Bridge Seismic Retrofitting Practices in the Central and Southeastern United States

Timothy Wright[1]; Reginald DesRoches, M.ASCE[2]; and Jamie E. Padgett, A.M.ASCE[3]

Abstract: This paper conducts a detailed review of the seismic hazard, inventory, bridge vulnerability, and bridge retrofit practices in the Central and Southeastern United States (CSUS). Based on the analysis of the bridge inventory in the CSUS, it was found that over 12,927 bridges (12.6%) are exposed to 7% probability of exceedance (PE) in 75-year peak ground acceleration (PGA) of greater than 0.20 g, and nearly 3.5% of bridges in the CSUS have a 7% PE in 75-year PGA of greater than 0.50 g. Since many of the bridges in this region were not designed with explicit consideration of the seismic hazard, many of them are in need of seismic retrofitting to reduce their seismic vulnerability. While several of the states in the CSUS have retrofitted some of their bridges, systematic retrofit programs do not currently exist. The review of retrofit practices in the region indicates that the most common retrofit approaches in the CSUS include the use of restrainer cables, isolation bearings, column jacketing, shear keys, and seat extenders. The paper presents an overview of the common approaches and details used for the aforementioned retrofit measures. This paper serves as a useful tool for bridge engineers in the CSUS as they begin to perform systematic retrofit of vulnerable bridges in the region.

DOI: 10.1061/(ASCE)BE.1943-5592.0000128

CE Database subject headings: Bridges; Earthquakes; Rehabilitation; Seismic effects; Geological faults; United States.

Author keywords: Bridges; Earthquakes; Retrofit; New Madrid Seismic Zone; State of the art.

Introduction

Recent earthquakes have illustrated that bridges can be vulnerable to damage, which can hamper recovery efforts and contribute to the indirect losses observed during earthquakes (Wesemann et al. 1996; Schiff and Tang 1999; Khater et al. 1990). While the seismic vulnerabilities of west coast bridges are well defined due to extensive empirical data and experimental and analytical testing, vulnerabilities of bridges in regions of moderate seismic activity, such as the Central and Southeastern United States (CSUS), are less well defined. (Note that for the purpose of this paper, the CSUS is comprised of the following states: AR, IL, IN, KY, MO, MS, and TN.) The characteristics of bridges in the CSUS vary significantly from west coast bridges, and there is a lack of empirical data from past earthquakes in this region to highlight seismic deficiencies that might exist. Previous analytical studies have indicated that many bridges in the CSUS are vulnerable to seismic damage, particularly nonseismically detailed continuous and simply supported multispan bridges with concrete or steel girders, which make up a large percentage of the bridges in the region (Nielson and DesRoches 2007a; Hwang et al. 2000).

While the failure of bridges during an earthquake can cause loss of life and impede emergency response, it can also have major implications on the economic recovery of a region in the months following the earthquake. From Fig. 1 it is clear that the transportation network in the CSUS is very dense compared to other regions of the country. The seven states that are in the proximity of the New Madrid Seismic Zone contain approximately 103,288 highway bridges. The transportation network of this region is critical for the commercial transport of goods across the United States. Aside from the large quantity of goods that travel through or end up in the region, it is estimated that over $1.58 trillion dollars of freight originate in the CSUS every year (Bureau of Transportation Statistics 2008). Because of the enormous volume of goods that travel through the dense transportation networks of the region, widespread damage to bridges from an earthquake in the CSUS would have adverse effects on the entire nation. According to the Mid-America Earthquake Center, a large earthquake in the New Madrid Seismic Zone could cause greater than $60 billion dollars in direct economic losses, in addition to more than 60,000 casualties in the state of Tennessee alone (Elnashai et al. 2008). Large cities, such as St. Louis and Memphis, which have largely been built with little seismic consideration, are particularly susceptible to sustaining severe and widespread damage in a large earthquake event in the region.

Since a majority of the bridges in the CSUS were built prior to explicit code requirements for seismic design, it is expected that widespread damage to the bridge infrastructure might occur in the case of a repeat of the 1811-12 New Madrid earthquakes. Many of the states have recognized the existing vulnerability and have begun to perform bridge retrofits in the region. However, funding constraints, the nature of the hazard in the CSUS, and the lack of clear understanding of the seismic behavior of bridges in the

[1]Graduate Research Assistant, School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Dr., Atlanta, GA 30332-0355 (corresponding author). E-mail: tim.r.wright@gatech.edu

[2]Professor and Associate Chair, School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Dr., Atlanta, GA 30332-0355. E-mail: reginald.desroches@ce.gatech.edu

[3]Assistant Professor, Dept. of Civil and Environmental Engineering, Rice Univ., 6100 Main St., MS-318, Houston, TX 77005. E-mail: jamie.padgett@rice.edu

Note. This manuscript was submitted on September 24, 2009; approved on April 9, 2010; published online on April 13, 2010. Discussion period open until June 1, 2011; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Bridge Engineering***, Vol. 16, No. 1, January 1, 2011. ©ASCE, ISSN 1084-0702/2011/1-82–92/$25.00.

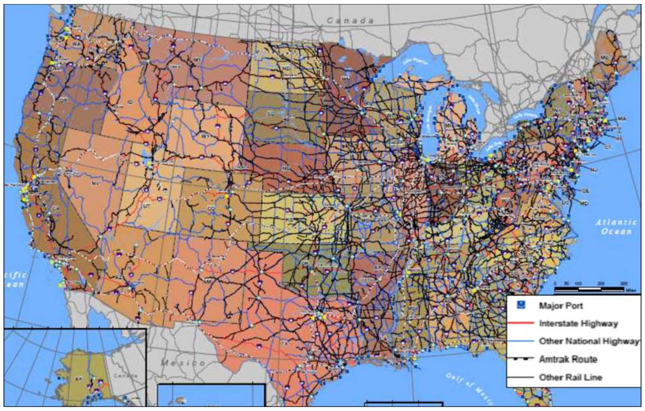

Fig. 1. Major transportation facilities' network of the U.S. [adapted from the Bureau of Transportation Statistics (2008)]

CSUS have led to very few bridges having undergone seismic retrofit. Moreover, widespread understanding of the types of retrofits that are available for addressing the common vulnerabilities of deficient CSUS bridges does not exist across all of the states in the region. This paper provides a detailed account of the common bridge retrofit practices across the seven states in the CSUS, with the goal of providing critical and timely information for states that are considering options for reducing the seismic vulnerability of their bridges.

