and truss are completed and connected together, gravity is effectively "turned on" upon removal of the shoring and dead loads will be shared between truss and arch based on relative stiffness. However, if the arch is completed first and used to support the bridge while repairing the truss, then the arch will be carrying 100% of the dead load upon completion of the truss (and vice versa).

6. How does the passing of time affect member forces?

As previously discussed, wood shrinks as it dries, and it can take years for a large green timber to dry to the point of equilibrium with ambient moisture conditions. There is greater shrinkage across the grain (that is, cross section)

Figure 3.10—A Burr arch bolted to the truss vertical (Quinlan Covered Bridge, 1849, Chittendon County, Vermont). The bolt is a 1- by 1-in. wrought-iron bolt penetrating 19 in. of wood, turned down to a 1-in. diameter at the threads (Used with permission from Katherine Hill PE, The Structures Studio – Structural Engineers).

than along the length of a timber. This means that shrinkage introduces larger gaps at the truss joints (perpendicular or angle-to-grain bearing) than at the arch joints (parallel-to-grain bearing). The increased play caused by the gaps that develop in the truss joints decreases the stiffness of the truss compared with the arch, causing a portion of the dead load in the truss to migrate into the arch.

Computer analysis of a Burr arch provides the engineer with a starting point for understanding the behavior of the system and estimating design forces for members and connections, but it is only a starting point. Engineering judgment is needed to account for numerous other factors that can affect the distribution of forces within the system.

From the discussions of traditional timber joinery, from analyzing a simple joint, and from considerations for analyzing a more complex Burr arch, it is apparent that covered bridges can have complex behavior that is difficult to model as is done with modern buildings. Having an engineer that understands the idiosyncrasies of covered bridges will allow for more efficient analysis and effective repair design.

Chapter 4: Supporting the Bridge for Repairs

For some bridge repairs, such as those focused on roof covering, siding, and decking, repair work can often be conducted without unloading the trusses or lifting the bridge. Additionally, limited structural repairs can sometimes be undertaken without shoring or extensive rigging on truss types that have many redundant members. For example, for a Town lattice truss, it may be possible to replace single lattice members because there are multiple lattice members present. Also, it may be possible to replace arch laminae across the depth of an arch when most of the laminae are intact.

Before more extensive repairs can be implemented, however, support of the bridge must be considered. When necessary, properly supporting the bridge prior to implementing repairs is accomplished through cribbing, shoring, staging, and rigging. Although these terms for supporting the bridge during repairs are sometimes used interchangeably, the following definitions point out the differences:

- Cribbing normally refers to a temporary support structure installed underneath the bridge to support a small area.
- Shoring refers to the process of temporarily providing support for the entire bridge during repairs.
- Staging refers to temporary structures for either access and/or support.
- Rigging refers to a system of ropes, cables chains, steel beams, or other supports used for temporarily supporting or moving materials, sections of the bridge, or the bridge as a unit.

In addition to these support mechanisms, moving the bridge off of its supports is sometimes done to facilitate repairs but this relies on adequate rigging, shoring, and cribbing during or after moving the bridge to prevent further damage and maintain (or recover) camber.

Cribbing, Shoring, Staging, and Rigging

For extensive truss repairs (such as replacing primary members), recovering lost camber, or installing new bed timbers, it is usually necessary to lift and support portions of the bridge while repairs are underway. Lifting and shoring are seldom focused on a single point along the length of a bridge. Instead, it is almost always necessary to lift and provide support at several points along the trusses, cribbing, or shimming at tie (column) locations to return lost camber to the trusses. Shoring and rigging strategies can generally be characterized as follows, although each bridge repair is unique and has specific conditions or situations that must be considered individually:

- Support from the riverbed. Timber piles can be driven into muddy river bottoms and configured to make bents for shoring. If the riverbed is rocky or sandy enough to support shoring without driving piles, timber cribs can be placed at jacking points. These can be supported on sand bags or makeshift raft foundations of large (3000- to 5000-lb) concrete blocks. These blocks are set into the river using a crane. Once in the water, they can be maneuvered into position from the bridge and leveled into foundations for timber cribs. Similarly, sand bags can be piled to provide a base for timber cribs; this is especially useful when working over uneven topography, which might be encountered along a riverbank, for example. It is often necessary to install coffers on the downstream side of these shores to prevent scour.
- Shoring from the abutments. The bridge abutments can provide useful foundations for shoring a bridge for repairs. Trusses or I-beams can be rolled into position across the bridge deck, cribbed over the abutments, and used to support needle beams for jacking and shoring the top chords of a bridge. If the abutments are wide enough, trusses or I-beams can be placed on either side of the bridge to support steel or timber needle beams for jacks and cribbing. When repairing a single truss, the shoring system can combine a beam placed in the bridge with one to the outside of the truss to be repaired.
- Suspension or cable-stay support. These rigging systems use cables supported on temporary pylons (or frames) to support a bridge while under construction. In cable-stay systems, stay cables fasten directly to (or over) the pylons (resulting in fan-shaped arrangements of the cables), whereas suspension systems use vertical suspenders connected to parabolic suspension cables. Cable shoring systems include proprietary systems (such as those by Dywidag Systems International USA, Inc., Bolingbrook, IL) but can also include custom-built systems with cables anchored to deadmen on either shore and supported on temporary timber towers. Related to these cable systems, a crane equipped with slings and spreaders can sometimes be used to lift and support discrete portions of a bridge while repairs are made, saving the expense of systems designed to support whole bridges.
- Shoring from existing supplementary support. Many covered bridges have already been altered to include supplementary support of the roadway, with I-beams or glulams supported on the

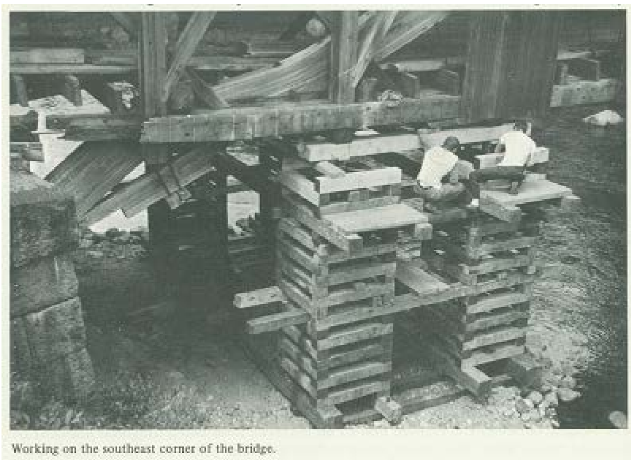

Figure 4.1—Cribbing installed to allow for repair of the deteriorated bottom chord in 1966 (Bartlett Bridge, ca. 1870, Carroll County, New Hampshire. Used with permission from Clifford-Nicol, Inc., Plymouth, New Hampshire).

Figure 4.2—Cribbing positioned to allow for repairs to the bottom chord and bedding timbers at the abutment (Fisher Railroad Bridge, 1908, Lamoille County, Vermont. Used with permission from Jan Lewandoski).

abutments and carrying the loads associated with the bridge deck. If supplementary members have sufficient capacity, they may be used to support crib towers erected on the roadway (inside the bridge) for shoring the top chords and making repairs to the trusses.

- Removing the bridge from the river. Smaller bridges of limited span can sometimes be removed from the river by crane (the size of the load will be a function of the capacity of the crane and the length and inclination of the boom) and placed on cribs or rails set up on the riverbank for this purpose. Once on temporary support, bottom chords can be shimmed to re-establish camber prior to making repairs.

Cribbing is one way to support a bridge for repair. In general, structural repairs should not be made when a bridge is under load. It is preferable to take the load off of members to be repaired, make the repairs, and then reapply the weight of the bridge. Cribbing allows you to transfer the weight of the bridge off the members to be repaired. Cribbing can be placed in the river if there is bedrock to serve as a foundation. If not, sandbags can serve as a base to support the cribbing timbers. Jacks are placed on top of the cribbing to raise the bridge members to remove the load, allowing repairs to be made. Cribbing is an art that is generally practiced by experienced bridgewrights. One of the early bridgewrights, Milton Graton, repaired many covered bridges and developed cribbing as part of the repair process that is widely used today (Fig. 4.1).

Knowing where to apply the cribbing below the bridge is critical. In some cases, cribbing and shoring are rather elaborate and need to be engineered because of the significance of the repairs needed to the bottom chord. For the bridge shown in Figure 4.2, the support was needed at the abutment to repair the bedding timbers. Additionally, cribbing and shoring were installed further from the abutment to support the heavy-timber lattice truss railroad bridge because of the need to repair the damaged timber that extends further from the abutment (Fig. 4.3). The cribbing and shoring allowed for replacing failed lattice members and adding supplementary braces to address displacement of the bottom chords just beyond the abutments (Fig. 4.4).

Shoring to support the bridge may require supports placed in the river. Although careful planning is critical, it is possible to place staging on a frozen river provided that the loads are not too heavy and the work can be completed before a thaw. More frequently, temporary foundations of large concrete blocks or sandbags can be leveled on the riverbed to support timber cribs (Fig. 4.5). Structural staging can be used for

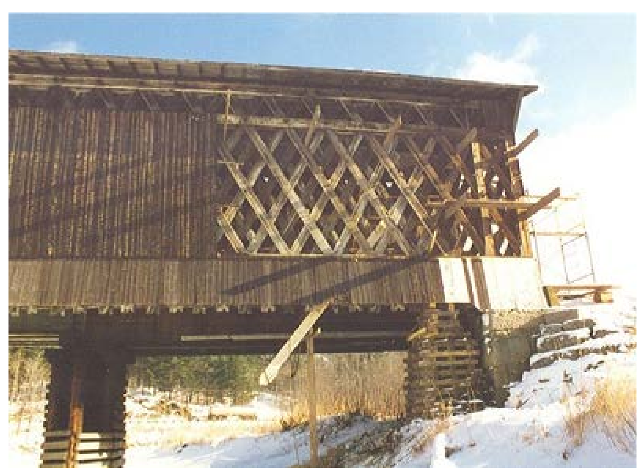

Figure 4.3—Cribbing under the Fisher Railroad Bridge (1908, Lamoille County, Vermont. Used with permission from Jan Lewandoski).

