

SEISMIC BRIDGE DESIGN IMPROVEMENTS THROUGH RESEARCH IMPLEMENTATION

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ABSTRACT

The California Department of Transportation (Caltrans) Seismic Research Program's goal is to identify the earthquake vulnerabilities of highway structures and to develop engineering solutions to address these problems. Research findings were incorporated into the seismic design code of bridges resulting in improvements in seismic performance. Key findings from the Caltrans Seismic Research Program are reviewed.

INTRODUCTION

The California Department of Transportation (Caltrans) launched a high priority research program in 1989 following the Loma Prieta earthquake. The main goal of the program was to identify the earthquake vulnerabilities of highway transportation structures and to develop engineering solutions to address these problems. Caltrans initiated testing of bridge components to determine their capacity and feasibility for seismic retrofit. These components include: different column configurations, footings, bent caps, restrainers, and pier walls tested under a quasi-static loading. Now Caltrans is testing newly designed bridges with modern details utilizing more sophisticated testing techniques. These techniques include shake table testing, which tests the system rather than just bridge components. Implementation of research findings and the development of better technology for retrofit work in the 1990's led to the development of the Caltrans Seismic Design Criteria for new bridges published in the 1999 then updated in the 2001 and 2004. This paper reviews key research findings and describes how these findings are incorporated into bridge design criteria to improve the seismic performance of California bridges.

CALTRANS SEISMIC RESEARCH PROGRAM

The objectives of the current Caltrans Seismic Research Program are to:

1. Facilitate the development of applicable problem-focused seismic research projects.
2. Expand the use of research findings by incorporating the research findings in the Caltrans design codes, guidance materials and other implementation, (resulting in improved transportation mobility, safety, reliability, performance, and productivity.)
3. Advance bridge seismic design and retrofit practice by expanding research efforts and incorporating research findings into practice.
4. Validate new design techniques.

5. Validate new materials/devices introduced by industry to be used in highways structures in order to improve seismic performance.

PAST PERFORMANCE OF TRANSPORTATION STRUCTURES IN CALIFORNIA

In the past forty years, earthquakes in California and around the world provided graphic evidence that bridges built using old design codes/assumptions were vulnerable to earthquakes. Studies of California bridges revealed the following vulnerabilities:

- Column details inadequacies
 - Pre 1971 Caltrans columns lacked flexural and shear strength as a result of inadequate confinement and lap splices.
 - Columns re-bars development into supersaturates as well as into footing was not adequate.
 - Inadequate details of flared columns.
 - Inadequate details of pier walls.
 - Inadequate joint shear capacity.
- Short inadequate hinge seats
- Inadequate details of bridge pier walls.
- Lack of shear strength of bent cap.
- Inadequate abutments details and gaps between bridge superstructure and the abutment back wall.
- Vulnerability of bridge rockers/bearings.
- Lack of lateral load capacity for existing piles.
- Inadequate connections between piles and bridge footings.
- Vulnerable performance of bridges as a result of soil lateral spreading and or liquefaction.

PRIORITIES FOR CALTRANS SEISMIC RESEARCH PROGRAM

1- Improved Bridge Seismic Design Details

Bridge Columns Testing Program

Testing at the University of California, San Diego after Loma Prieta identified the Caltrans column vulnerabilities and provided a basis for developing retrofit schemes. Later the University of Nevada, Reno performed shake table testing for pre-1971 designs as well as testing different schemes on retrofitted columns. New columns details were tested for circular columns and rectangular columns with interlock spirals. This testing demonstrated that the current Caltrans design for circular columns is effective. Dynamic testing of jacketed columns demonstrated the adequacy of Caltrans column retrofit program. Design guidelines were developed for interlocking spiral columns. (Sanders, et al, 2002) (Correal, et al, 2002)

Flared Column Testing

Testing revealed that flared columns were vulnerable because plastic hinge formed at the base of the flare during the seismic event creating stiffer columns. Caltrans developed new details with lighter flare reinforcement and different sizes of horizontal gaps between the column and the bridge suffit. Quasi-static testing was performed at the University of California, San Diego and later shake table testing at University of Nevada, Reno. This research demonstrated the adequacy of the proposed details with the recommendation to increase the horizontal gap size in flared columns to avoid gap closure and to prevent extensive shear damage to the columns and the cap beams. (Sanders, et al, 2002)

Pier Wall Testing Program

Caltrans tested several types of pier wall details at University of California, Irvine. The results of this research led to assessment of the existing wall capacities and schemes to repair and retrofit these walls. (Haroun, et al, 1997)

Column Bents Strengthened by In-Fill Walls

Caltrans tested the use of in-fill walls at the University of Nevada, Reno and the University of California, Irvine to verify the performance of this retrofit measure. Various types of in-fill walls used throughout California were tested (6" gap at top of the wall, no gap, dowels into bent cap, no dowels in cap, etc.). All types tested performed in a satisfactory manner. The most efficient type of wall had no gap at the top, and no dowels into the bent cap. (Pulido, et al, 2003)

