Enhancing Seismic Design Criteria for Our Nation's Vulnerable Bridges

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Recent earthquakes, such as the 1989 Loma Prieta and 1994 Northridge earthquakes in California and the 1995 Kobe earthquake in Japan, have caused severe damage to a considerable number of bridges. This extensive damage and loss of life emphasized the need to develop new procedures and specifications to assess existing bridges and to improve the seismic design of new bridges.

OVERVIEW

The seismic specifications for highway bridges have been through significant changes as a result of damaging earthquakes. In 1956, bridge specifications included a static load approach for the design of bridges in seismic zones (*1*). This approach was mainly based on the Structural Engineering Association of California (SEAOC) Blue Book, which specified a percentage of the dead load and used it as lateral loads to account for seismic forces. Recognizing the shortcomings of this approach, in 1968 the California Department of Transportation (Caltrans) included the effect of the dynamic characteristic of bridges in the seismic design process. Elastic dynamic analyses were performed thereafter during the seismic design of California bridges. However, after the significant highway bridge damage during the 1971 San Fernando earthquake, Caltrans adopted additional seismic design criteria in 1973 that included

- Seismicity,
- Soil effects,
- Dynamic characteristics, and
- Ductility reduction factor (*1*).

In addition, rigorous reinforcement detail provisions for reinforced concrete bridge columns were incorporated in Caltrans bridge design specifications.

In 1975, the American Association of State and Highway Transportation Officials (AASHTO) adopted Caltrans criteria for the seismic design of highway bridges. In 1978, recognizing the need for national criteria that should include the effect of earthquakes that are different from California's earthquakes, the Federal Highway Administration (FHWA) commissioned the Applied Technology Council (ATC) to develop seismic design guidelines for highway bridges (*2*). The guidelines were comprehensive in nature and embodied several new concepts that departed significantly from the procedures that existed at that time. Although the guidelines specified ultimate earthquake loads, they utilized an elastic modal analysis procedure in conjunction with a force reduction factor to account for the nonlinearity of the response during strong earthquakes. AASHTO adopted the ATC-6 document as "Guide Specifications" for the seismic design of highway bridges.

Another milestone in the seismic design of highway bridges came after the 1989 Loma Prieta earthquake. The collapse of Cypress Viaduct and the damage to the San Francisco-Oakland Bay Bridge proved the continued vulnerability of highway bridges and the need to further modify the seismic specifications. This earthquake also exposed the impact of highway bridges on the national economy and the necessity of having such important structures serviceable after such events. Following the Loma Prieta earthquake, Caltrans increased its funds for seismic bridge research by more than twenty-fold. Large-scale bridge components were tested under static and dynamic loads to study and improve their seismic performance. In addition, Caltrans commissioned the ATC to study its Bridge Design Specification and revise it to include the latest information in ground motion and seismic design. A new document was prepared, ATC-32, which contains state-of-the-art information about seismic design of concrete bridges (*3*). This document can be regarded as a benchmark in bridge seismic design because it placed an emphasis on the deformation capacity of bridge components during cyclic loading.

On the other hand, after the Loma Prieta earthquake, AASHTO adopted the 1983 Guide Specification of seismic design as part of the Standard Specification and made it mandatory to include seismic effects during the design process (*4*). It also adopted the bridge base isolation in "Guide Specifications" as additional means to reduce seismic forces (*5*). In 1992, FHWA initiated the National Center for Earthquake Engineering Research (NCEER) Highway Project, which is a comprehensive seismic research program for bridges and highways (*6*). This research consisted of two separate FHWA-sponsored projects. Both projects involved research studies on the seismic vulnerability of highway construction in the United States, including bridges, pavements, tunnels, retaining structures, slopes, and embankments. The existing infrastructure study, which is administered by the Multidisciplinary Center for Earthquake Engineering Research, is a 6-year project concentrating on the development of revised and up-to-date seismic retrofit guidelines to provide cost-effective tools for improved evaluation and seismic upgrading of the existing highway network. The new construction study is a 4-year project in which improved seismic design guidelines for future highway construction are being developed.

DIRECTIONS AND CHALLENGES FOR THE FUTURE

As we enter the new millennium, the challenge will be to identify critical areas that need to be studied in order to develop new and more advanced design criteria. The biggest emphasis will be on the development of performance-based design, including issues related to ground motion, new analytical and experimental studies, and new technologies. These design aspects are discussed briefly in the rest of the paper.

Performance-Based Design

The primary goal of bridge codes is to provide life safety to the users. For seismic conditions, this provision traditionally has been accomplished by designing bridges with sufficient strength, integrity, and ductility. During the 1994 Northridge earthquake, we observed that bridges designed or retrofitted to the current standards performed at or above expectation. However, the usability of the bridges after the earthquake and the costs of repair were disappointing. We now believe that it is insufficient to consider only a life-safety performance level for seismic design in active seismic zones. We also need to consider seismic design in a manner that limits the repair costs and the time needed to complete the repair.

Performance-based design involves the design and construction of bridges that will resist earthquakes in a predictable manner. It includes the selection of appropriate parameters, such as bridge period, stiffness, etc., to control the behavior of the structure during earthquakes. These performance levels, which are the heart of performance-based design, represent a significant challenge for the future.

