SAFEGUARDING HIGHWAY INFSTRUCTURE

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ABSTRACT:

This paper gives a brief overview of measures taken in the USA to protect highways and bridges from earthquake damage. It focuses on ten years of applied research carried out by MCEER, University at Buffalo for the Federal Highway Administration, a division of the US Department of Transportation. MCEER managed a series of integrated projects, which are guided by blue-ribbon panels of nationally renowned technical experts. The projects concentrate on bridges and other highway structures that are critical links in the transportation network and put an emphasis on producing tangible deliverables that provide practitioners with a means of implementing this new knowledge. It will also explain how the research, along with laboratory experimentation and the post-earthquake evaluation of actual performance, is used by the American Association of State Transportation Officials (AASHTO) to modify bridge design specifications.

KEYWORDS: highways, bridges, research

1. INTRODUCTION

Highway bridges are a vital link in the transportation network. Each year, over 10,000 of the almost 600,000 existing bridges in the USA are replaced or rehabilitated. The designs used on these structures benefit from millions of state and federal dollars that have been spent on research, much of it done at MCEER, University at Buffalo. This research and the resultant change to standard design practice, through incorporation into AASHTO design specifications, will lead to improved performance of bridges in the event of an earthquake. This paper summarizes over ten years of applied research carried out by MCEER for FHWA as a series of integrated projects, which were guided by blue-ribbon panels of nationally renowned technical experts. The research described in this paper was accomplished through the following projects:

- Project 106: Seismic Vulnerability of Existing Highway Construction (1992-2004)
- Project 112: Seismic Vulnerability of New Highway Construction (1992-1999)
- Project 094: Seismic Vulnerability of the Highway System (1998-2007)
- Project 020: Innovative Technologies and Their Applications to Enhance the Seismic Performance of Highway Bridges (2007 – present)

The studies have dealt with methods for assessing the seismic vulnerability of existing bridges, strategies for cost-effectively improving bridges with conventional and innovative technology, network-level damage assessment and impact on traffic patterns, analysis of complex, long-span structures, analysis and remediation of geotechnical issues, and development of improved criteria for the design of new structures using a displacement control philosophy. The projects provided project deliverables that provide practitioners with the necessary resources to implement this new knowledge.

2. PROCESS OVERVIEW

In general, the process of safeguarding highway infrastructure starts with the determination of its condition and the risks faced from extreme events such as earthquakes. Analytical and experimental research can contribute to the body of knowledge needed to reduce the risk of damage to structures such as bridges. In addition, when an earthquake strikes, an observation of performance can provide feedback that can be used to refine the design methods so that the impact of an event can be reduced. New knowledge from research and lessons learned from real-world experience is then used to develop new guidance for design professionals. This can be in the form of new manuals, guidelines, training courses, professional conferences or other means of technology transfer. Eventually, this new knowledge is incorporated as “best practice” by AASHTO into their bridge design specification that is used by transportation agencies for designing new bridges.

Existing bridges (and other roadway features) pose a different problem. As state-of-the-art for the design of bridges improves over time, the design used for bridges that were built in the past becomes dated. While a bridge that is only a few years old may offer essentially the same protection as a recently designed one, bridges that were designed before the 1970’s do not have some of the detailing, considered standard practice today, that provides basic protection from earthquakes. Agencies must make programmatic decisions to accept the higher level of risk on these older bridges, or to retrofit them so that their performance is more in line with current expectations. Often, the importance of a structure, and the cost associated with improving it, along with the probability of occurrence of a significant earthquake, play a dominant role in determining the best course of action. AASHTO has traditionally taken the lead in setting design standards for new bridges; FHWA has provided guidance on the retrofitting existing structures.

2.1 Needs Assessment

The US implemented a comprehensive bridge inspection program soon after the 1967 catastrophic collapse of the Silver Bridge in Kentucky. Though improved upon over the years, the framework for bridge safety established after that failure is still used today: visual inspections providing evaluation data that is posted in the National Bridge Inventory (NBI). This and other inventory information is used to formulate federal Sufficiency Ratings (SR's) that are used to prioritize work and allocate funds. Using these ratings, certain at-risk bridges are defined as *structurally deficient*. Though this does not mean that the bridge is unsafe, the term is used to draw attention to needs that should be addressed.

Though the requirement for regular bridge inspections is a federal mandate, some states supplement these with more intensive programs and procedures of their own so they can more accurately determine what deficiencies their bridges might have and so they can manage their resources better to address these concerns. Examples are:

- Post-event bridge inspections (e.g. to look for scour damage after a flood)
- Requirement that field inspections be done by a registered professional engineer
- Documentation of any changed condition in a detailed report with photos.
- Policy of "flagging" bridges for defects that pose an immediate hazard or imminent risk.
- Inspection using various non-destructive testing (NDT) techniques.
- In-depth inspections or site-specific Structural Integrity Evaluations
- Hazard-specific vulnerability assessment programs (e.g. NYSDOT VA program)
- Use of a bridge management System (BMS) such as PONTIS.