Figure 4.4—Repairs being made to the failed lattice members and bottom chords after placement of cribbing and shoring (Fisher Railroad Bridge, 1908, Lamoille County, Vermont. Used with permission from Jan Lewandoski).

shoring and may double as a work platform. The staging comes with jack heads that will carry lintels of wood or steel.

For shoring truss chords and decks, timbers, steel beams, or wood I joists suspended below the bridge deck often make up part of the shoring (Figs. 4.6 to 4.10). The shoring provides a walkway beside the bridge deck and can be used to support members that are to be repaired. Jacks can be placed on the shores when it is necessary to remove loads from members that require repair. As with cribbing, setting the staging is an art. Although the repairs are the final product, the logistics of repair implementation — setting the cribbing, shoring, and staging — are essential to

Figure 4.5—Shoring of the Israel River Bridge in progress. Note the staging hung from the cribs (Israel River Bridge, 1862, Coos County, New Hampshire. Used with permission from Jan Lewandoski).

Figure 4.6—Steel I-beams supported on timber cribs laid on the abutments. Timber shores were placed across the steel beams at each column, and the top chord was jacked. Note the suspended staging for accessing the bottom chords and deck frame (Best's Covered Bridge, 1899, Windsor County, Vermont. Used with permission from Jan Lewandoski).

implementing effective repairs and are frequently more challenging than the repair carpentry.

Rigging makes use of cables, chains, or other means to lift or support heavy timbers, staging, shoring, assemblies (for example, trusses), or the entire bridge. In the context of covered bridges, rigging typically involves the use of cables for lifting or providing temporary support (Figs. 4.11 and 4.12).

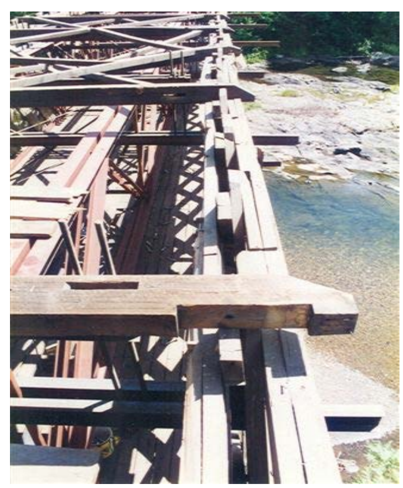

Figure 4.7—Temporary steel trusses installed above the deck for shoring this Town lattice truss bridge. After rolling the trusses through the bridge, they were cribbed over the abutments and used to support the top chords at several points along their length (Dummerston Covered Bridge, 1872, Windham County, Vermont. Used with permission from Jan Lewandoski).

Figure 4.8—Supplementary beams installed to support the roadway in an earlier repair were used to shore one of the queenpost trusses for repair. Note the repair at the bottom chord and replacement bed timber and arch brace (Lumber Mill Covered Bridge, ca. 1890, Lamoille County, Vermont. Used with permission from Jan Lewandoski).

Figure 4.10—Structural wood I-joists used as shoring beneath the truss chords and deck (Blair Bridge, 1829, 1969, Grafton County, New Hampshire).

The Cornish–Windsor Bridge is the longest two-span covered bridge in North America. The main support structures are Town lattice trusses, visible after the siding was removed (Fig. 4.13). A proprietary cable-stay system (Dywidag Systems International USA, Inc.) was used to shore the bridge for repairs. Primary cables were rigged on temporary steel frames, with cable stays supporting steel needle beams inserted below the top chords at regular intervals. With this system, it was possible to restore camber to the spans.

Modular support trusses are available to slide into the opening of a covered bridge, connect to the timber trusses, and remove loads from the wood trusses so that repairs can be made. These modular trusses essentially provide jacking points along the entire length of the bridge, so that the bridge can be fully supported to recover camber and make repairs. In this way, modular support trusses can expedite repairs and decrease the need for other means of structural support. The trusses are typically panel systems that are extended through the bridge from abutment to abutment. The weight of the multispan truss is not insignificant and requires care in installation to prevent damage to the timber bridge that may already be in fragile condition (Figs. 4.14 and 4.15). Monitoring movement at key locations, such as piers, may be desirable. Although accelerometers, lasers, or other sensors can be used to monitor movement or vibration, sometimes watching for vibrations in a cup of water strategically placed can be as useful as more sophisticated sensors (Fig. 4.16).

Other Considerations

Moving the bridge is accomplished either by setting rails and towing the bridge, raising and lifting the bridge off of its

Figure 4.9—Staging and shoring installed prior to beginning structural repairs (Blair Bridge, 1829, 1969, Grafton County, New Hampshire). The siding has been removed to facilitate repairs to the trusses, and the staging serves as a walkway to safely access the bridge.

Figure 4.11—Rigging using a crane, equipped with slings and spreaders to lift and support the portion at the abutment. Additional shoring of the Big Eddy included a timber crib near the middle of the river to decrease the effective span by approximately 40% (Waitsfield Village Bridge (or Big Eddy Bridge), 1833, Washington County, Vermont. Used with permission from Jan Lewandoski).

Figure 4.12—Using a crane to rig cable stays for supporting a small section of the bridge while repairs were made (Waitsfield Village Bridge (or Big Eddy Bridge), 1833, Washington County, Vermont. Used with permission from Jan Lewandoski).

supports, or lifting it with a crane. In the temporary location, it can be repaired without working over the river (Fig. 4.17). If it is deemed necessary to remove the bridge from the river to most effectively achieve the needed repairs, the crane operator must coordinate with the structural engineer to identify locations for attaching cables and rigging. The structural engineer will need to provide a rigging plan specifying the lifting points, cable sizes, and connection details. This information, much of which can be derived from the engineer’s structural model, is critical to avoid damage to the bridge during lifting.

Cofferdams are useful when repairs to piers and abutments are necessary. The cofferdam serves as a temporary enclosure around a pier or adjacent to an abutment to allow for the water at the base of the pier to be drained (Fig. 4.18). Once watertight, the enclosure creates a dry area for the repair work to proceed.

Repairing timber bridges can require custom sawmilling to obtain timbers in lengths not readily available or when transportation logistics may be prohibitive. The spruce log shown in Figure 4.19 was sawn into a 60-ft-long,

Figure 4.14—Acrow multispan panel truss being inserted (Blair Bridge, 1829, 1869, Grafton County, New Hampshire. Used with permission from Katherine Hill).

12- by 12-in. timber for replacing the decayed bottom chord of a small queenpost truss bridge.

When a bridge is over a deep ravine, moving the bridge or installing shoring may be challenging or infeasible because of logistics, cost, or environmental concerns. In these situations, it may be possible to install additional structure and avoid disassembly and repair procedures that require shoring. For example, on the bridge in Figure 4.20, many of the connections on the lower ends of the kingposts and diagonals had failed because of inadequate end distance in the connections. Shear blocks were installed to help transfer load between the diagonal and the vertical posts (Fig. 4.21) in areas of the timbers unaffected by deterioration.

In summary, cribbing, shoring, staging, rigging, and perhaps moving the bridge can all be part of the logistics necessary to implement effective repairs to covered bridges and provide the desired performance for decades to come.

References

Graton, M.S. 1978. The last of the covered bridge builders. Plymouth, New Hampshire: Clifford-Nicol, Inc.

Figure 4.13—Rigging (Cornish-Windsor Covered Bridge, 1866, Sullivan County, New Hampshire, and Windsor County, Vermont. Used with permission from Jan Lewandoski and D. Huston).

Figure 4.15—View from inside the bridge of the Acrow multispan panel truss as it is being inserted into the bridge (Blair Bridge, 1829, 1869, Grafton County, New Hampshire. Used with permission from Katherine Hill).

Figure 4.16—Monitoring pier movement using a paper cup filled with water to watch for vibrations (Blair Bridge, 1829, 1869, Grafton County, New Hampshire).

Figure 4.17—Bridge removed from the river for repairs. This small Burr arch truss bridge has been removed from the river (by crane) and temporarily shored on I-beams for repair. Because repairs included the addition of lamina to the arch and replacement of decayed bottom chord members to increase cross section of the chords, it was more efficient and cost-effective to move the bridge to implement the repairs (Bowers Covered Bridge, 1919, Windsor County, Vermont. Used with permission from Jan Lewandoski).

Figure 4.18—Constructing a cofferdam to allow for work on the pier (Blair Bridge, 1829, 1869, Grafton County, New Hampshire).

Figure 4.19—Felling a locally available tree to meet size requirements and transportation limitations (Lincoln Gap Covered Bridge, 1879, Washington County, Vermont. Used with permission from Jan Lewandoski).

Figure 4.20—A deep ravine that limits access to the bridge from below (Blow-Me-Down Covered Bridge, 1877, Sullivan County, New Hampshire).

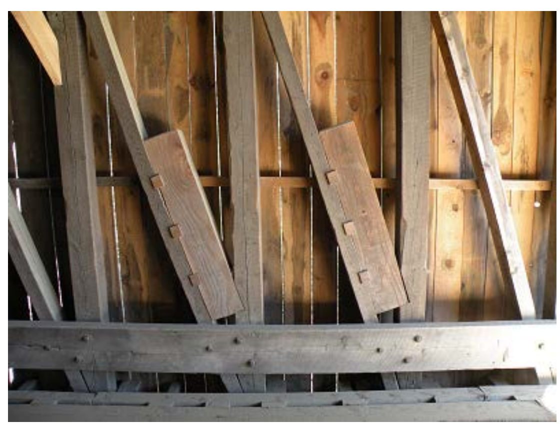

Figure 4.21—Shear blocks to transfer load between diagonal and vertical members that have deteriorated connections that could not practically be repaired from below (Blow-Me-Down Covered Bridge, 1877, Sullivan County, New Hampshire).

Chapter 5: Repairs

The first question that should be asked when someone suggests that repairs are needed is whether the bridge currently provides the required level of safety for its intended use. It may be obvious. A bridge with reverse camber (in other words, it is sagging) probably warrants some attention if it is intended to carry vehicular traffic. If it is just a matter of running a computer model and concluding that the bridge is inadequate (and therefore needs reinforcement or replacement), further consideration is warranted. Things to consider are the intended use and what the condition assessment revealed. If the bridge shows no signs of distress, it is possible that repairs may not be necessary.