Seismic Activity in the CSUS

The New Madrid and Wabash Valley seismic zones are located along the Mississippi River and stretch from Arkansas and Tennessee north to Indiana and Illinois. During the years of 1811 and 1812, four of the largest earthquakes to have occurred in the continental United States took place in a matter of 3 months in this region. Three of the earthquakes are estimated to have had magnitudes ranging from 7.8 to 8.1 on the Richter scale. While there have not been earthquakes of magnitude 6.0 or greater in over a hundred years, the threat of large earthquakes in the future exists. According to some researchers, there is a 90% probability that a magnitude 6 or 7 earthquake will occur within the next 50 years (Hildenbrand et al. 1996). The danger presented by earthquakes is not only a function of the size of the earthquake but is also a function of the underlying geology. Because much of the CSUS is comprised of unconsolidated soils and river sediments, large earthquakes in the region have the potential to cause more widespread damage than earthquakes of similar magnitude on the west coast (Street et al. 2001).

Inventory and Characteristics of Bridges in the CSUS

From the data provided in the National Bridge Inventory (NBI) [Federal Highway Administration (FHWA) 2008], a detailed inventory analysis of the bridges in the seven states of focus was conducted. The bridges are categorized into the 10 most common bridge classes in the region, according to material and construction type, as defined in previous studies (Nielson 2005). For the purpose of this paper, only highway bridges are considered, and all culvert and tunnel bridges are excluded from the overall study. The average age and number of highway bridges in each of the 10 different bridge classes in the region are summarized in Table 1. The 10 bridge classes capture 89.5% of bridges in the region. It is also important to note that the average age of all bridges in the region is just over 38 years old, with 25.3% of the bridges being over 50 years old. Furthermore, 72.6% of the bridges were built prior to 1990, which is typically the year that seismic standards were implemented in bridge design in the CSUS (AASHTO 2006).

Seismic risk assessments of bridges in the region have shown bridges in the CSUS to be highly deficient for the design level earthquakes (Zatar et al. 2008; Capron 2008; Imbsen et al. 1999). Some structural deficiencies observed were nonductile columns, insufficient bearing capacities, and seismically deficient footings and piles (Capron 2008). Analytical studies of bridges in the region have found that common vulnerabilities of bridge components in the CSUS include (but are not limited to) brittle steel bridge bearings, instability of rocker bearings, short seat widths, potential deck pounding, and damage to abutments (DesRoches et al. 2004a; Nielson 2005). Fragility studies, or analyses of damage probability conditioned on a given earthquake intensity, have revealed that the four classes of CSUS bridges most vulnerable to suffering extensive or complete damage are nonseismically designed multi-span continuous (MSC) steel and multi-span simply supported (MSSS) steel girder bridges, followed by MSC concrete and MSSS concrete girder bridges (Nielson and DesRoches

Table 1. Summary of the CSUS Bridge Inventory Based on the 2008 NBI Data

Name	Abbreviation	Number	Percentage (%)	Average age (year)
Multispan continuous concrete girder	MSC concrete	8,271	8.0	25.75
Multispan continuous steel girder	MSC steel	11,935	11.6	37.70
Multispan continuous slab	MSC slab	5,019	4.9	37.48
Multispan continuous concrete box girder	MSC concrete box	618	0.6	29.95
Multispan simply supported concrete girder	MSSS concrete	17,822	17.3	37.06
Multispan simply supported steel girder	MSSS steel	6,774	6.6	50.56
Multispan simply supported slab	MSSS slab	3,412	3.3	44.33
Multispan simply supported concrete box girder	MSSS concrete box	4,580	4.4	30.17
Single-span concrete girder	SS concrete	21,454	20.8	34.35
Single-span steel girder	SS steel	12,554	12.2	42.76
Other		10,849	10.5	47.87
Total		103,288	100.0	38.29

Table 2. Summary of Structural Evaluation Levels for the 10 Bridge Classes Based on NBI Ratings

NBI structural evaluation	MSC bridges				MSSS bridges				SS bridges	
	Concrete	Steel	Slab	Concrete box	Concrete	Steel	Slab	Concrete box	Concrete	Steel
N	0	0	0	0	0	0	0	0	0	0
0	6	7	11	0	66	59	7	2	32	185
1	0	0	0	0	0	0	0	0	0	0
2	21	215	135	2	716	1,070	156	88	362	1,931
3	25	110	56	3	335	251	68	83	324	525
4	144	769	371	13	1,703	1,325	514	245	1,557	1,865
5	603	1,604	942	63	4,968	1,530	785	496	3,197	2,341
6	1,507	3,352	1,416	143	3,381	1,331	780	992	4,376	2,361
7	2,877	3,868	1,320	259	2,511	776	581	1,227	4,844	1,587
8	2,474	1,625	670	112	3,964	395	485	1,426	6,391	1,283
9	602	382	98	21	155	32	33	18	315	459
Unrated	12	3	0	2	23	5	3	3	56	17

2007a). As seen in Table 1, these bridges comprise a significant percentage of the CSUS highway bridge inventory, totaling approximately to 43.5%.

With the information available in the NBI database (2008) for the CSUS highway bridges, Microsoft Access was used to query the NBI structural evaluation ratings for bridges within the 10 different bridge classes (summarized in Table 2). By aggregating the various structural evaluation ratings of the bridges into three classes—good/great condition (rating of 7–9), fair condition (rating of 4–6), and poor condition (rating of 1–3)—a better visual representation of the overall structural condition of the various bridge classes for the region is obtained. The pie charts in Fig. 2 summarize the bridge conditions for the six most common bridge classes in CSUS based on the aggregated structural evaluation levels (poor/fair/good) formulated in this paper.

Because the majority of the bridges in the region were designed without adequate consideration of potential seismic loads, and many bridges are naturally deteriorating with age, two conclusions arise. As the structures continue to age and further degrade structurally, they may become increasingly vulnerable to seismic activity. A recent study has illustrated the potential for significant increase in seismic vulnerability of typical CSUS bridges due to aging and deterioration from corrosion (Ghosh and Padgett 2010). This study indicates that over a bridge's service life, an earthquake having over 30% lower peak ground acceleration (PGA) could lead to the same probability of damage. This increase in seismic vulnerability coupled with the aging of bridges and deterioration of structural condition exhibited in the inventory analysis presented herein indicate a heightened need for systematic retrofit of CSUS bridges. Additionally, many of the states in the CSUS region that have conducted seismic retrofit have indicated that these seismic upgrades are often coupled with repair activities. Because bridges in the region continue to approach the end of their design lives, repair and maintenance over-