2.2 Lessons Learned

In addition to the accumulation of condition data from the state administered bridge inspection programs, there has been an abundance of information collected after natural disasters. Over the past several decades, California, in particular, has been struck by earthquakes, each of which has contributed to the existing body of knowledge in a unique way. After the San Fernando earthquake of 1971, the California DOT (Caltrans) initiated revisions in its seismic design criteria and began development of new criteria for future bridge designs. It was this event that prompted initiation of a seismic retrofit program, focused on mid-span hinges and abutment joints. Post-earthquake performance assessments from this event and others changed Caltrans' design and retrofit procedures, and these lessons were eventually reflected in national practice.

2.3 Key Agency Stakeholders

Approximately 45% of all spending for transportation infrastructure comes from the federal government. The current transportation funding plan is providing $223 billion for the period 2005 through 2009 (Better Roads, July 2008). This funding is administered by FHWA and sent to State Departments of Transportation (DOT's) for contracts with private construction companies. Other funding is provided directly by bridge owners, i.e. authorities, states, counties and cities. AASHTO is an independent association of state transportation officials that has historically played an important role in maintaining and improving the country's infrastructure. This democratic organization maintains it own set of design standards and these have become the de-facto standard for the country. AASHTO members approve any specification changes through a democratic vote, with each state carrying one vote. Industry associations such as American Road and Transportation Builders Association (ARTBA) have a vested interest in the funding process but these organizations do not directly control allocation of public funds.

2.4 Formulation of Research Needs, Research Accomplishment, Specification Development, and Acceptance into Practice

Most funding for research comes from the federal government, through a set aside in the funding legislation. State DOT's manage their own research, participate in pooled fund studies with other states, and benefit from research administered by the Transportation Research Board (TRB). Research problem statements are solicited from TRB's technical committees and prioritized among all received. AASHTO has a standing committee on research (Technical Committee T-11) and works closely with TRB to insure that research projects are driven by the needs of AASHTO. Highway research in the US is typically conducted at educational institutions such as University at Buffalo, but projects often involve practicing engineers.

Although not mandatory, most changes to AASHTO specifications are accomplished through projects carried out under TRB's National Cooperative Research Program (NCHRP). These projects synthesize new knowledge and put them into a technical specification suitable for adoption by AASHTO. Once guidelines and specifications are officially adopted by AASHTO, there is an inherent incentive for agencies to use this standard in their practice. Although not legally bound to do so, there is less liability exposure if a designer follows what is considered the profession's standards. A prudent engineer or agency will document any deviation from the established standards so that the rationale for the decision can be followed in the future.

2.5 Cycle of Challenges and Opportunities

At the Fifth National Seismic Conference, (MCEER 2006) the Chief Engineer for Caltrans, Rick Land, illustrated the iterative process used to improve the resilience of California's transportation infrastructure. This graphic presents a broad process that occurs over many years.

Figure 1. The Challenge-Opportunity Cycle as defined by Caltrans' Chief Engineer.

3. RESEARCH ACCOMPLISHMENTS

3.1 Design of New and Replacement Bridges

In 2007, AASHTO modified its guidance for the seismic design of bridges. Until then, the AASHTO specification was largely based on design philosophies and methods that were developed in the 1980's. This meant that as extensive research contributed to an advanced understanding of the behavior of bridges under dynamic loading, the official specification did not incorporate what had been learned from. The gap between state-of-the-art and state-of-the-practice had widened such that need for adoption of more modern specification was evident. AASHTO modified their design specification and adopted a new guide specification to offer two alternatives for the design of new bridges. A Technical Review Team, made up of representatives of various DOT's, played an important review role to assure that the new guidelines were practical and implementable, with eleven state DOT's conducting trial designs prior to adoption.

3.1.1 AASHTO Guide Specification

Technically, the document reflects a move toward performance based design, instead of a prescriptive force based approach. A structure in a seismically active zone will be analyzed to insure that it can accommodate displacements without collapse. A conservative support length is recommended (a minimum factor of safety of 1.5). The approved guide specification is intended to achieve minimal damage to bridges during moderate earthquake ground motions and to prevent collapse during rare, high-amplitude earthquakes. A no-collapse performance is mandatory for all bridges but inelastic damage may be tolerated in regions of high demand for the sake of cost. A 1,000 year return period (approximately equivalent to a 7% probability of exceedance in 75 years) was adopted as the hazard level in lieu of the 500 year event used in the past.