The purpose of this chapter is not to provide details on all possible repairs for covered bridges but to provide decision makers with a sense of the options available to them when repairs are necessary. *The Last of the Covered Bridge Builders* (Graton 1978) has a wealth of information from a bridgewright's perspective about the idiosyncrasies of how covered bridges perform and how to repair them. Depending on the goals for the bridge, repairs tend to come under one of the following categories:

- Rehabilitating the bridge
- Strength enhancement
- Increasing clearance
- Increasing durability

As indicated in The Secretary of the Interior's Standards for the Treatment of Historic Properties, distinctive materials, features, and construction techniques or craftsmanship should be preserved whenever possible, which may limit some repairs. If repairs are necessary, they should be applied using the gentlest methods possible. As discussed in Chapter 2, prior to determining if repairs are necessary, the existing condition should be evaluated to determine the appropriate level of intervention needed.

Figure 5.1—Weathered bottom chord in good condition (Blair Bridge, 1829, 1869, Grafton County, New Hampshire).

Rehabilitating the Bridge Using Traditional Timber Repairs

Based on the condition assessment and engineering analysis, an informed decision about repairs can be made. Perhaps the wood siding or timbers are only weathered, and maintenance is all that is required. Perhaps there is isolated deterioration that should be addressed, but the bridge is able to carry the required loads. If deterioration is more widespread or members have failed, then multiple repairs may be necessary. If there are areas of deterioration severe enough to require repair or in-kind replacement of a member, the deteriorated material should be replaced with the same species and should match the original material in composition, design, color, and texture. Repairing timbers using traditional timber framing techniques and joinery are well suited to maintaining the historic character of the bridge.

Figure 5.1 shows the exposed bottom chord of a truss. It looks a bit weathered, and there are small seasoning checks on the outer face. Seasoning checks are a natural characteristic of wood that develop as the wood dries and shrinks until it comes into equilibrium with environmental conditions of humidity and temperature. The short seasoning checks on this timber are approximately parallel to the long edge of the timber. That indicates that the timber has very little slope of grain and is a high-grade timber for structural purposes, at least based on the outer face. Looking for checks or large knots on the other faces is the means of assessing the grade, which is discussed later in this chapter. For this timber, no repairs are needed.

If deterioration caused by wood decay or insect attack has decreased the cross section of the timber to the point at which it is no longer able to perform its intended function, replacement is warranted. Figure 5.2 shows a bedding timber, also called a bolster beam. The bedding timber distributes the load of the bottom chord at the abutment to prevent overstress that could result in crushing. For timber that is in direct contact with other materials, such as

Figure 5.2—Bedding timber supporting the bottom chord of the truss. Note spacer blocks to provide separation that limits moisture absorption from the concrete into the bedding timber, thereby extending the service life of the bedding timber (Cornwall-Salisbury Covered Bridge, 1865, Addison County, Vermont).

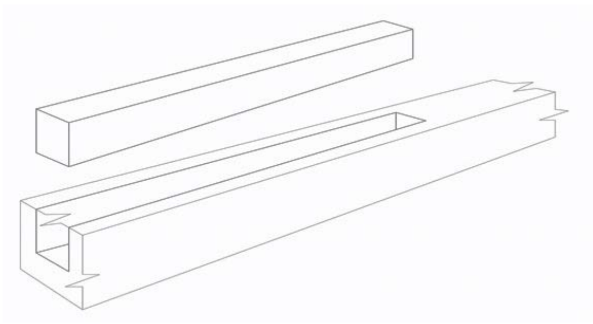

Figure 5.3—Typical dutchman repair. The decayed portion of the existing member is removed, and a new piece is cut to fit tightly into the void. The repair may be secured with mechanical fasteners and/or an adhesive (Used with permission from Keri Stevenson).

concrete or masonry, moisture can migrate from the concrete or masonry into the bottom face of the timber. After prolonged contact with moisture, the timber can provide a favorable environment for wood decay. The bottom chord of a truss is a difficult member to replace because of numerous connections. The bedding timber carries the load from a quarter of the bridge into the abutment (because there is one at the end of each bottom chord). If a bedding timber deteriorates, replacing it is easier and less costly that repairing the bottom chord. The bedding timber is there to protect the bottom chord of the truss from deterioration. In essence, it can be considered sacrificial. The bedding timber in Figure 5.2 has wood spacer blocks under it to create a barrier between it and the concrete.

Wood dutchman repairs (Fig. 5.3) can be let into deteriorated portions of bridge members in which decay is limited in extent. Dutchman inserts will improve the bearing area of deteriorated members, improve the performance of connections, and fill recesses and cavities that might otherwise collect water. Using wood to make the repairs has the advantage of introducing repair materials that have physical and mechanical properties that are similar to the original material while maintaining aesthetic continuity.

Traditional scarf joints, such as those shown in Figure 5.4, can be used to splice new timber into deteriorated members. These repairs are not invisible, but the visual impacts are not obtrusive or unattractive, and the joinery is interesting to look at. Limited replacement of decayed portions of members using traditional joinery has the advantages of preserving the salvageable portions of historic fabric as well as the historic craft tradition that produced the original construction.

Although many repairs can be done in situ, damaged timbers are often temporarily removed from the bridge for repair. The tenon in the post shown in Figure 5.5 had deteriorated, but the rest of the post was intact. Splicing in a new tenon allows for restoring the strength of the joint while keeping much of the historic fabric.

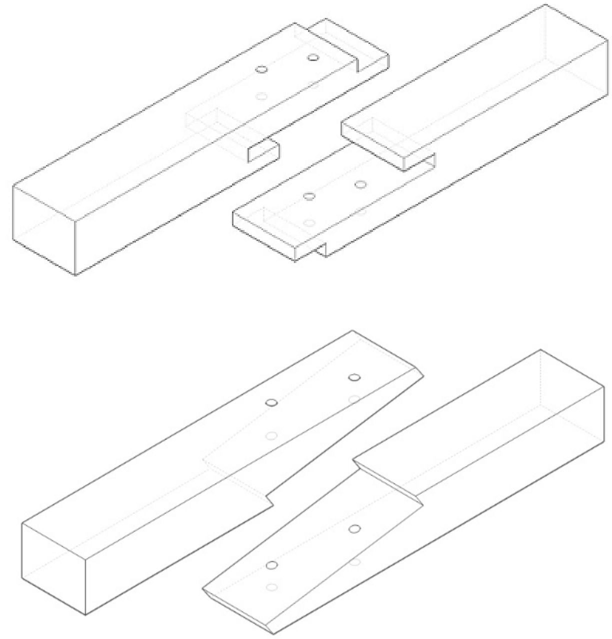

Figure 5.4—Two forms of a scarfed splice: half-lap with nose or bladed scarf (top) and stop splayed (bottom) (Used with permission from Keri Stevenson).

When making a traditional timber joinery repair, it is critical that the moisture content of the replacement timber be in a similar range to the original member. If a green timber, one that has a high moisture content, is used for the repair, the green replacement timber will shrink after the wood dries. The joint will not have the tightness between the wood surfaces in the repair to ensure a good connection. The repair should be done at essentially the same moisture content. With a moisture meter, the moisture contents of the original and replacement timbers can be measured. Because shrinkage properties vary between species and orientation of the timber, repairing in-kind with the same species, moisture content, and wood quality will ensure a long-lasting repair.

Figure 5.5—Tenon repair on the bottom of a post. The tenon was spliced into the deteriorated area, saving the rest of the post.

Figure 5.6—Circular-saw marks of decking boards (North Hartland Twin Bridge, 2001, Windsor County, Vermont).

If structural timbers are thoroughly deteriorated, the best way to recover adequate capacity is by replacing the member in-kind. When the structural members of a bridge are replaced, material should be used that matches the original in species and is of at least equal quality. In some cases, higher quality material (species or grade) may be warranted to decrease the likelihood of needing to do a similar repair in the near future. Higher quality materials will have greater structural capacity and greater durability; therefore, the investment in making the replacement will yield better performance and long-lasting results.

Although using the same species, moisture content, and wood quality are key to a successful structural repair, there are historical reasons for repair or replacing nonstructural material in-kind as well. Siding, roofing, or decking (which is structural) that is visible to the public may have characteristics that, if not replicated, may be obvious replacement material. Features such as saw marks can be specified on repair material to ensure that the textural characteristics of the historic material are not lost (Fig. 5.6). Recent repairs where the wood looks new compared with original fabric do not need to be artificially weathered to match the appearance (Fig. 5.7). Replacement material, structural or not, will weather with time and develop a similar patina to the original material.

Figure 5.7—Replacement of a bottom chord timber (Parvin Bridge, 1921, Lane County, Oregon).

Figure 5.8—Bottom chord and post repaired using spliced timber (Bunker Hill Covered Bridge, 1895, Catawba County, North Carolina. Used with permission from DCF Engineering).

Partial replacement using traditional timber joinery (or mechanical fasteners, although they should be used sparingly) allows for retaining the sound wood while limiting the amount of cribbing, shoring, or staging needed to implement the repair. The overuse of bolts and steel side plates in connections is detrimental to the aesthetics of the historic covered bridge, but more importantly, the steel allows for moisture to be trapped between the wood and the steel, possibly leading to decay of the wood or corrosion of the steel at the interface, which is a location at which the condition is difficult to observe during inspection and maintenance of the bridge. This is not to say that steel should not be used in repairs, just that it should be used sparingly and with consideration of unintended consequences.

Figure 5.8 shows a post and bottom chord that have been repaired using the same wood species and timber joinery. The damaged portions of the post and bottom chord, including the connections, were cut away and the replacement timber was spliced to the sound wood of the original members. When the same wood species, grade, and quality are used at the same moisture content, an effective in-kind repair is likely to be a long-term repair.