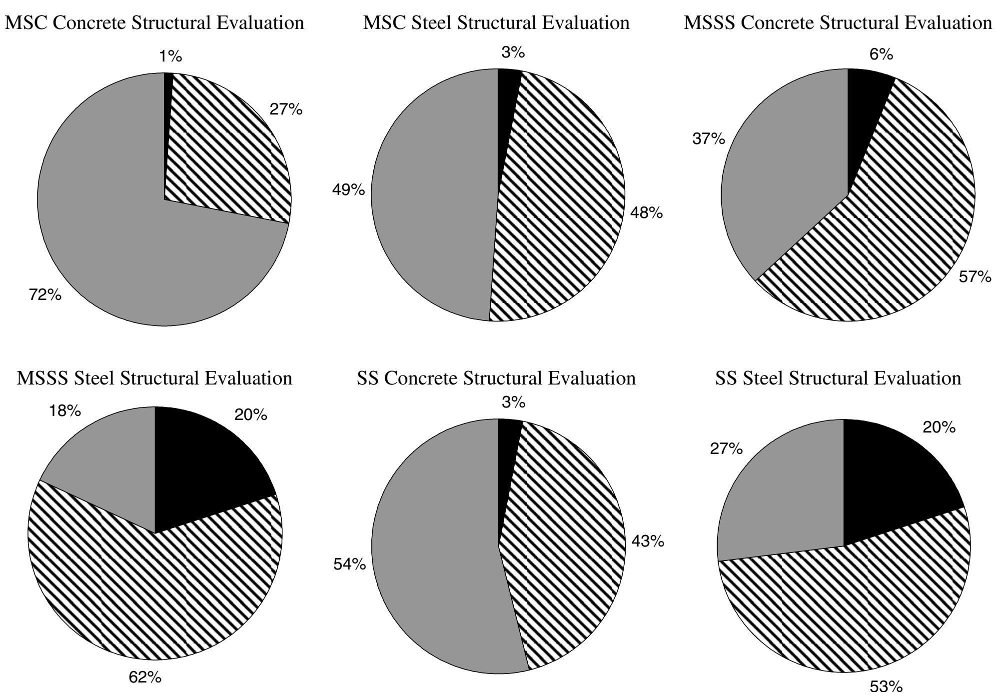

Fig. 2. Pie charts summarizing the formulated structural evaluations of the six most common bridge classes in the CSUS

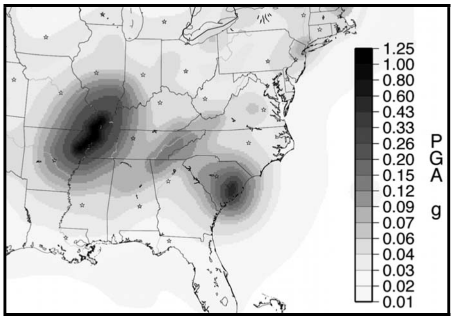

Fig. 3. Uniform hazard map of the horizontal component PGA with PE 7% in 75 years for NEHRP Site Class B/C (Harmsen, personal communication, August 11, 2009; image courtesy of the U.S. Geological Survey)

hauls will likely be performed in order to lengthen the service lives of many of the bridges. These periods of maintenance construction will allow for the logical and congruent integration of new seismic retrofits into bridge maintenance or rehabilitation projects.

History of Seismic Design and Retrofit of Bridges in the CSUS

Seismic bridge retrofit is the practice of modifying bridges and bridge components or adding additional elements to reduce their overall seismic vulnerability and improve their performance in earthquakes. Retrofits in the CSUS typically aim to decrease force demands on vulnerable components, reduce deck displacements, strengthen key components of bridges, or any combination of the three. Seismic bridge retrofits, while extremely common on the west coast of the United States, have been implemented less frequently in the CSUS due in large part to the infrequent nature of seismic events in the region.

In the 1950s and 1960s, California witnessed a huge expansion of its highway and freeway networks. Because this expansion took place before modern seismic codes were developed, the bridges built during this period were particularly susceptible to damage during earthquakes. During the 1971 San Fernando earthquake, some freeway overpasses collapsed, leading to the recognition that many of California's bridges, as constructed, were not sufficiently designed to withstand an appropriate level of ground motion. At that time, the California Department of Transportation implemented a state-wide retrofit program aimed at inspecting and identifying the deficient structural components (Mellon and Post 1999). During the periods of 1971 and 1997, over 3,000 bridges were retrofitted as part of the state's retrofit program (Yashinsky 1998). The comprehensive retrofit program initiated by Caltrans following the 1971 earthquake resulted in significantly fewer losses and bridges damaged in subsequent earthquakes, namely, the 1989 Loma Prieta and 1994 Northridge earthquakes (Yashinsky 1998).

A main area for concern in the CSUS is that seismic design codes in the region were not developed or adopted until the 1990s, so a majority of current bridges have been built with little or no seismic detailing. The Central U.S. Earthquake Consortium has worked with the U.S. Department of Transportation and the seven states in the CSUS to increase the awareness of the seismic risk in the region (CUSEC 1996). A key focus of the collaborative effort was to encourage the development or adoption of adequate seismic design criteria as well as the development of bridge retrofit programs.

The seismic awareness in the region has undeniably grown in recent years. In 2006, the New Madrid Seismic Zone Catastrophic Planning Project was launched, with the goal of attaining a level of national readiness in the event of a "catastrophic" earthquake in the CSUS (FEMA 2008). This initiative includes participation from the federal, state, and local levels and is the largest planning initiative in U.S. history. Parallel with efforts to increase the nation's preparedness for an earthquake in the region, design codes for the CSUS have also undergone necessary revisions. The "Comprehensive Specification for the Seismic Design of Bridges" project, completed in 2002, was a major milestone in that it proposed design specifications that would provide a more rational and uniform approach to bridge seismic design throughout the entire United States (ATC/MCEER 2002). This helped to bring the inadequate seismic design codes for bridges in the CSUS to a level more comparable to the west coast, whose seismic design codes were already quite robust. The newest bridge codes in the CSUS have also adopted the use of a 7% probability of exceedance (PE) in 75-year hazard for the life safety performance objective in new design. The life safety performance objective aims at providing a low probability of collapse, although the bridge may suffer significant damage and/or disruption to service. Under this minimum design objective, the bridge might also require partial or complete replacement after an earthquake. The 7% PE in 75-year uniform hazard map for the region is shown in Fig. 3. Based on the bridge inventory analysis performed, it was found that over 12,927 bridges (12.6%) have 7% PE in 75-year PGA of greater than 0.20 g, and nearly 3.5% of bridges in the CSUS have a 7% PE in 75-year PGA of greater than 0.50 g. Table 3 summarizes the 7% PE in 75-year PGAs for the inventory of bridges in the CSUS. Based on the large number of bridges in the region likely to experience significant earthquake loading, many of the existing bridges may require seismic retrofit in order to satisfy current minimum design standards for new bridges. Furthermore, the 7% in 75-year event is the upper level earthquake considered in the two level performance based retrofit recommended by the recent edition of the *Seismic Retrofitting Manual for Highway Structures: Part 1—Bridges* [Federal Highway Administration (FHWA) 2006]. Under the current criteria, most standard bridges would be retrofit to meet life safety objectives for the upper level 7% in 75-year event, while some essential bridges would be retrofit to provide for limited repairs and near immediate operation for emergency vehicles.