3.1.2 Hazard Maps

At AASHTO's request, U.S. Geological Survey (USGS) produced new paper maps of the U.S. that show the distribution of earthquake shaking levels that have a certain probability of occurring. The new plots are for 7% probability of exceedance in 75 years. In addition, USGS produced a ground motion software tool on CD that will show the maps in Adobe's pdf format, provide peak ground accelerations (PGA's) and spectral accelerations retrievable by using zip code of the bridge site (or latitude-longitude coordinates), and generate map values at the B-C Boundary, that in combination with PGA, Ss, and S1 produce the design Acceleration Response Spectrum (ARS) curves for specific bridge sites These tools provide the most accurate and detailed information possible to assist engineers.

3.1.3 Two Allowable Design Methods

Since there was an existing LRFD specification that is force based, the ballot item approved by AASHTO in 2007 is in two parts. It updates the current force-based bridge design specification while at the same time presents the alternative of using a newly developed seismic guide specification that employs a displacement based approach. There are thus two documents available to designers, with the second being the more advanced school of thought on the subject.

- LRFD Bridge Design Specifications (force based)
- AASHTO Guide Specifications for LRFD Seismic Bridge Design (predominantly displacement based)

Documents will be available for purchase from AASHTO in the near future. The actual text of the 2007 ballot items is available on line now at the following URL: http://cms.transportation.org/?siteid=34&pageid=1484

3.2 Existing Bridges

Whereas AASHTO has historically established and maintained standards for the design of new bridges, FHWA stepped up in the 1980's to produce guidance on the protecting existing bridges from earthquake damage. In 2006, it replaced its 1995 manual on retrofitting bridges with a major re-write produced by a team of MCEER researchers. The two volumes set "Seismic Retrofitting Manual for Highway Structures," consists of

Part 1: Bridges, and
Part 2: Retaining Structures, Slopes, Tunnels, Culverts, and Roadways.

The latter volume is the first comprehensive attempt at presenting information on these types of structures. Each incorporates the experience gained from recent earthquakes and the intense seismic-research effort that has recently been developed and conducted in several structural testing laboratories.

3.2.2 Truss Bridges

Since the AASHTO specifications generally apply only to regular bridges with a span less than 500 feet, MCEER's Highway Seismic Research Council advised that there was a need for guidance particular to special long-span bridges that fall outside of the specifications. Since 80% of the existing long span bridges in the U.S. are steel trusses, a task was initiated to write a manual that captured the knowledge of the relatively few experts who had designed seismic retrofits for this type of bridge. A detailed investigation into one particular aspect of truss members was conducted. Two products are available:

- Seismic Retrofit Guidelines for Complex Steel Truss Highway Bridges, by T. Ho, R. Donikian, T. Ingham, C. Seim and A. Pan
- "Seismic Vulnerability Evaluation of Axially Loaded Steel Built-up Laced Members," by K. Lee and M. Bruneau

3.3 Loss Estimation

Public domain software called REDARS (Risks from Earthquake Damage to Roadway Systems) has been developed to perform network wide analysis of the traffic impacts Earthquake damage to highway systems can severely disrupt traffic flows and operations at the network level, thus leading to widespread logistical and economic impacts on post-earthquake emergency response and recovery. REDARS has been developed to enable transportation decision makers to evaluate and prioritize how various seismic-risk-reduction strategies will improve post-earthquake traffic flows so as to minimize the risk of severe economic disruption after an earthquake caused by severed critical links. The following references relate to loss estimation.

- REDARS 2: Methodology and Software for Seismic Risk Analysis of Highway Systems, by S.D. Werner, C.E. Taylor, S. Cho, J-P. Lavoie, C. Huyck, C. Eitzel, H. Chung and R.T. Eguchi
- REDARS Validation Report, by S. Cho, C.K. Huyck, S. Ghosh and R.T. Eguchi
- "Fragility Considerations in Highway Bridge Design," by M. Shinozuka, S. Banerjee and S-H. Kim
- "Statistical and Mechanistic Fragility Analysis of Concrete Bridges," by M. Shinozuka, S. Banerjee and S.H. Kim
- "Seismic Vulnerability of Timber Bridges and Timber Substructures," by A.A. Sharma, J.B. Mander, I.M. Friedland and D.R. Allicock

3.4 Innovative Response Modification Technologies

3.4.1 Isolation

Over the past 20 years, seismic isolation has become a proven technology that has been used over 200 bridges in the U.S., and thousands of bridges world-wide. This strategy can also be used on rehabilitation projects or in the design of new bridges to decrease the load demand placed on substructures and foundations. Even though isolation bearings are more expensive than traditional bearings, the strategy often provides a net cost savings due to the reduced need to strengthen the substructure and foundation to accommodate seismic demands. Current isolation design relies on proprietary information from manufacturers as well as AASHTO's "Guide Specifications for Seismic Isolation Design," 1999, and the 2000 Interims. FHWA has recently made available supplementary material that expands upon the AASHTO specification.