An experienced craftsperson that understands timber joinery can produce tight structural joints that will work and last for decades. That is what is needed with a spliced repair. A loose joint will not only fail to correctly transfer the loads across the joint but will allow for moisture intrusion into the joint that can lead to early failure caused by wood decay, thereby requiring another repair well before it should be needed. The splices in Figure 5.8 in the bottom chord of the truss eliminated the need to replace the entire bottom chord. A number of other splices are visible in the post and the diagonal, all using traditional timber joinery.

Figure 5.9 is an example of an arch that had some deterioration in laminae that made up the arch, probably caused by decay that developed with time. Rather than replacing the entire arch, it was possible to open the arch

Figure 5.9—Replaced laminations in a double Burr arch truss (Pulp Mill Covered Bridge, 1820, Addison County, Vermont).

Figure 5.11—Deep ravine, which made use of shoring cost-prohibitive (Blow-Me-Down Covered Bridge, 1877, Sullivan County, New Hampshire).

and replace the individual laminations. That is usually the best means of doing an arch repair. It is typically not necessary to replace the entire end of the arch unless it is in poor condition (Fig. 5.10). If not properly integrated with the rest of the arch, replacing a segment of the entire cross section of an arch can introduce stresses into the connections between the original and replacement segments that alter the behavior of the arch. As was discussed in Chapter 3, the distribution of loads between the arch and the associated truss is complicated and any effort to repair the arch should strive to maintain the balance of load distribution. If individual laminations are in need of replacement or repair, replacing the individual laminations is possible using an experienced craftsperson.

Understanding the structural behavior of a bridge, in part through proper engineering analysis, is key to implementing effective repairs. When a repair is not as simple as a partial or full replacement, innovative solutions to challenging repair situations may be necessary. The bridge shown in Figure 5.11 had failed corbels at the bottom of the truss posts. The wood joinery that connected the vertical posts to the diagonals and the bottom chord of the truss had decayed and needed to be repaired. The bridge crosses a deep ravine, making the use of cribbing and shoring to support the bridge during repairs costly and challenging. The craftsperson used a sistered diagonal in which the short replacement timber bears in a new notch in the post (Fig. 5.12). The repaired diagonal has a shear key between the members to adequately transfer the loads. Although not the most elegant or aesthetic treatment, the repair is functional, it leaves the historic structural system in place, and it addresses site conditions, which are beyond the control of the engineer and the bridgewright or contractor.

Many contractors believe that obtaining the quality of wood and timber to match that of the piece being repaired is impossible. However, the reality is that timber of the original quality still available. There are less than 700 historic covered bridges remaining in the United States. They are not all being repaired at the same time, and on any given bridge, a finite volume of timber is needed to do the repairs. Through good specifications, the proper quality of material can be acquired (Figs. 5.13 and 5.14). There may be more expense, but the cost of the material is more than offset by the longevity of the repair.

Figure 5.10—Blending of replacement laminations near the end of an arch with original laminations that are still in good condition (Mechanicsville Covered Bridge, 1867, Ashtabula County, Ohio).

Figure 5.12—Sistered diagonal repair, using shear keys to transfer load (Blow-Me-Down Covered Bridge, 1877, Sullivan County, New Hampshire).

Figure 5.13—High-quality lumber procured for bridge repairs (Blair Bridge, 1829, 1869, Grafton County, New Hampshire).

Sometimes sourcing the material requires being a bit creative. Many bridges are in rural areas with forest or woodlots nearby. For example, repairs have been made for which a 60-ft-long bottom chord was needed. That length can be challenging to purchase today, as well as to transport long distances to the site. If it is a single timber that is needed, a local wood lot or forest may have a tree that can yield timber of the required length. Purchasing the tree from the landowner, milling the timber, then allowing it to dry (obtaining a moisture content similar to the rest of the timber in the bridge) is a solution to a problem not often considered with other construction projects.

Reclaimed material is becoming more readily available. It can be used for smaller members, such as joists and girders, in the same species, grade, and quality as the material that was in the original bridge. Reclaimed timber may be available in larger dimensions, although these sizes may be more difficult to find. Bear in mind that if only a dozen large timbers are needed for a project, they are available somewhere. It may take time to source them, but it is definitely worthwhile because it increases the longevity of the repair and preserves the original integrity and historic character of the bridge without other augmentations.

Strength Enhancement

Strength enhancement is primarily considered during rehabilitation and when load upgrades are needed. For rehabilitation, the bridge is basically performing but has suffered some deterioration or maybe some failure of local members and needs to be repaired. The repairs can be made using traditional timber repair methods as previously discussed. The members that have deteriorated or been damaged will be repaired or replaced. Load upgrades are required when the bridge cannot support anticipated loads based on engineering analysis. In cases like these, bridges need to be strengthened. There are several means to increase load capacity. One approach that is often overlooked but can account for slight increases in allowable design values of the existing timbers is through visual grading of the timbers.

Figure 5.14—High-quality timber procured for bridge repairs (Blair Bridge, 1829, 1869, Grafton County, New Hampshire). Note the end checks (which are the result of the timbers drying) and proper storage with spacers to allow for air circulation.

Visual Grading to Determine Strength of Bridge Members

Material properties are important to the structural engineer when wood members carry loads, which is especially important with covered bridges. To determine if the existing timbers can carry the required structural loads, it is important to know the appropriate strength and stiffness properties of the wood. Identification of the wood species is an important factor, not only to calculate the wood's strength and stiffness but also to determine if there will be significant differential shrinkage if other woods are used for repairs. For wood in good condition, with no decay or insect damage, an estimate of strength can be made by determining the species of the wood and visually grading the wood members.

The first step in visual grading is identifying the wood species. Although some individuals can identify wood species in the field using a hand lens, the most reliable means to accurately identify species is done by examining anatomical features of the wood under a microscope.

Typically, to determine the species of a wood member, a sample as small as 0.5 to 1 in. long or a small core (0.5 in. or less in diameter) should be taken from an inconspicuous location. A representative number of samples should be taken from every framing member type (not from every member) to be graded. These samples can be analyzed for species identification by a university or a wood consultant (for a fee).

After the species is identified, then width and thickness, knot size, knot location, and slope of grain can be measured in the field and used to determine the allowable grade.

Knowing the grade enables strength properties to be assigned for design and structural analysis. For new wood construction, structural engineers rely on design values referenced in building codes to determine an acceptable species, size, and grade for a particular load condition. For existing covered bridges, engineers often rely on current codes and standards to determine adequacy of the wood members. However, current standards are generally based on lower quality material than is found in many historic covered bridges, that is, current codes and standards allow for larger knots than are found in older material. It is not that the older material is much better than new material but more that the new material is allowed to have larger defects, which decreases the design properties for the member.

Because many older bridges were constructed before building codes or design values for wood products were established (and, thus, before grade stamps were used), engineers inexperienced with historic structures or materials are often in a quandary when determining what design values are appropriate. Frequently, a species and grade are assumed, leading to wood members being declared structurally deficient. The result is often an overly conservative estimate of design values and unnecessary replacement, repair, and retrofit decisions, accompanied by higher project costs.

Although estimates of strength and stiffness can be made by knowing the species, establishing the grade, and therefore the design properties, is more involved. In situ grading of structural members in a covered bridge should not be conducted unless the individual is familiar with appropriate standards and has the knowledge of how grades are established within the design codes.

Knots and slope of grain are generally considered the most significant strength-limiting characteristics in lumber and timber that affect both the structural grade and material properties. Three major strength-reducing effects arise from the presence of a knot: (1) part of the timber cross section is decreased because harder, denser, but structurally weaker knotwood takes the place of the regular wood fibers; (2) a stress concentration, and subsequent decrease in capacity, is induced by the material inhomogeneity of the knot surrounded by the rest of the timber; and (3) the growth pattern of the trunk is disrupted by the branch that caused the knot, which results in considerable distortion of the grain angle around the knot. This grain angle distortion can allow for the development of tensile stresses perpendicular to the grain and the formation of checks and microfractures as the wood dries.

The location of the knot has an impact on member strength. Therefore, within industry-developed grading rules, there are knot size limitations based on the location of the knot. Centerline knots on the wide face of a member have the least impact on grade and therefore have the largest allowable knot size. Edge knots generally increase localized tensile stresses and therefore have smaller knot size limitations. This information can be useful to the structural engineer. Not only is the position of a knot known in a

Figure 5.15—Large edge knot in a diagonal brace (Eldean Covered Bridge, 1860, Miami County, Ohio). Note how the grain deviates around the knot and “runs out” at the edge of the member. This creates a weak location in the member.

particular timber but also the position along the length of the timber is known. For example, the grade-limiting knot may be on the bottom face of the bottom chord near midspan. Being in tension, that knot size and position will influence the performance of the bottom chord, and the grade is particularly important for that case. In contrast, if the grade-limiting knot is on the upper face near the end of another bottom chord, the influence on structural performance is much smaller. Based on grading rules, each knot (if the same size) would result in the same structural grade being assigned, even though the knot near the end on the upper face has much less influence on the performance of the chord.

One reason knots have such impact on the strength capacity of a timber is because of the distorted grain angle that occurs as the tree grows around the branch. When logs are milled into lumber and timber, the areas of distorted grain can be cut in such a way that segments of grain “run out” at one or several locations along the lumber’s length rather than extend parallel along the entire length of the board (Fig. 5.15). The same effect can occur if the timber is milled at an angle that is not parallel to the grain or if the entire log is twisted because of spiral growth patterns in the tree. Areas of cross grain, or where the grain runs out, create deviations in the way stresses are transmitted throughout the piece and concentrate stresses at the point at which the wood fibers have been discontinued, which significantly weakens the member.

Slope of grain is generally measured as a ratio of rise to run, that is, the number of inches the grain slopes upward or downward within a given distance (generally 8, 10, 12, or 15 in.) that is parallel to the long axis of the member (Fig. 5.16). Because seasoning (drying) checks in timber generally follow the slope of grain, determining the slope of grain on painted timbers can be achieved relatively easily by examining drying checks. All visible faces of the timber should be examined for slope of grain because not all faces will exhibit the same extent of slope of grain. Twist in a

Figure 5.16—Slope of grain as evidenced by the presence of seasoning checks (Seguin Covered Bridge, 1850, Chittenden County, Vermont).

member is also indicative of slope of grain when seasoning checks are absent (Fig. 5.17). Although not always conclusive, this approach closely correlates with results achieved using laboratory methods for measuring slope of grain, which are not practical for field use.