In light of the growing awareness, many states in the region,

Table 3. Summary of PGA (g) with a 7% PE in 75 Years for All Bridges in CSUS

PGA (g)	0.0–0.1	0.1–0.2	0.2–0.3	0.3–0.4	0.4–0.5	0.5–0.6	0.6–0.7	0.7–0.8	0.8–0.9	0.9–1.0	1.0+
Number of bridges	72,601	17,211	5,185	2,704	1,494	956	579	480	413	257	859
Percentage of bridges (%)	70.67	16.75	5.05	2.63	1.45	0.93	0.56	0.47	0.40	0.25	0.84

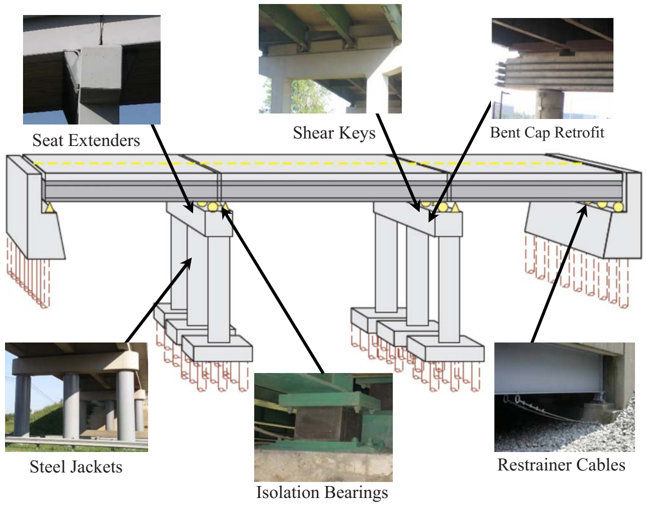

Fig. 4. Example of a three-span simply supported bridge and some potential component retrofits common in the CSUS

such as Illinois, Indiana, Kentucky, Mississippi, Missouri, and Tennessee, have begun implementing seismic retrofitting programs for their bridges. While there has been an increased awareness of seismic risk to bridges in the region, state retrofit programs still range significantly from state to state in the CSUS. Some states, such as Mississippi, have performed seismic evaluations of bridges and implemented retrofits that are explicitly seismic in nature. Other states, such as Tennessee, Indiana, and Illinois, have made rough estimates of the number of bridges needing seismic retrofit, but address the implementation of the retrofits only when bridge replacement or rehabilitation occurs. From a preliminary survey of state bridge engineers by the Federal Highway Administration (FHWA) (Smith, personal communication, November 2007), it was determined that few states in the CSUS have comprehensive and current bridge retrofit programs. Many states performed rudimentary seismic evaluations of their bridge inventories in the early and mid-1990s but typically do not have a complete understanding of seismic bridge retrofit activities currently needed. The results of the survey suggest that there is a need for a better understanding of the range of retrofit measures being adopted in the CSUS and their design objectives. A thorough review of the current retrofit practices in the region was conducted as a part of this study and is detailed below.

Overview of Seismic Retrofit Approaches

There are five primary retrofit measures used to retrofit bridges in the CSUS: seismic isolation, longitudinal and transverse restrainers, seat extenders, column strengthening, and bent cap strengthening. These measures are employed to address seismically deficient components of bridges in the region. The methods of retrofit can be applied individually or in combination, with the main objective of reducing the bridge's overall vulnerability to seismic loading. Because many bridges in the region have yet to reach the end of their service lives, seismic retrofit is often favored over total replacement of bridges. Fig. 4 shows a generic bridge, highlighting some of the common CSUS bridge component retrofits which will be discussed in this paper. Through site visits, meetings with state DOT officials, and a thorough evaluation of bridge plans, the writers of this paper have conducted a detailed review of the retrofit practices and measures used in the various states that make up the CSUS. The five retrofit approaches introduced—including their purpose, typical detailing, and example applications throughout the CSUS region—will be detailed below.

Seismic Isolation

By introducing special seismic isolating or damping elements into a bridge, the seismic performance of the bridge can be greatly enhanced. There are three main objectives when adding seismic isolation bearings to bridges: to shift the natural frequency of the structure out of the region of dominant earthquake energy, to increase damping in the structure, and last, to lessen the dynamic reactions between the bridge superstructure and substructure (Wendichansky et al. 1995; Mayes et al. 1984, 1994). Isolation bearings are often used to limit the forces that could be placed on deficient bridge piers. The isolation retrofit strategy is beneficial because it reduces the need to perform costly retrofit of deficient piers and foundation elements. The two main types of seismic isolators used in the CSUS are elastomeric bearings (both with and without a lead core detail) and slider bearing isolation systems. In addition to isolation benefits, retrofitting bridges by replacing existing bearings with isolators also provides unique advantages by eliminating the vulnerability of the current bridge bearings, one of the more vulnerable bridge components in typical CSUS bridges.

Elastomeric bearings usually consist of alternating layers of

a) b) c)

Fig. 5. (a) Elastomeric bearing detail [adapted from Priestley et al. (1996)]; (b) installed in Indiana (HW50 Red Skeleton); and (c) installed in Illinois

a) b)

Fig. 6. (a) Friction pendulum (sliding) bearing found on the Hernando DeSoto Bridge in Tennessee; (b) a friction bearing used in conjunction with an elastomeric bearing in Illinois

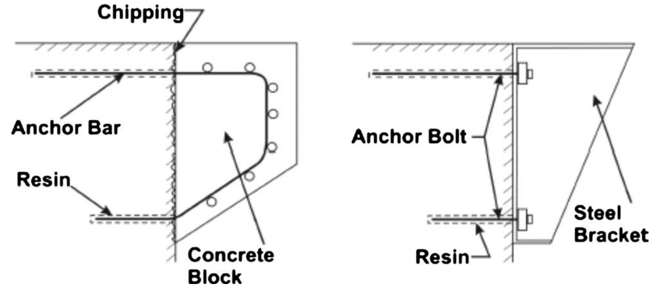

Fig. 7. Details of concrete corbel (left) and steel bracket (right) seat extenders [adapted from Priestley et al. (1996)]

rubber and steel plates, and often have a lead core to dissipate seismic energy. Fig. 5(a) shows an illustration of a typical elastomeric bearing (without lead core). Elastomeric bearings typically have steel flanges on the top and the bottom to allow a fully fixed connection to both the super- and substructures. This type of isolation bearing has been used in the construction of bridges and buildings for nearly 40 years (Stanton and Roeder 1992).

Sliding or slider bearings, as the name suggests, allows for relative motion between the bearing and the bridge. These bearings support vertical loads, but provide very little resistance to lateral loads. They are typically used in conjunction with elastomeric isolators. One of the largest benefits of using a slider bearing is the added damping and energy dissipation due to the friction during sliding.

While isolation bearing systems are very successful at altering the natural frequency of a bridge, they also often result in a corresponding increase in displacements of the bridge deck which must be accounted for. For example, previous analytical studies have illustrated the potential for excessive pounding between the superstructure and abutment (Padgett and DesRoches 2008; DesRoches et al. 2004b; Jankowski et al. 1998). The increase in displacements in the structure can be addressed by adding a damping system to the structure, either built into (lead core in an elastomeric bearing) or in parallel (viscous or hysteretic dampers) with the isolators (Chang et al. 2002).