- "Seismic Isolation of Highway Bridges," by I.G. Buckle, M. Constantinou, M. Dicleli and H. Ghasemi

This manual includes additional information on principles of isolation and thoroughly explains the benefits that can be gained when they are used on new or existing bridges. It provides analysis methods and design examples for various bearing types that are available and presents a summary of U.S. applications.

As the use of seismic isolation bearings becomes more common place, and as the ones in service age, it becomes increasingly important to understand how they perform over time. The following are results of research on the long term performance of isolation bearings:

- "Performance of Seismic Isolation Hardware Under Service and Seismic Loading," by M.C. Constantinou, A.S. Whittaker, Y. Kalpakidis, D.M. Fenz and G.P. Warn
- Performance Estimates for Seismically Isolated Bridges, by. G. Warn and A. Whittaker

MCEER has pioneered a next-generation isolation bearing and has documented the research that has been done over the past eight years in the following report:

- Roller Bearings: Theory, Performance and Design, by G.C. Lee, T. Niu, Z. Liang and J. Song

3.4.2 Other Technologies

The following reports illustrate the types of research tasks that have been undertaken.

- "Review of Energy Dissipation of Compression Members in Concentrically Braced Frames," by K. Lee and M. Bruneau, 10/18/02, (PB2004-101638, A10, CD-A10).
- Seismic Performance of Steel Girder Bridge Superstructures with Ductile End Cross Frames and Seismic Isolators, by L.P. Carden, A.M. Itani and I.G. Buckle
- Seismic Performance of Steel Girder Bridge Superstructures with Conventional Cross Frames, by L.P. Carden, A.M. Itani and I.G. Buckle
- "Further Development of Tubular Eccentrically Braced Frame Links for the Seismic Retrofit of Braced Steel Truss Bridge Piers," by J.W. Berman and M. Bruneau, 3/27/06.
- "Built-Up Shear Links as Energy Dissipators for Seismic Protection of Bridges," by P. Dusicka, A.M. Itani and I.G. Buckle, 3/15/06.
- "Seismic Retrofit of Bridge Steel Truss Piers Using a Controlled Rocking Approach," by M. Pollino and M. Bruneau, 12/20/04 (PB2006-105795).

- "Review of Current NDE Technologies for Post-Earthquake Assessment of Retrofitted Bridge Columns," by J. Song, Z. Liang and G.C. Lee

3.5 Foundations & Geotechnical Considerations

In the past, because most earthquake failures materialize as structural damage, there has been a tendency to under-emphasize the importance of geotechnical issues. Over the years, it is becoming increasingly evident that soil conditions and the foundation play a major role in a structure's ability to withstand an earthquake. Whether subsurface conditions lead to the amplification of ground accelerations or to liquefaction of supporting ground, a sound understanding is critical to any good design.

Although the 2008 AASHTO ballot item is expected to address issues such as how to assess the potential for liquefaction and deal with the threat, the above mentioned Recommended LRFD Guidelines for the Seismic Design of Highway Bridges contains a Liquefaction Study Report that is considered the best available information now. Additional foundations and geotechnical reports that are of interest are:

- "Bridge Foundations: Modeling Large Pile Groups and Caissons for Seismic Design," by G.R. Martin and I. Po Lam
- "Liquefaction Remediation in Silty Soils Using Dynamic Compaction and Stone Columns," by S. Thevanayagam and G.R. Martin
- "Centrifuge Modeling of Permeability and Pinning Reinforcement Effects on Pile Response to Lateral Spreading," by Dobry, Abdoun, Gonzalez
- Modeling of Seismic Wave Scattering on Pile Groups and Caissons, by I. PoLam, H. Law and C.T. Yang

CONCLUSION

Thanks to the iterative, continuous improvement process that has evolved in the US, each new bridge is intrinsically safer than the bridge it is replacing. Nevertheless, catastrophic events like the collapse of the I-35W bridge in Minneapolis in 2007 and numerous failures resulting from Hurricane Katrina's storm surge in 2005, highlight the fact that the goal of having safe and secure bridges is a moving target. While MCEER's past earthquake-oriented research has been extremely beneficial, there is still much to be done to protect against other natural hazards.

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