Seasoning checks, which are separations between wood fibers that do not fully penetrate the width or thickness of a member, are common in structural timbers and rarely affect the performance of a wood member. Splits are separations of wood fibers that extend completely through the width or thickness of a wood member. Short splits typically do not affect the performance of a wood member, but long splits should be evaluated by the engineer if there are concerns about shear strength in beams or buckling in columns.

Increasing Load Capacity by Augmenting or Reinforcing Existing Members

Increasing the load capacity of a bridge can be achieved by adding supplemental supports or augmenting existing members with stronger materials. The trusses are the key elements that support the bridge, but frequently, the limiting factor in carrying load is the deck itself. Simply increasing the number of floor joists may allow for a significant increase in capacity, providing the deck is adequate. Adding an arch to a trussed bridge can also increase capacity. The

Figure 5.17—Slope of grain in a vertical post as indicated by slight twisting at the top of the post (Pine Bluff Covered Bridge, 1915, Putnam County, Indiana).

Figure 5.18—U-bolt tying together a scarf joint in the bottom chord (Taftsville Covered Bridge, 1836, Windsor County, Vermont).

Cornish-Windsor Bridge over the Connecticut River had four radial arches installed in the 1980s to augment the Town lattice trusses. Adding arches is rarely done because it significantly alters the historic character of the bridge. It is more common to use stronger materials to augment the existing timbers or connections where they are deficient.

Steel U-bolts placed on opposite sides of the timbers can be used to augment the connection capacity between the timbers. The goal is to tie the chord together when minor damage or deterioration is present in or near the connection, but this does not warrant a full repair. The timber shown in Figures 5.18 and 5.19 is a bottom chord with a splice between two timbers. The steel U-bolts allow for increasing the strength of the poor connection by maintaining tightness between the timbers. Because the bottom chord is in tension, the connection wants to open under load; the U-bolt helps to keep the bottom chord timbers together and decreases sag in the bridge. Rather than steel U-bolts being used, connections in the original timbers are often joined with timber joints

Figure 5.19—U-bolt tying together a scarf joint in the bottom chord (Taftsville Covered Bridge, 1836, Windsor County, Vermont).

Figure 5.20—Lightning bolt splice used to join two timbers in a bottom chord (Blair Bridge, 1829, 1869, Grafton County, New Hampshire).

using shear blocks, such as the lightning bolt splice shown in Figure 5.20.

The use of bolts, lag screws, and nails to reinforce connections and splices is evident on prior repairs to covered bridges. Fully threaded structural fasteners are gaining acceptance in North America after being introduced in Europe prior to 2010. These fasteners have the advantage of being manufactured from high-strength steel and are self-tapping, that is, they do not require predrilling. With design values approaching those for bolts, these fasteners provide a less labor-intensive reinforcement option that does not alter the appearance of the bridge as the installation of steel plates or multiple bolts often do. Because they are being used in new construction and rehabilitation of timber structures, it is reasonable to expect that these fasteners will be increasingly considered as a viable repair strategy for reinforcing and strengthening traditional joinery.

Increasing Load Capacity Using Laminated Timber

There are a number of ways that mechanically laminated decking or glulam beams and deck panels have been used in covered bridges. Truss chords or floor beams made of glulam with higher allowable design values than solid timber is one way to increase load capacity. Although the use of glulam may not satisfy the intent of The Secretary of the Interior's Standards for the Treatment of Historic Properties in terms of in-kind replacement, it is a viable solution for increasing the capacity of a bridge that must carry vehicular traffic.

Glulam is made of various wood species, typically Douglas-fir or southern pine. It can be engineered and manufactured to provide specific design properties, often greater than those possible with high-quality solid timbers. For architectural effect, it is possible to have glulam fabricated with rough edges to better replicate the weathered, textured surface of the timbers they are replacing. In addition to the higher design properties of glulam, fabricating a single continuous truss chord without splices eliminates the strength reduction associated with the loss of net section

Figure 5.21—Glued-laminated timber joists for increasing the load-carrying capacity of the deck (Cornwall-Salisbury Covered Bridge, 1865, Addison County, Vermont).

from the timber shear blocks and butt joints between adjacent chord segments.

If multiple glulam segments are joined with steel plates, care should be taken to ensure that moisture does not get trapped between the steel and the glulam, leading to decay. Because only a few joints will be used, careful installation of the joint is critical to ensure proper load transfer and to limit the opportunity for moisture to be trapped in the joint. Glulam can be produced in less time than it may take for a large solid timber to dry to a moisture content at which it can be installed in the bridge. If exposure level is high and durability a concern, glulam (as with solid timber) can be pressure-treated to increase durability.

Often somewhat hidden from public view, glulam truss chords and floor beams are unobtrusive and can be installed using many of the same methods used for solid timbers (Fig. 5.21). Glulam connections often consist of steel angles and plated connectors, rather than traditional timber joinery, to take advantage of the higher design properties (Fig. 5.22). Glulam can also be used for bedding timbers (Figs. 5.23 and 5.24).

Solid lumber planks were traditionally used for decking, occasionally with two lines of running planks parallel to the long axis of the bridge for wheels (Fig. 5.25). The running

Figure 5.22—Installing a glulam bottom chord in a Town lattice truss ca. 1988 (Cornish-Windsor Covered Bridge, 1866, Sullivan County, New Hampshire, and Windsor County, Vermont. Used with permission from DCF Engineering).

Figure 5.23—Glulam bottom chord and floor beams being installed ca. 1988 (Cornish-Windsor Covered Bridge, 1866, Sullivan County, New Hampshire, and Windsor County, Vermont. Used with permission from DCF Engineering.)

planks could more easily be replaced than deck boards after physical abrasion from traffic decreased their thickness. Running planks were considered sacrificial; that is, maintenance of the deck included periodic replacement of these planks. Decking designed to carry greater loads relied on the composite action of the decking rather than on each deck plank carrying the load.

Mechanically laminated decking places the deck boards on edge, then secures them to one another with nails, and in later versions screws, to provide a stiffer and stronger deck than simple plank decks. The same construction technique is used to construct the arches in covered bridges to give them composite action so they act as a unit rather than several loose boards. Mechanically laminated decks have been used for several decades. The composite action can increase the capacity of the decks considerably. Since the early 1990s, stress-laminated decks have been in use (Figs. 5.26 and 5.27). The difference between the traditional mechanically laminated deck connected with nails or screws and a stress-laminated deck is that, with stress-laminated decks, the deck boards are joined with steel rods that extend across the entire width of the deck. The threaded rods are stressed in

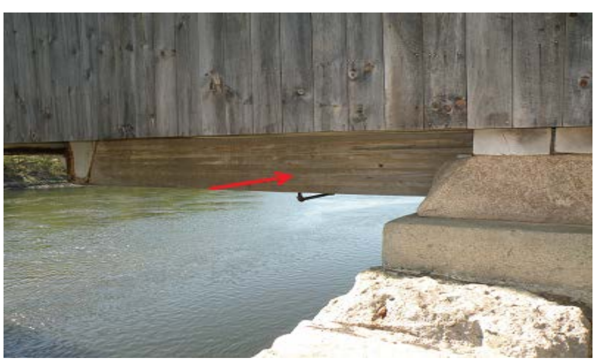

Figure 5.24—Glulam used as a bedding timber (Cornish-Windsor Covered Bridge, 1866, Sullivan County, New Hampshire, and Windsor County, Vermont).

Figure 5.25—Running planks (Parvin Bridge, 1921, Lane County, Oregon).

tension and clamped along the edges of the deck to squeeze the deck boards together. The resulting increase in friction between the boards improves the composite action compared with the use of many nails or screws. Glulam panels that are fabricated off site can also be used as replacement decking to increase the capacity of the bridge.

Increasing Load Capacity by Reinforcing with Fiber-Reinforced Polymers

Fiber-reinforced plastics or polymers have been used for a number of years to strengthen timber, concrete, steel, masonry, and stone structural members. Typical applications include column-to-beam connections, seismic retrofitting, repair of corrosion-damaged beams and columns, bridge decks, piles, precast prestressed concrete shells, and roof structures. FRPs are considered to have a number of advantages, including a wide range of products with specified tensile strengths; low mass; ease of fabrication; custom colors, coatings, and geometry; resistance to corrosion; and low transportation costs. Additionally, FRPs can be made from recycled plastics. However, FRPs have some disadvantages. These disadvantages include high initial costs and the need for highly trained and specialized

Figure 5.26—Stress-laminated deck viewed from below (Seguin Covered Bridge, 1850, Chittenden County, Vermont).

Figure 5.27—Stress-laminated deck as the wearing surface (Doyle Road Covered Bridge over Mill Creek, 1868, Ashtabula County, Ohio).

Figure 5.28—Overview (Goodpasture Covered Bridge, 1938, Lane County, Oregon).

engineers to design the structural systems and address potential creep, rupture, and shrinkage issues.

Research was conducted by the Constructed Facilities Center and the Institute for the History of Technology and Industrial Archaeology of West Virginia University to develop methods to strengthen structural wood members of historic covered bridges using Glass-Fiber-Reinforced Polymer (GFRP) composite materials. Laboratory experiments were conducted to test the effects of GFRP composite materials (both plates and rebar) on the bending and shear capacities of structural members. The specific objectives were to develop methods to strengthen truss and arch members and floor beams and to identify the adhesives necessary to fix the GFRP composite materials in place. The experiments were intended to result in repairs that comply with The Secretary of the Interior's Standards for the Treatment of Historic Properties.

The results of the testing were somewhat mixed. In tension tests, GFRP rebar embedded in wood members performed relatively well. In small-scale bending tests, strength and stiffness were improved by bonding a GFRP plate to the tension face of the member. However, considerable surface preparation was necessary to ensure an adequate bond. Bonding of the GFRP plate also required routing a cut-out for the placement of the plate along the tension side of the test specimens. Initial bending tests with GFRP rebar at the top and bottom of the test specimens did not improve member performance. This method may be more suitable for compression members in trusses. In shear tests, the shear capacity of GFRP members decreased slightly compared with a solid timber control specimen.