Research has shown that the stiffness of elastomeric bearings is temperature sensitive. The stiffness and energy dissipated per cycle increase as temperature decreases (Ghasemi and Higgins 1999). When using this type of bearing in areas of extreme cold, the increased stiffness of the elastomeric bearing should be considered in the design.

In the CSUS, many bridges have been retrofitted with various forms of isolation. Figs. 5(b and c) show the application of elastomeric bearings in Indiana and Illinois. They can also be found in Tennessee, Missouri, and other states in the region. Fig. 6(a) shows a slider bearing (friction pendulum bearing) installed in Tennessee, while Fig. 6(b) shows a slider bearing used in conjunction with an elastomeric bearing in Illinois.

Longitudinal Retrofits

If bridge span seat lengths are insufficient, as they often are on many CSUS bridges, the relative displacement caused during an earthquake can result in unseating of the spans, which will trigger the collapse of the bridge. Unseating of spans, observed in past earthquake events (Li et al. 2008; Cooper and Van de Pol 1991), has also been identified as a common vulnerability of CSUS bridges (Nielson and DesRoches 2007b; DesRoches et al. 2004a). This problem has been addressed through a number of potential retrofitting approaches that fall into two main categories: an inadequate seat length can be increased or the relative movement of bridge spans can be explicitly limited. Seat extenders and catcher blocks fall into the first category while longitudinal restrainer bars and cables, bumper blocks, and shock transmission units (STUs) fall into the second. These types of retrofits are relatively simple and inexpensive, yet have been shown to be very effective measures in preventing unseating of bridge spans (Padgett and DesRoches 2008; Padgett 2007; Vlassis et al. 2004).

Seat Extenders and Catcher Blocks

Seat extenders can be applied to bents or abutments by adding a concrete corbel or attaching structural steel bracket (Fig. 7). They are attached to the sides of the bent caps and are flushed with the top of the bent cap. While seat extenders do not alter the dynamic response of the bridge, they increase the seat length of the span and reduce the vulnerability to unseating of a bridge span in the event that a bridge span slides off the bent cap. According to Hipley (1997), seat extenders are the least expensive and most basic retrofit to prevent unseating of the spans. Previous detailed analytical studies have shown that seat extenders have one of the highest cost-benefit ratios for reducing the seismic vulnerability of typical bridges in the CSUS when compared to other traditional retrofit measures (Padgett et al. 2009). Fig. 8(a) illustrates the use of steel bracket seat extenders in Tennessee, while Fig. 8(b) highlights the use of steel brackets and beams in Missouri to create a seat extender for multiple bridge girders. Practice in the CSUS tends to utilize seat extenders that provide approximately 12 in. (30.5 cm) of additional seat width.

Catcher blocks are similar to seat extenders, except that they are attached to the tops of bents and abutments when there are vulnerable tall bearings or rocker bearings. The blocks are there to "catch" the girders in the event that the span falls off the bearing or the bearings fail. Catcher blocks are often used when the deck is supported by tall bearings, such as high-type steel fixed or rocker bearings, or there is insufficient room to anchor seat extenders [Fig. 8(c)].

Restrainers

Longitudinal bar and cable restrainers are used to prevent excessive longitudinal movement of bridge spans. This retrofit uses steel bars or cables attached to adjacent spans and/or to the bridge abutment to limit the longitudinal motion of the bridge deck. Cable restrainers have been used extensively in California and have been identified as a relatively simple and inexpensive retrofit strategy to minimize the risk of unseating (Priestley et al. 1996).

a) b) c)

Fig. 8. (a) Seat extenders installed on an I-40 bridge in Tennessee; (b) a beam seat extender in Missouri; and (c) catcher blocks provided for a vulnerable bearing in Missouri (Poplar Street Complex)

During the 1994 Northridge earthquake as well as the 1989 Loma Prieta earthquake, most cable restrained bridge spans performed adequately (Cooper et al. 1994; Housner and Thiel 1995; Moehle et al. 1995).

Restrainer cables usually consist of galvanized 0.75 in. (19 mm) diameter steel cables and have lengths between 5 ft (1.52 m) and 10 ft (3.05 m). Depending on the ambient temperature conditions in the region of installation, the slack provided may be up to 0.75 in. (19 mm). Several researchers have found that the amount of slack provided can significantly alter the response of the bridge to seismic activity (Saiidi et al. 1996; DesRoches and Fenves 2000). In the CSUS, restrainer cables are a relatively popular retrofit measure though the details vary significantly across the region. The state of Tennessee alone has retrofitted over 200 bridges with restrainer cables (DesRoches et al. 2004a,b). Some of the various configurations for restrainer cables found throughout the CSUS are shown in Fig. 9.

High-strength galvanized ASTM-A 722 bars operate similar to restrainer cables, except that they are stiffer and more ductile than cables. The goal of the restrainer design is for the restraining component to remain in the elastic region, so the added ductility of bars is not considered a major advantage [Federal Highway Administration (FHWA) 2006]. The reduced flexibility also requires that the bars are much longer than cables in order to allow for the same range of motion of the structure [Federal Highway Administration (FHWA) 2006]. For these two reasons, restrainer bars have historically been used much less frequently than restrainer cables, although they have been applied in the CSUS. Restrainer bars can be installed in various arrangements, but typically join the superstructure (girders) to the substructure (columns, abutments, etc.). Fig. 10(a) shows a restrainer bar in Indiana oriented such that it provides lateral and longitudinal restraints for the bridge span. Fig. 10(b) pictures a restrainer bar joining adjacent spans of a bridge in Missouri.

Bumper Blocks and STUs

Bumper blocks are usually made from structural steel beams and are attached to the bottoms of the girders on both sides of a bent cap. They protrude above the elevation of the bent cap and restrict excessive movement of the bridge span (toward the support at the end of the span where the bumper blocks are installed). There is typically a gap of approximately 2–6 in. (5.1–15.2 cm), allowing some motion of the bridge span, but the bumper blocks are intended to stop the longitudinal movement before unseating occurs. Fig. 11(a) illustrates the use of bumper blocks on a Missouri bridge as a longitudinal retrofit measure.

STUs allow for slow motion, such as thermal expansions and contraction without appreciable resistance. During rapid or sudden motions, such as those caused by earthquakes, however, STUs are able to provide rigid resistance to movement. STUs applied on a Missouri bridge are illustrated in Fig. 11(b).