Performance-based design is based on the principles that were adopted in the SEAOC Vision 2000:

1. Define a series of standard performance levels for the seismic design. The importance of the bridge, thus its performance criteria, should be selected based on safety, and on the economical and social consequences of the given damage state.
2. Define a series of reference earthquake hazard and design levels. Within a defined period of time, a given seismic source zone may produce small magnitude events, several moderate earthquakes, and a few large magnitude events. The goal of the performance-based design is to control the risk associated with a bridge structure to predetermined levels of acceptability.
3. Recommend uniform design procedures that can be adopted nationwide based on performance-based design (*7*).

Issues Related to Ground Motion

The ground motion intensity, duration, and frequency content present an influencing parameter on the seismic design of bridges. Several issues pertaining to ground motion have been raised in the past few years and were the basis of a FHWA/NCEER Workshop on the National Representation of Seismic Ground Motion for New and Existing Highway Facilities (*8*). For example,

- Should new (1996) U.S. Geological Survey (USGS) maps provide a basis for the national seismic hazard portrayal of highway facilities? If so, how should they be implemented in terms of design values?
- Should energy or duration be used in a design procedure?
- How should site effect be characterized for design?
- Should vertical ground motions be specified for design?
- Should near source ground motions be specified for design?
- Should spatial variations of ground motions be specified for design?

Issues Related to Mathematical Modeling and Analysis

Mathematical models and analysis techniques represent the demand side of the overall design equation. Many aspects of analysis need to be addressed in the new millennium. Some of them are related to bridge foundations and response of bridge columns.

Many researchers have investigated the effect of foundation and abutments on bridge response. Currently, however, there are no uniform guidelines for foundation and abutment mathematical models. Consequently, there is an urgent need to establish uniform guidelines to model different abutment and foundation types. This model should include the cyclic response of soil and soil-structure interaction.

Another issue is related to the need to develop or refine models to simulate the hysteretic behavior of bridge columns under flexure and shear deformations. The models should include the effect of cyclic loading, fatigue failure of reinforcing steel, and the opening or closing of concrete cracks. These models should be calibrated to large-scale experimental testing.

Structural Design Issues and Experimental Testing

During the past 10 years several tests have been conducted on various bridge components; however, experimental studies that relate the performance of bridge components to overall system performance are still needed. In addition, we need to relate component behavior to physical quantities, such as strain values, and to establish relationships between dynamic and static testing for flexure and shear. The effect of strain rate and other dynamic characteristics should be evaluated and compared with the static push-pull testing.

New Technologies

The new millennium will provide a challenge to the earthquake engineering community to develop new technologies that will improve the seismic performance of bridges. These new technologies will consist of new construction materials (smart materials) and protective systems. Theoretical, experimental, and field evidence confirm the benefits of these cost-effective technologies and their potential to reduce earthquake losses in highway bridges. These technologies should be further studied experimentally and analytically to enhance their seismic performance.

SUMMARY

Major earthquakes during the past 40 years have revealed the vulnerability of highway bridges to seismic loads and the need for the development of effective bridge seismic design criteria and retrofitting techniques. As we move into the new millennium, more studies will be conducted and new factors will be considered to further enhance bridge seismic design and to develop new criteria. The directions and challenges for the future relate to the development of performance-based design criteria, the incorporation of several aspects of ground motion in bridge design, the performance of advanced analytical and experimental studies, and the exploration of the development and feasibility of new technologies. As many more researchers, consultants, and state and federal agencies get involved in this interesting, important, and complicated problem of bridge design, it is critical to develop better coordination for all these activities. This coordination will help to identify critical problems, avoid duplication, optimize resources, and achieve fast implementation of the research results. The Transportation Research Board, through the Task Force on the Seismic Design of Bridges and other related committees, can play a major role in the development of new and more reliable seismic bridge design criteria in the new millennium.

REFERENCES

1. *Seismic Design of Highway Bridges.* FHWA, U.S. Department of Transportation, Prepared by Imbsen and Associates, March 1992.
2. *Seismic Design Guidelines for Highway Bridges*. Report FHWA/RD-81/081. FHWA, U.S. Department of Transportation, October 1981.
3. *Revised Caltrans Bridge Design Specifications, ATC-32*. Applied Technology Council, Redwood City, Calif., 1994.

4. *Standard Specifications for Highway Bridges*. American Association for State Highway and Transportation Officials, 15th Edition, 1989, and Interim Specifications 1990, 1991.
5. *Guide Specifications for Seismic Isolation Design*. American Association of State Highway and Transportation Officials, June 1991.
6. *The NCEER Highway Project*. Annual Report to AASHTO Highway Subcommittee on Bridges and Structures, National Center for Earthquake Engineering Research, May 10, 1995.
7. *Performance Based Seismic Engineering of Buildings*. Vol. I, Structural Engineers Association of California, April 3, 1995.
8. *Proceedings of the FHWA/NCEER Workshop on National Representation of Seismic Motion for New and Existing Highway Facilities*. Technical Report NCEER-97-0010. FHWA/NCEER, San Francisco, Calif., September 1997.