For all laboratory tests, specimens were tested indoors at near constant moisture content and temperature. The effect of temperature and moisture fluctuation on the adhesive was not considered and could be a factor in performance in practical application. As indicated from the research, obtaining a high-strength bond between the composite and the wood is difficult, and this would be even more true in the field with the weathered, uneven surface of existing timbers. The surface preparation to obtain a good bond requires a very high level of skill and quality control, some of which is difficult to maintain under field conditions. Additionally, finding a steady, reliable source of composite material has been challenging because of market limitations. Until these issues are resolved, it is unlikely that FRPs will provide a reliable means of increasing the load capacity of covered bridges.

Increasing Load Capacity through Post-Tensioning

The capacity of a covered bridge can be increased, or at least restored to its original capacity, by post-tensioning. Post-tensioning involves adding steel cables or rods to carry some of the load that the bottom (tension) chord may not be able to carry because of its species, size, or grade. The Goodpasture Covered Bridge in Oregon (Fig. 5.28) carries very significant highway loads, including logging trucks. One option that allowed for maintaining the historic integrity and aesthetics of the bridge while increasing load capacity was to insert post-tensioning cables (strands). Steel rods could also have been used; using rods would have simplified the anchorage details and made it much easier to retension should it be necessary to make adjustments. In either case, as with any significant repair, proper shoring and staging was required to prevent damage to the bridge

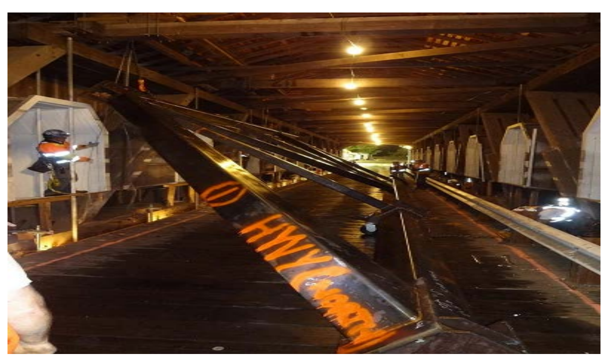

Figure 5.29—First steel truss being inserted into a bridge (Goodpasture Covered Bridge, 1938, Lane County, Oregon. Used with permission from OBEC Consulting Engineers).

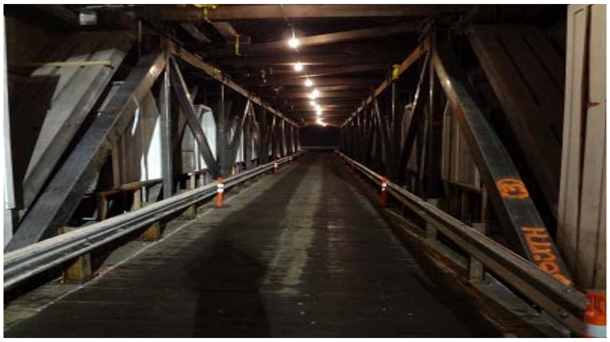

Figure 5.30—Steel support trusses erected in a bridge prior to installing post-tensioning hardware (Goodpasture Covered Bridge, 1938, Lane County, Oregon. Used with permission from OBEC Consulting Engineers).

during repairs. Steel trusses were erected inside the bridge to provide temporary support (Figs. 5.29 and 5.30).

The ends of the bottom chords had steel plates attached to them to serve as the anchors for the cables (Figs. 5.31 and 5.32). The cables, each made up of several strands, were threaded through steel guides along the length of the bridge to prevent abrasion that could damage the cables or bottom chord timbers (Fig. 5.33). The contractor did not have access under the bridge and could not replace the floor beams. Therefore, the strand guides were attached to the bottom chords about midway between each pair of floor beams. After the strands were installed, hydraulic jacks were used to apply 20,000 lb of tension to the strands. The tensioning process transferred some of the tension that was carried by the timber bottom chord, which was highly stressed in tension, into the cables (Fig. 5.34). As a result, the bottom chord was no longer the controlling member in the bridge and the rated capacity increased from 15 to 44 tons to support loads associated with heavy trucks.

One final note on post-tensioning; the tension in the cables (or rods) can be monitored remotely (and relatively inexpensively) to determine if the bridge is being

Figure 5.32—Steel end plate that serves as the anchor for the steel strands, viewed from below (Goodpasture Covered Bridge, 1938, Lane County, Oregon).

overloaded or the tension in the cables (or rods) is changing with time because of temperature fluctuations or creep.

Increasing Clearance

Lack of adequate clearance, either within the bridge or above the waterway, has resulted in damage to bridge members from oversized vehicles and loss of several bridges from flooding. Glulam beams have been used to essentially lower the deck from its original position, thereby increasing the height of vehicles that can pass through the bridge. Clearance is increased because the floor beams are attached to the bottom of the glulam, thus lowering the deck. This repair also offers the advantage of increasing the capacity of the bridge. Although effective, inserting the glulam dramatically alters the interior bridge aesthetics (Fig. 5.35).

Reducing Risk Caused by Overload

The use of glulam or steel beams installed underneath, attached to the abutments but not in contact with the bridge, acts as a safeguard if the bridge becomes overloaded. The bridge can be repaired without altering the original construction. But if load-carrying capacity is marginal, the glulam or steel beams serve as a restraint to carry the intended loads if excessive deflection occurs because of a

Figure 5.31—Steel end plate at the end of the bottom chord serving as the anchor for the steel strands (Goodpasture Covered Bridge, 1938, Lane County, Oregon. Used with permission from OBEC Consulting Engineers).

Figure 5.33. Steel strands threaded through a guide to prevent abrasion of either the cables or the bottom chord timbers (Goodpasture Covered Bridge, 1938, Lane County, Oregon).

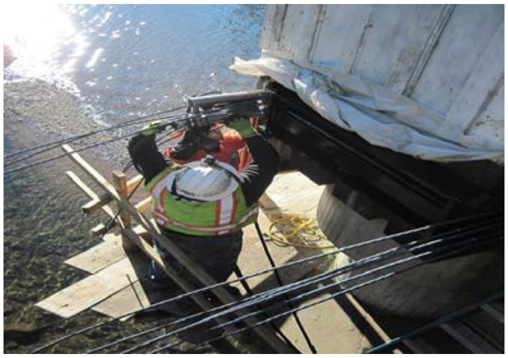

Figure 5.34—Jacking the steel strands to introduce tension into the cables (Goodpasture Covered Bridge, 1938, Lane County, Oregon. Used with permission from OBEC Consulting Engineers).

temporary overload. This approach is completely reversible and does not affect the integrity of the original bridge.

Adding girders below a bridge is not always effective because the stiffness of the bridge trusses is typically much higher than the stiffness of girders (glulam or steel) of reasonable depth. It takes significant deflection to transfer the load from the trusses to the supplemental girders. Engineering analysis can determine the merits of this option. Although the girders may be designed for the total load, the trusses will still carry a significant proportion of the load. The supplemental girders are effective only if the trusses deflect enough for the girders to pick up some of the load.

The installation of glulam or steel beams underneath a bridge eliminates some of the space between the bottom of the bridge and high water and creates an opportunity for debris to accumulate against the bridge during a flood. Many bridges have been lost as a result, and this possibility should be accounted for when considering this type of augmentation.

Increasing Durability

When conditions do not allow wood to dry and the likelihood of wood decay or insect attack is high, the use of pressure-treated timbers should be considered to improve

Figure 5.35—Root Road Covered Bridge, 1868, Ashtabula County, Ohio.

Figure 5.36—Pressure-treated bedding timbers used for increased durability (Shoreham Bridge, 1897, Addison County, Vermont).

durability (Fig. 5.36). Pressure treating timber is discussed in numerous publications that give the benefits and drawbacks of using chemically treated wood. Some wood species can be treated quite easily, such as southern yellow pine, whereas others are difficult to treat and rely on mechanical means, such as incising Douglas-fir to improve penetration of treatment into the wood (Fig. 5.37).

Although durability is most commonly referenced in terms of the ability of wood to resist biological attack, durability can also be increased by mechanical means. Vehicular damage to portal openings and knee braces, which add stiffness to the connections between the roof framing and trusses, is especially common. In spite of height limits being clearly posted, vehicles either knowingly or inadvertently enter a bridge that does not have adequate clearance, causing damage to the bridge.

An option for increasing internal clearance is the use of natural knee braces (Figs. 5.38 and 5.39). A natural knee brace comes from the base of a tree where the roots extend or from the juncture of a branch with the trunk. It forms a very strong brace that increases clearance for over-sized vehicles.

In summary, there are several options for repairing a covered bridge. The first question should be does the bridge need to be repaired based on its current condition and

Figure 5.37—Pressure-treated glulam repair (Parvin Bridge, 1921, Lane County, Oregon).

Figure 5.38—Natural knee brace; the curvature of the brace follows the grain (North Hartland Twin Bridge, 2001, Windsor County, Vermont).

Figure 5.39—Natural knee braces (North Hartland Twin Bridge, 2001, Windsor County, Vermont).

intended use? If so, maintaining the historic character of the bridge should be the driving force behind any repair strategy. Rehabilitating the bridge because of deterioration with time, enhancing the load capacity, increasing clearance, and increasing durability to provide a long service life and to extend the maintenance cycle depends on understanding the bridge condition and behavior and how to properly support the bridge during repair. A bridge that is properly repaired can provide decades of reliable performance before significant repairs are needed again.

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Chapter 6: Maintenance

Covered bridges often suffer from a lack of regular maintenance. This can lead to deterioration and failure of wood roofing and siding, which protect the structural timbers and trusses, and in extreme circumstances, failure of critical structural members. Routine inspection and maintenance can significantly extend the service life of a covered bridge and may require only a day each year to conduct a thorough visual inspection and limited probing to identify potential problem areas. Cleaning and maintaining the painted surfaces are essential maintenance tasks. Decreasing the effects of wood decay or insect attack through the use of remedial wood preservative treatments can be very cost effective, and installing fire protection monitoring, alarm, or sprinkler systems can prevent the loss of a bridge from careless acts or vandalism.