Transverse Retrofits

The main purpose of transverse retrofitting is to prevent excessive transverse movement of the bridge deck during earthquakes in the event of bearing failure. Typical bridges in the CSUS may be susceptible to damage caused by excessive motions in the transverse directions, and therefore, transverse retrofits are present throughout the region. The two most common types of bridge retrofits that address an inadequate resistance to transverse exci-

a) b) c)

Fig. 9. Restrainer cables (a) in Kentucky connecting two adjacent girders; (b) in Tennessee (SR59 over I-40) connecting girders to the abutment; and (c) in Illinois attached to girders and wrapped around bent beam

a) b)

Fig. 10. (a) Restrainer bars in Indiana resisting longitudinal and lateral displacements; (b) restrainer bars in Missouri (Poplar Street Complex) joining adjacent girders at a center span

a) b)

Fig. 11. (a) Bumper blocks; (b) STUs in Missouri

a) b)

Fig. 13. (a) Bent cap retrofit in Missouri using posttensioned rods; (b) a bent cap retrofit in Illinois using shear reinforcement and confinement on the end regions of the bent cap

tations are shear keys and keeper brackets. A third, less common type of transverse retrofit is the use of restrainer bars oriented transversely across bridge elements, usually joining the superstructure to the bent beam, columns, or abutments [Fig. 10(a)]. Shear keys and keeper brackets operate under the same basic premise. They provide additional lateral restraint to motion in the event that the bridge deck bearings fail.

Shear keys are usually reinforced concrete blocks that are attached to the bent beams with dowels. They are placed between the girders that support the bridge deck and serve to transmit lateral forces from the superstructure to the substructure. Increasing the ability of the superstructure to transmit transverse loads to the substructures creates an added demand on the substructure components. For this reason, some shear keys may be designed to "fuse" (fail) at a given force level to limit the force transmitted to the substructure. This can avoid the need for additional costly retrofits to the substructure, while also effectively isolating the superstructure (Chen and Duan 1999). Analytical studies have found shear keys to be a suitable retrofit for MSC steel girder bridges, whose bearings are vulnerable in the transverse direction (Padgett and DesRoches 2008). Keeper brackets serve the same function as shear keys but are applied in a different manner. Keeper brackets are made of structural steel and are attached to the top of the bent cap on both sides of a girder and, like shear keys, transmit lateral forces from the superstructure to the substructure. Both of these retrofit strategies have been used extensively throughout the CSUS region. Figs. 12(a and b) show an installed shear key retrofit and installed keeper bracket retrofit in Tennessee. Fig. 12(c) highlights the use of a keeper bracket retrofit in conjunction with an elastomeric bearing retrofit on an Indiana bridge.

Bent Cap Retrofits

Bent caps transfer loads from the bearings of a bridge to the columns. The main deficiency with bent caps in the CSUS is a lack of reinforcing for adequate shear and flexure. The general approach to retrofitting bent caps is to increase the shear or flexural strength of the bent cap, especially at the joints between the bent cap and columns, so that a plastic hinge will develop in the column before damage occurs in the bent cap. Three ways to achieve this enhanced strength in the bent beam are with posttensioned rods, external shear reinforcement, or through the addition of a concrete or steel bolster.

One of the most common ways to increase the strength of the bent cap is by applying an initial compressive strength in the bent beam. This is accomplished by using posttensioned rods that are placed along the outside of the bent cap or by placing prestressing tendons in ducts that are cored through the length of the cap beam (Priestley et al. 1996). Another popular way to increase the strength of the bent beam is to apply shear reinforcement externally on the bent cap. Steel plates are placed along the top and bottom of the bent beam. The two plates are then connected with metal rods along the sides of the bent cap to increase the shear capacity of the bent cap. Encasing the existing bent cap with steel or concrete is yet another way to increase the flexural and shear strength of the bent beam. Previous experimental testing has showed that the addition of concrete bolsters to bridge bent caps can cause a significant increase in the energy dissipation capacity of a bridge (Sanders et al. 1998). Furthermore, concrete and steel encasements at column-bent cap joints have been found to be effective forms of retrofit, although they create new critical sections at the edges of the jacketing (Priestley et al. 1996; Thewalt and Stojadinovic 1995). These various bent cap retrofit measures

a) b) c)

Fig. 12. (a) Shear key provided on a Tennessee bridge (SR 59 over I-40); (b) keeper brackets in Tennessee (Chambers Chapel Road over I-40); and (c) keeper brackets used with an elastomeric bearing (Bridge 2 66 Diamond) in Indiana

a) b)

Fig. 14. (a) Bent cap retrofit in Missouri using steel encasement; (b) a bent cap retrofit using reinforced concrete encasement in Tennessee (Dayview Plantation Road over I-40)

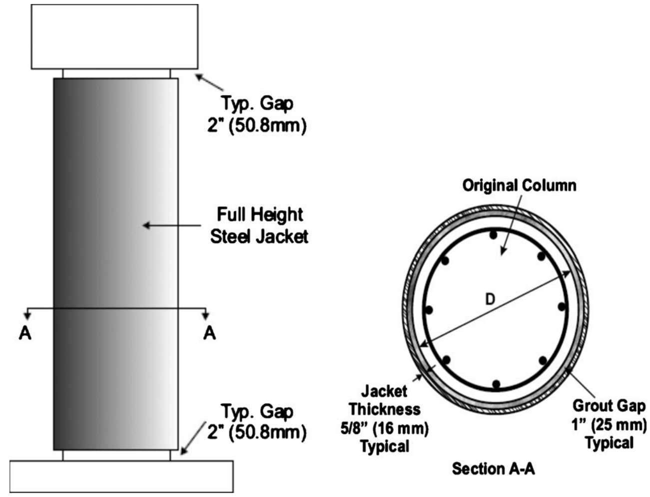

Fig. 15. Details of a typical full column steel jacket

have been installed in several states throughout the CSUS (Figs. 13 and 14).

Column Retrofit

A column's inability to withstand seismic loading typically arises from inadequate reinforcement and seismic detailing. Insufficient lap splices and inadequate transverse reinforcement within the columns are the two most common vulnerabilities in bridges in the CSUS. These issues lead to low ductility capacities and shear strengths for columns. Retrofitting strategies that address column deficiencies often aim to enhance the confinement for concrete columns in order to provide an increased ductility capacity and/or improved lap splice performance. Some examples of such retrofitting strategies include steel jacketing, concrete overlays, cable column wraps, and jacketing with fiber composite wraps.

Steel jacketing is used to increase flexural ductility of columns while also increasing the columns' shear strength. Steel jackets are typically A36 steel casings and can be applied in full or partial column height. In the case of full column jacketing, a 2 in. (51 mm) space is usually provided at the ends of the column to prevent bearing on the bent cap or footings and prevent increases in moment capacity (Priestley et al. 1996). The minimum recommended shell thickness of a steel jacket is 0.375 in. (9.5 mm) and the maximum thickness should not exceed 1 in. (25 mm) [Federal Highway Administration (FHWA) 2006]. An unintended consequence of column jacketing is an increase in column stiffness by approximately 10–15% for the case of partial height jackets (Chai et al. 1991) and 20–40% for the case of full height jackets (Priestley et al. 1996). In the CSUS, steel jackets have been applied in partial height to target plastic hinge regions in the column as well as in full height to improve the shear strength of the column. A typical cross section of a column with a steel jacket is shown in Fig. 15. A review of the state of retrofit practice in the region reveals that steel jacketing is the most common column retrofit in the CSUS.