Cleaning

Dirt, loose vegetation, grit, and litter can accumulate anywhere on a bridge where wind or water drainage takes it. The buildup of debris traps additional moisture and creates a favorable microenvironment for active wood decay. Removing the debris through periodic cleaning with brooms, shovels, leaf blowers, or other readily available cleaning implements is a simple but essential task in maintaining a bridge.

Many covered bridges are not on paved roads or at least may not have paved approaches. Gravel, dirt, and grit accumulate on the approach, and then foot and vehicular traffic aid in moving some of the debris onto the bridge. Precipitation further moves the debris onto the wearing surface, running boards, supporting timbers, and trusses (Figs. 6.1 and 6.2). Wind blows loose vegetation (leaves, pine needles, grass, etc.) into areas of the trusses that are not well drained for this larger debris (Figs. 6.3 and 6.4). With time, it is trapped and allows for moisture to accumulate and be absorbed into the wood at that spot. Left in place long enough, the trapped, moist material can allow the growth of grass, shrubs, and even trees. Identifying and removing vegetation and trapped debris is easy and highly effective in protecting the bridge (Fig. 6.5).

Some bridges have features that limit the accumulation of debris by providing natural drainage below the guardrail (Fig. 6.6), between the wearing surface decking (Fig. 6.7), or other areas. It is important to maintain the historic character of the bridge, but if opportunities are available to improve drainage and limit accumulation of debris that do not change the historic character of the bridge, they should be considered to decrease maintenance demands. Installing a grate or a cattle guard at an approach will significantly decrease the quantity of gravel and loose vegetation that accumulates on the bridge by providing a drainage

Figure 6.1—Debris build-up on bridge wearing surface and at the approach (Century Bridge, 1868, Ashtabula County, Ohio).

mechanism that intercepts debris before it reaches the bridge (Fig. 6.8).

Cleaning under the bridge is equally important. Debris flowing downstream can collect on piers, abutments, rocks, and low-flow areas (Fig. 6.9). With sufficient build-up, the debris may contact the bedding timbers, lower chords of the trusses, or siding. As with accumulated debris on the bridge, debris and vegetation that is in contact with the wood can result in active wood decay. Potentially more serious, sufficient build-up of debris can restrict flow of the waterway during periods of high rainfall, run-off, or flooding that can erode the material around the piers and abutments. The loss of material, or scour, can result in destabilization of the bridge supports and has resulted in collapse of bridges. Bridge siding and lower chord members are frequently loosened, damaged, or lost as the result of impacts by brush and other debris carried down waterways by high water.

Wildlife can also present maintenance challenges with covered bridges. Rodents and mammals may nest and inhabit the less accessible areas of a bridge because of the protection the closed areas provide against predators. This can be under the bridge superstructure, on the abutments, between truss chord members, behind lattice work, and on the roof framing. Various insects can also inhabit a bridge but seldom cause damage except for (most commonly) termites, carpenter ants, and carpenter bees. Various

Figure 6.2—Debris build-up on wearing surface (Century Bridge, 1868, Ashtabula County, Ohio).

Figure 6.3—Vegetation debris build-up (Century Bridge, 1868, Ashtabula County, Ohio).

Figure 6.4—Debris build-up between boards and adjacent to siding (Ballard Road Covered Bridge, 1883, Greene County, Ohio).

Figure 6.5—Debris accumulation and incipient vegetation colonization (Houck Covered Bridge, 1880, Putnam County, Indiana).

Figure 6.6—Gap under guardrail allows debris to be washed away. Compare with guardrail in Figure 6.2 that rests directly on the wearing surface (Willard Covered Bridge, 1871, Windsor County, Vermont).

Figure 6.7—Gaps between the decking that allow for drainage of water and fine debris (Goodpasture Covered Bridge, 1938, Lane County, Oregon).

Figure 6.8—Steel grate on approach to bridge to intercept debris before it reaches the wearing surface of the bridge (Baker's Camp Covered Bridge, 1901, Putnam County, Indiana).

Figure 6.9—Debris build-up under bridge (Stevenson Road Bridge, 1877, Greene County, Ohio).

inhibitors can be installed in some locations to discourage bird and rodent access to the bridge. Nail strips and other devices have been used successfully to prevent birds and rodents from building nests on the upper surfaces of exposed roof framing members and top chords of trusses (Fig. 6.10).

Vegetation and Moisture Management

After cleaning, the two most cost-effective measures for extending the life of covered bridges are controlling water and vegetation management. These measures can greatly improve the environment around the bridge. If organic debris and vegetation are cleared from around the perimeter of covered bridges, debris build-up within the interior is removed and maintained, and the interior of the bridge has minimal exposure to moisture, the occurrence of and rate of deterioration caused by decay fungi will typically be slowed. Moisture management is often incorporated into the construction of the bridge. That is the purpose of the roof and siding. Additionally, the roof eaves and the portals may extend several feet beyond the trusses to add more protection from wind-blown precipitation (Fig. 6.11).

Without vegetation management, covered bridges can be engulfed in the invasive trees, shrubs, and grasses that spring up without periodic maintenance (Fig. 6.12). This overgrowth creates a moist microclimate conducive to decay

Figure 6.11—Overhangs on the roof and portals protect the truss members and decking from moisture damage and decay (Lincoln Gap Covered Bridge, 1879, Washington County, Vermont).

fungi through a combination of denser shade, decreased airflow around the bridge members, and increased nitrogen production. Denser shade decreases surface temperatures of bridge members and allows water vapor released from transpiration to condense more rapidly on the members. Concentrations of leafy vegetation also can decrease airflow, which decreases rates of evaporation. Dense clusters of vegetation drop leaves that release nitrogen as they decompose and allow growth of decay fungi.

As previously discussed, vegetation and inorganic debris can accumulate along the edges of the roadbed, between the running boards on the road surface, between truss members, and at bridge supports and abutments. Although some people view vegetation cover as part of the aesthetic character of the bridge, it was not the intent of the bridge builder nor is it in the interest of the current bridge steward (Fig. 6.13). Increased vegetative cover often attracts insects, rodents, and larger animals that can damage structural timbers, roofing, and siding. Dense vegetation with accumulated debris also increases the risk of fire.

Siding and Roofing

Siding and roofing protect the structural members of the bridge. Failure to maintain the roof and siding provides an

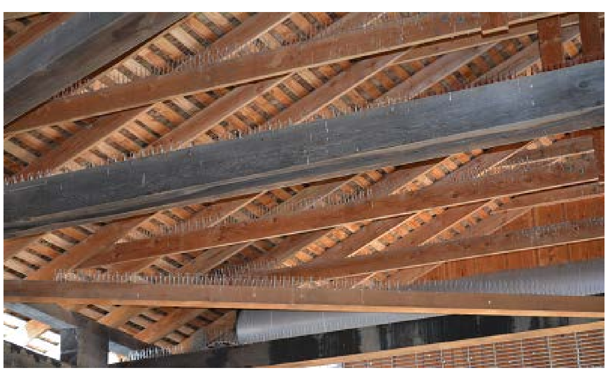

Figure 6.10—Nails used to discourage birds and rodents (Lowell Covered Bridge, 1945, Lane County, Oregon).

Figure 6.12—Vegetation (West Engle Mill Road Covered Bridge, 1877, Greene County, Ohio).

Figure 6.13—Vegetation removal as part of bridge maintenance (West Engle Mill Road Covered Bridge, 1877, Greene County, Ohio).

opportunity for moisture to find its way to the structural members, possibly resulting in decay or insect attack. Missing or loose shingles or boards allow precipitation into the interior space of the bridge. Repairing or replacing loose or missing shingles and boards should be a routine part of periodic maintenance.

The siding, and occasionally the roof, may have been painted. However, some covered bridges were never painted or finished with a coating, and the application of a coating in such cases should only be considered if the structure will otherwise be compromised because of nondurable wood species being exposed to the elements (Figs. 6.14 and 6.15). In most cases, adherence to The Secretary of the Interior’s Standards for the Treatment of Historic Properties is the best practice for preserving historic fabric, context, and authenticity. Weathered wood may not be as durable as painted wood, but if it is considered a characterizing feature of a historic bridge, it should not be painted without considering the change of context.

Extending the service life of the protective roofing and siding may require periodic painting (of wood that was originally painted) to prevent the wood from cracking or splitting caused by excessive weathering. Peeling paint and failed coatings offer insufficient protection to the wood substrate, resulting in shorter service periods and more frequent maintenance (Figs. 6.16 and 6.17).

Figure 6.14—This bridge may never have been painted, or the paint has weathered away (Benetka Road Covered Bridge, ca 1900, Ashtabula County, Ohio).

Figure 6.15—It is possible that this bridge was never painted (Durgin Covered Bridge, 1869, Carroll County, New Hampshire).

There are many causes of paint failure and often multiple conditions that contribute to the degradation of coatings and wood substrates. Frequently, these conditions can be addressed through appropriate selection and application of coatings, but this requires correctly identifying the cause(s). As such, some understanding of wood and coating deterioration is necessary when considering the need for repair or replacement of wood substrate materials and/or reapplication of an exterior coating. Mechanisms of wood deterioration were discussed in Chapter 2, and there are excellent sources of information on paint failure listed in the References section.

Siding and roofing that was never painted or has been improperly maintained will weather. Weathering of wood is the result of the action of cyclic wetting and drying, exposure to ultraviolet (UV) light, and erosion of the wood through wind-blown debris (a process similar to sand blasting). Weathering is a long-term process and is a factor in the deterioration of wood siding and roofing when maintenance has been allowed to lapse and protective coatings have failed or have begun to fail. However, weathering affects intact paint as well; weathering processes can lead to soiling of intact paint surfaces and to chalking and erosion of the paint. Where paint is lost, weathering gradually erodes the exposed, uncoated wood fibers. The process is slow enough, however, that exterior woodwork

Figure 6.16—Paint failure on the siding (Rolling Stone Covered Bridge, 1915, Putnam County, Indiana).

Figure 6.17—Paint failure on the siding (Stevenson Road Bridge, 1877, Greene County, Ohio).

can often survive several decades without a protective coating before significantly decreasing serviceability.