Concrete overlays are also used to provide increased confinement of the column. Like steel jacketing, concrete overlays can be applied in full or partial column height. Longitudinal and transverse steel reinforcements are typically both provided in these concrete casings. In some instances, concrete overlays can be used in conjunction with a steel jacket. Figs. 16 and 17 highlight the use of both full and partial height column encasements via steel jacketing and concrete overlays in Tennessee, Missouri, and Illinois.

Less common types of column retrofitting in the region are cable column wraps and jacketing with fiber composite wraps. These retrofits, like steel jacketing, and the use of column overlays aim to increase column confinement in order to achieve better ductile and shear capacity. Fiber composite wraps may be continuous or applied in strips and can be effective on square as well as circular columns (Priestley et al. 1996). A cable column wrap applied to a bridge in Illinois is shown in Fig. 18(a). Figs. 18(b and c) show Illinois bridge columns retrofitted with continuous fiber wraps as well as fiber wraps applied in strips.

a) b)

Fig. 16. (a) Full column steel jacketing used in Tennessee (SR 196 over I-40); (b) partial height steel jacketing in Missouri focusing on plastic hinge regions of the columns

a) b)

Fig. 17. (a) Concrete column overlay under construction in Tennessee (Hernando DeSoto Bridge I-40); (b) a partial height concrete encasement of a column in Illinois (Poplar Street Complex)

a) b) c)

Fig. 18. (a) Cable wraps applied to the base of columns in Illinois; (b) continuous fiber composite wrap in Illinois; and (c) fiber composite wraps applied in strips in Illinois (Poplar Street Complex)

Summary and Conclusions

The seismic hazard in the CSUS is characterized by low probability, high consequence events, with a potential for widespread damage in the case of a repeat large event, such as the 1811-12 New Madrid earthquakes. Based on the analysis of the bridge inventory in the CSUS, it was found that over 12,927 bridges (12.6%) are exposed to 7% PE in 75-year PGA of greater than 0.20 g, and nearly 3.5% of bridges in the CSUS have a 7% PE in 75-year PGA of greater than 0.50 g. Moreover, over 72.6% of the bridges in the region were built prior to 1990, which is typically the year that seismic standards were implemented in bridge design in the CSUS. Since many of the bridges in this region were not designed with explicit consideration of the seismic hazard, many of them are in need of seismic retrofitting to reduce their seismic vulnerability. Some structural deficiencies common in the CSUS bridges include nonductile columns, insufficient bearing capacities, small seat widths, and potential deck pounding issues. Given the potential risk to highway bridge infrastructure in the CSUS and the need for support as states begin to evaluate and engage in seismic retrofit activity, this paper has provided a detailed review of the retrofit practices initiated in the region. Common retrofits in the region have been identified and include the use of seismic isolation bearings, column jacketing, and other measures of column confinement, restraining devices to prevent unseating, and the use of shear keys and keeper brackets to limit transverse deck movement. This paper serves as a useful tool for bridge engineers in the CSUS as they begin to perform systematic retrofit of vulnerable bridges in the region.

Acknowledgments

This study has been partially supported by the Earthquake Engineering Research Center program of the National Science Foundation under Award No. EEC-9701785 (Mid-America Earthquake Center) and the FHWA Pooled Funds Study Grant No. TPF5-155. The writers would like to thank all those that assisted in gathering the data for this paper. In particular, the writers would like to acknowledge the following individuals that provided them with valuable information, access to bridges, and contributed their time: Mr. Ralph Anderson, Mr. Daniel Tobias, Mr. Allen Thomas, Mr. Mark Capron, Mr. Robert Turner, Mr. Brad Ridgley, and Mr. Ed Wasserman.

References

AASHTO. (2006). "Recommended LRFD guidelines for the seismic design of highway bridges." *NCHRP 20-7(193) Task 12*, Washington, D.C.

ATC/MCEER. (2002). "Comprehensive specification for the seismic design of bridges." *NCHRP Rep. No. 472*, AASHTO, Washington, D.C.

Bureau of Transportation Statistics. (2008). *State transportation statistics 2008*, RITA Research and Innovative Technology Administration, Washington, D.C.

Capron, M. (2008). "Seismic evaluation of the I-155 Bridge over the Mississippi River." *Proc., 6th National Seismic Conf. on Bridges and Highways: Seismic Technologies for Extreme Loads*, MCEER, Charleston, S.C.

Chai, Y. H., Priestley, M. J. N., and Seible, F. (1991). "Seismic retrofit of circular bridge columns for enhanced flexural performance." *ACI Struct. J.*, 88(5), 572–584.

Chang, S.-P., Makris, N., Whittaker, A. S., and Thompson, A. C. T. (2002). "Experimental and analytical studies on the performance of hybrid isolation systems." *Earthquake Eng. Struct. Dyn.*, 31(2), 421–443.

Chen, W. F., and Duan, L. (1999). *Bridge engineering handbook*, CRC, Boca Raton, Fla.

Cooper, J. D., Friedland, I. M., Buckle, I. G., Nimis, R. B., and Bobb, N. M. (1994). "Northridge earthquake: Progress made, lessons learned in seismic-resistant bridge design." *Public Roads*, 58(1), 26–36.

Cooper, T. R., and Van de Pol, M. (1991). *Bridge damage review. Loma Prieta earthquake*, ASCE, Los Angeles.

CUSEC. (1996). *Earthquake vulnerability of transportation systems in the Central United States*, Central U.S. Earthquake Consortium, Memphis.

DesRoches, R., Choi, E., Leon, R. T., Aschheim, M., and Dyke, S. T. (2004a). "Seismic response of multi-span steel bridges in Mid-America: Part I: As-built response." *J. Bridge Eng.*, 9(5), 464–472.

DesRoches, R., Choi, E., Leon, R. T., and Pfeifer, T. (2004b). "Seismic response of multi-span steel bridges in Mid-America: Part II: Retrofitted." *J. Bridge Eng.*, 9(5), 473–479.

DesRoches, R., and Fenves, G. L. (2000). "Design of seismic cable hinge restrainers for bridges," *J. Struct. Eng.*, 126(4), 500–509.

Elnashai, A. S., Cleveland, L. J., Jefferson, T., and Harald, J. (2008). "Impact of earthquakes on the Central USA." *Mid-America Earthquake Center Rep. No. 08-02*, FEMA, Washington, D.C.

Federal Highway Administration (FHWA). (2006). *Seismic retrofitting manual for highway structures: Part 1—Bridges*, Publication No. FHWA-HRT-06-032, Research, Development, and Technology Turner-Fairbank Highway Research Center, McLean, Va.