If extensive weathering has occurred or if the wood is continually wet because of environmental conditions that have not been addressed (for example, poor drainage), new coatings will not adhere well to the wood substrate. If coatings are to be applied to weathered surfaces, an acceptable compromise between surface preparation and preservation of the historic, weathered wood substrate and coating performance and durability must be achieved. In the same manner, decisions regarding the repair or replacement of weathered wood surfaces should strike a balance between preserving the authentic appearance of a historic bridge and ensuring that siding and roofing continue to protect the structural integrity of the bridge.

If a bridge has not been painted in several decades, testing for lead paint is recommended. Prior to conducting repairs on the bridge, it may be necessary to do abatement of the lead, paying careful attention to prevent contamination of the water below the bridge. Regardless of the presence of lead, a paint analysis should be conducted if there are questions regarding the bridge's historic paint scheme or if there is evidence of coating incompatibility.

For most bridges, the reapplication of a coating to exposed wood surfaces is a consideration when deterioration in the form of peeling paint, weathered wood substrates, or even failures of the building envelope have begun to appear and there are concerns about the long-term serviceability of the wooden members. If moisture problems and subsequent deterioration were caused by a lack of paint maintenance, there is generally no need for extensive replacement of weathered siding or roofing, unless it has deteriorated or is no longer able to protect the structural timbers.

The current best practice for exterior coatings applied to wood substrates is to either replace or sand all weathered wood surfaces to expose fresh wood prior to coating application. This approach, although appropriate for ensuring the longevity of the coating, fails to account for the visual impact that sanding and/or replacing weathered wood fabric will have on the appearance of a historic bridge. The need to sand exposed wood surfaces and remove the rough texture of the wood surface prior to reapplication of a coating can therefore be a complex issue to consider.

Proper application procedures for paints and stains are critical. Coatings should be applied to sound wood that is free of dirt, flaking paint, and loose wood fibers. After determination of lead content of any existing paint has been made, appropriate paint removal efforts can be undertaken, if necessary. These steps may include hand-scraping areas of peeling paint, low-grit media blasting of the old surfaces, or the use of infrared heating devices that allow for the softened paint to be scraped from the wood surface.

There is considerable technical literature available regarding coatings and coating applications on wood substrates. Some of these resources are listed in the References. Because technologies are always evolving, it may be difficult to find information on new products; however, the preponderance of research conducted during the past 80 years indicates that it is not necessarily the nature of the product but the thoroughness of the surface preparation, sound application procedures, and routine maintenance that result in a long-lasting protective coating. Therefore, decisions regarding a specific coating may be less significant than those regarding surface preparation, application, and regular maintenance.

Regarding the siding and roofing, although the intent should be to maintain the historic character of the bridge in accordance with The Secretary of the Interior's Standards for the Treatment of Historic Properties, there may be valid reasons for using alternate materials. The most common area of historic bridges to warrant material substitutions is the roof. In some climates, wood shingles may not be readily available that equal the quality of the historic shingles. The maintenance and replacement costs may warrant consideration of a material with a longer service life. Additionally, concerns about fire may warrant consideration of fire-retardant shingles or a composite or metal roof covering. Such substitutions can be made successfully without jeopardizing the visitor experience of the bridge (Fig. 6.18).

Fire Protection

The USDA Forest Service's report *Evaluating Fire-Damaged Components of Historic Covered Bridges* provides decision makers with a wealth of information on the effects of fire on covered bridges. Discussions about fire and bridges are generally separated into the following topics:

- Assessing fire damage
- Repairs to fire-damaged timbers
- Fire prevention and control

Figure 6.18—Replacement of original roof with metal roof, perhaps to limit maintenance costs (Seguin Covered Bridge, 1850, Chittenden County, Vermont).

After a fire has occurred, either naturally or by vandalism (including arson and unintentional starts from camp fires or smoking), assessing the extent of damage is similar to the assessment process described in Chapter 2. Thinner wood elements, such as siding and roofing, that have developed char are probably in need of replacement. Larger structural timbers may have surface scarring, char, or a loss of material. The structural engineer typically conducts an analysis of the remaining sound wood to determine if repair, reinforcement, or replacement is required using the same repair procedures discussed in these guidelines.

From a maintenance perspective, fire prevention and control systems are key to protecting bridges, particularly in remote, isolated areas, where access to a water supply or fire station is limited and where bridges are subject to frequent vandalism. Fire alarms, sprinkler systems, and lightning rods are effective strategies to decrease loss caused by fire (Figs. 6.19 and 6.20). Fire-retardant treatments can be applied to the timbers and wood members to decrease the burning potential. Removing vegetation near the bridge can help prevent fires from spreading to a bridge and eliminate hiding places for vandals. Also, automated perimeter lights can deter vandals. Many of these measures can be included in routine inspection and maintenance programs to afford better protection of the bridge.

Remedial Treatments to Retard Decay and Insect Attack

Biological growth is an indication of a favorable environment for wood decay (Fig. 6.21). It does not mean

Figure 6.19—Fire Box (Cornish-Windsor Covered Bridge, 1866, Sullivan County, New Hampshire, and Windsor County, Vermont).

Figure 6.20—Fire alarm system (Durgin Covered Bridge, 1869, Carroll County, New Hampshire).

that decay fungi are active, or even present, but it is a visual sign that warrants closer inspection. If the wood is soft and easily penetrated by an awl, the decayed wood should be assessed for continued service as discussed in Chapter 2. If the decay area is small and does not compromise the structural integrity of the timber or the bridge, remedial chemical treatments can be used to extend the service life for perhaps decades before the timber needs to be replaced.

There are two general paths to extending the life of wood: nonchemical means (through moisture management and maintenance previously discussed) and chemical means (through the use of wood preservatives). Wood preservatives are generally grouped into two categories: preservatives used for in situ, remedial treatment of in-service wood and preservatives used for the pressure treatment of new wood used to replace deteriorated elements.

In situ treatments are typically applied to the wood surface and cannot be forced deeply into the wood. However, they can be inserted into the center of large wooden members via treatment holes, which are then plugged with a dowel to allow for periodic reapplications. These preservatives are available as liquids, rods, or pastes. Pressure-treated wood, on the other hand, generally has much deeper and more uniform preservative penetration, depending on the wood species and treatment process but cannot be applied in situ. Pressure-treated timber can be used as replacement material when the original timber, such as a bedding timber, has deteriorated to the point where repair is no longer feasible.

Figure 6.21—Biological growth found on this floor beam indicates favorable conditions that could lead to decay (Stewart Bridge, 1930, Lane County, Oregon).

Figure 6.22—Material interface between the base of the arch and the concrete abutment where remedial treatments, such as borates, can extend the service life of the timber (Durgin Covered Bridge, 1869, Carroll County, New Hampshire).

Used as a common remedial chemical treatment, borate rods can be inserted into holes drilled in the wood where deterioration is likely (Fig. 6.22). Borates are low-level toxicity preservatives that are used to improve the durability of both new and in-service wood products. Borates are not an alternative to pressure-treated wood that will be in ground contact. They require moisture to migrate through the wood; therefore, they are placed where the wood is likely to be frequently damp, such as near the exposed end grain, near the bottom face of members close to ground contact and at exposed, wood–wood connections where members meet, including repair splices.

Borates effectively control termites, carpenter ants, a variety of beetles, and other wood-boring insects. Topical borate treatments (liquids) applied to the surface offer no protection to the interior of large-dimension members and are not recommended. Borate rod installation is not complicated and can be completed by anyone with basic carpentry skills and appropriate tools. To install borate rods, holes are drilled on a nonvisible face of a timber or near vulnerable joinery, the rods are inserted and the holes are filled with either a pressure-treated wood plug or a plastic threaded plug (to allow the insertion of additional rods during future inspection cycles). These rods are typically effective for 3 to 10 years depending on environmental conditions, but they should be regularly inspected and used as part of a cyclical, long-term maintenance program.

Figure 6.23—Missing treenail connection (Benetka Road Covered Bridge, ca 1900, Ashtabula County, Ohio).

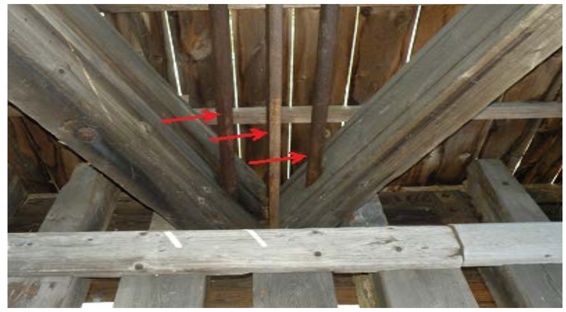

Figure 6.24—Minor surface corrosion (rust) (Shoreham Bridge, 1897, Addison County, Vermont).

Pressure-treated wood may be considered as a replacement option when conditions would result in deterioration of untreated replacement wood; examples include below-ground timbers, where termite infestation is likely, or places in which maintenance is likely to be difficult because of remote location or lack of access. Specifying the correct pressure-treated wood depends on its specific use. To help guide selection of pressure-treated wood, the American Wood Protection Association (AWPA) developed Use Category System (UCS) standards.

Connections and Fasteners

The bridge should be visually inspected for missing or loose connections. In particular, treenails (pegs) used in the lattice-work of trusses and traditional timber joinery are often collected as souvenirs. The people who collect the pegs do not recognize that the pegs are essential to the structural performance of the bridge (Fig. 6.23).

As discussed in Chapter 2 on condition assessments, corroded metal fasteners can indicate moisture and salt issues. Light surface corrosion (rust) is generally not problematic and need only be monitored (Fig. 6.24). Severely corroded metal that has either a loss of material or a build-up of corroded metal may require cleaning or warrant replacement of the steel connectors to avoid potential failure of the connection (Fig. 6.25).

Repairing and restoring a covered bridge properly is the primary means of keeping the bridge in service and preserving the craft that went into building the bridge for

Figure 6.25—Severely corroded bolts (Potter's Covered Bridge, 1871, Hamilton County, Indiana).

future generations to appreciate. It is an investment that requires decision makers to understand the roles of condition assessment and engineering analysis in selecting cost-effective shoring and repair strategies. Maintenance is the means of protecting that investment.

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