Federal Highway Administration (FHWA). (2008). *National Bridge Inventory data*, FHWA, Washington, D.C.

FEMA. (2008). "New Madrid Seismic Zone catastrophic plan." *Release No. HQ-08-250*, Washington, D.C.

Ghasemi, H., and Higgins, M. S. (1999). "Sizing up seismic bearings." *Civ. Eng. (N.Y.)*, 69(7), 54–59.

Ghosh, J., and Padgett, J. E. (2010). "Aging considerations in the development of time-dependent seismic fragility curves." *J. Struct. Eng.*, to be published.

Hildenbrand, T. G., Griscom, A., Van Schmus, W. R., and Stuart, W. D. (1996). "Quantitative investigations of the Missouri gravity low: A possible expression of a large, Late Precambrian batholith intersecting the New Madrid seismic zone." *J. Geophys. Res., [Solid Earth]*, 101(B10), 21921–21942.

Hipley, P. (1997). "Bridge retrofit construction techniques." *2nd National Seismic Conf. on Bridges and Highways*, Office of Earthquake Engineering, Sacramento, Calif.

Housner, G. W., and Thiel, C. C., Jr. (1995). "The continuing challenge: Report on the performance of state bridges in the Northridge Earthquake." *Earthquake Spectra*, 11(4), 607–636.

Hwang, H., Jernigan, J. B., and Lin, Y. W. (2000). "Evaluation of seismic damage to Memphis bridges and highway systems." *J. Bridge Eng.*, 5(4), 322–330.

Imbsen, R. A., Pecchia, D. D., Davis, G. V., and Chang, G. S. (1999). "I-40 Mississippi River Bridge seismic retrofit." *Proc., 1999 Structures Congress: Structural Engineering in the 21st Century*, ASCE, Reston, Va., 41–44.

Jankowski, R., Wilde, K., and Fujino, Y. (1998). "Pounding of superstructure segments in isolated elevated bridge during earthquakes." *Earthquake Eng. Struct. Dyn.*, 27(5), 487–502.

Khater, M., et al. (1990). "Lifelines performance during the October 17, 1989 Loma Prieta earthquake." *NIST Spec. Publ.*, 796, 344–362.

Li, J., Peng, T., and Xu, Y. (2008). "Damage investigation of girder bridges under the Wenchuan earthquake and corresponding seismic design recommendations." *Earthquake Eng. Eng. Vib.*, 7(4), 337–344.

Mayes, R. L., Choudhury, D., Crooks, R. S., Jones, D. M., and Knight, R. P. (1994). *Seismic isolation retrofit of existing bridges*, ASCE, Reston, Va.

Mayes, R. L., Jones, L. R., Kelly, T. E., and Button, M. R. (1984). *Base isolation concepts for seismic bridge retrofit*, ASCE, San Francisco.

Mellon, D. E., and Post, T. J. (1999). "Caltrans bridge research and applications of new technologies." *U.S.–Italy Workshop on Seismic Protective Systems for Bridges*.

Moehle, J., et al. (1995). "Highway bridges and traffic management." *Earthquake Spectra*, 11(S2), 287–372.

Nielson, B. (2005). "Analytical fragility curves for highway bridges in moderate seismic zones." Ph.D. thesis, Georgia Institute of Technology, Atlanta.

Nielson, B. G., and DesRoches, R. (2007a). "Analytical seismic fragility curves for typical bridges in the central and southeastern United States." *Earthquake Spectra*, 23(3), 615–633.

Nielson, B. G., and DesRoches, R. (2007b). "Seismic performance assessment of simply supported and continuous multispan concrete girder highway bridges." *J. Bridge Eng.*, 12(5), 611–620.

Padgett, J. E. (2007). "Seismic vulnerability assessment of retrofitted bridges using probabilistic methods." Ph.D. thesis, Georgia Institute of Technology, Atlanta.

Padgett, J. E., Dennemann, K., and Ghosh, J. (2009). "Risk-based seismic life-cycle cost-benefit analysis (LCC-B) for bridge retrofit assessment." *Struct. Safety*, 32(3), 165–173.

Padgett, J. E., and DesRoches, R. (2008). "Three-dimensional nonlinear seismic performance evaluation of retrofit measures for typical steel girder bridges." *Eng. Struct.*, 30(7), 1869–1878.

Priestley, M. J. N., Seible, F., and Calvi, G. M. (1996). *Seismic design and retrofit of bridges*, Wiley, New York.

Saiidi, M., Maragakis, E. A., and Feng, S. (1996). "Parameters in bridge restrainer design for seismic retrofit." *J. Struct. Eng.*, 122(1), 61–68.

Sanders, D. H., Saiidi, M., and Martin, T. (1998). "Seismic strengthening of column-pier-cap connections." *Transp. Res. Rec.*, 1624, 93–100.

Schiff, A. J., and Tang, A. K., eds. (1999). "Chi-Chi, Taiwan, earthquake of September 21, 1999 lifeline performance." *Technical council on lifeline earthquake engineering monograph*, Vol. 18, ASCE, Reston, Va., 1–217.

Stanton, J. F., and Roeder, C. W. (1992). "Elastomeric bearings. An overview." *Concr. Int.*, 14(1), 41–46.

Street, R., Woolery, E. W., Wang, Z., and Harris, J. B. (2001). "NEHRP soil classifications for estimating site-dependent seismic coefficients in the Upper Mississippi Embayment." *Eng. Geol. (Amsterdam)*, 62(1–3), 123–135.

Thewalt, C. R., and Stojadinovic, B. (1995). "Outrigger knee joint seismic upgrade design procedure." *Proc., National Seismic Conf. on Bridges and Highways*, Federal Highway Administration and California Dept. of Transportation, San Diego.

Vlassis, A. G., Maragakis, E., and Saiidi, M. (2004). "Experimental evaluation of longitudinal seismic performance of bridge restrainers at in-span hinges." *J. Test. Eval.*, 32(2), 96–105.

Wendichansky, D. A., Chen, S. S., and Mander, J. B. (1995). "In-situ performance of rubber bearing retrofits." *National Seismic Conf. on Bridges and Highways, Progress in Research and Practice*, FHWA, San Diego, Calif.

Wesemann, L., Hamilton, T., Tabaie, S., and Bare, G. (1996). "Cost-of-delay studies for freeway closures caused by Northridge earthquake." *Transp. Res. Rec.*, 1559, 67–75.

Yashinsky, M. (1998). "Performance of bridge seismic retrofits during Northridge earthquake." *J. Bridge Eng.*, 3(1), 1–14.

Zatar, W., Harik, I. E., and Choo, C. C. (2008). "Seismic risk assessment of priority bridges along I-24 in Western Kentucky." *Proc., 6th National Seismic Conf. on Bridges and Highways: Seismic Technologies for Extreme Loads*, MCEER, Charleston, S.C.