Bent Cap Testing

Testing of pre-1971 details demonstrated inadequate bent cap shear capacity. A retrofit scheme using composite material performed satisfactorily. Later, new details for two-column bents with circular columns designed based on the current Caltrans guidelines were tested and found to be highly ductile. In addition the testing demonstrated that the two-way hinge reinforcement may yield even under small earthquakes and the yielding may go undetected due to a lack of surface damage. Methods to realistically estimate the forces at the hinges and connections were developed. (Sanders, et al, 2002) (Saiidi, et al, 2002)

Expansion Joints and Restrainers

Caltrans supported several studies to develop restrainers systems at University of California, Los Angeles and University of California, Berkeley. These studies demonstrated the effectiveness of restrainers in preventing collapse in many bridges. (Maragakis, et al, 2002) The performance of restrainers was quantified and verified with field data then recommendations were made on the important restrainer parameters and the Caltrans restrainer design procedure was modified.

Later at the University of Nevada, Reno, the response of bridge restrainers under seismic loading was studied using experimental shake table testing and an analytical research program. As a result of this research program design charts to be used by design engineers were developed to estimate the hinge opening and cable forces under different seismic loading. (Maragakis, et al, 2002)

2- Soil/Foundation Interaction

Abutment Research

Caltrans sponsored research programs to study the interaction between the bridge abutment and soil at the University of California, Davis. The research provided parameters for realistic modeling for the bridge boundary conditions. A research team from the University of Nevada, Reno conducted full-scale measurements. These measurements showed that the high damping of the abutments in typical short California bridges reduced the seismic demand on substructure substantially. (Caltrans Seismic Design Criteria, 2004)

Geotechnical Earthquake Engineering Research

Caltrans sponsored research projects to provide an assessment of bridge foundations in different soils and to study soil liquefaction. The research findings raised the level of certainty in the analysis. The results obtained from the Strain Wedge Model, SWM Program compared well with the University of California, Los Angeles test on a full-scale laterally loaded column shaft and the Treasure Island test on full-scale laterally loaded piles and pile groups in liquefied soil. This research work provided an alternative method of analysis to the commonly available procedure. (Ashour and Norris, 2002)

Large Shaft Performance Under Seismic Loading

A full-scale 6 feet diameter column with a drilled shaft foundation was tested. This research studied the soil-structure interaction of the shaft system. During this testing the formation and behavior of plastic hinges in drilled shaft foundation structures were verified. A full methodology for developing p-y curves and predicting soil-structure interaction was completed based on these research findings. (Caltrans Seismic Design Criteria, 2004)

3- Advanced Composite Materials Evaluation Program

Caltrans is sponsoring and monitoring research in an attempt to establish reliable composite products (fiber reinforced polymers, FRP) and develop installation techniques to solve seismic problems. Different full size specimens retrofitted by different FRP composite manufacturers were tested to determine the best retrofit scheme. Based on test results, composite products were used to retrofit selected bridges such as arch bridges.(Caltrans Seismic Advisory Board, 2003)

A Composite In-Field Monitoring Program was developed to determine the durability of composite materials. FRP composite samples and sensors were placed under real environmental conditions. Composite samples were retrieved periodically and tested. Test data from the samples retrieved periodically did not show deterioration under durability testing. Infrared photogrammetry did not show additional delimitation from existing voids in the FRP composite jackets. Environmental data showed humidity trapped inside the column jacket. This information verified the need for long-term durability testing for humidity.

4- Seismic Response Modification Devices, SRMD

San Francisco Bay area steel toll bridges have long spans and are lightweight. These features can result in large displacement during a seismic event. Innovations were needed to change the seismic behavior of these bridges using SRMD devices to modify their seismic demands. Large displacements can be accommodated using devices such as Friction Pendulum Bearing or controlled by using Viscous Damper. A full scale-testing program was conducted at the University of California, San Diego to test and validate these devices. (Caltrans Seismic Advisory Board, 2003)

Effect of Heating on Viscous Fluid Dampers

The effect of rising temperatures as a result of cyclic loading on the capacity of seismic devices was raised during testing of these devices to determine their adequacy for seismic loading when used in bridges. An experimental and analytical research program was conducted at University of California, Berkeley to study the effect of temperature (heating) on the response of Viscous Fluid Dampers under both service and seismic loading. As a result of this research program a design methodology on how to estimate the effect of heat and energy dissipation on the viscous Fluid Dampers was developed.

5- Developing New Design Tools

Caltrans continues to support research that may lead to the development of rational design tools. Without better modeling and material characterizations, engineers make conservative assumptions that lead to more uncertainties and increase the cost of design and construction of highway bridges.

6- Highway Bridges Instrumentation

Caltrans continues to work with the Department of Conservation in The Strong Motion Instrumentation Program (SMIP) to instrument highway bridges and ground sites for earthquake motions. The sensors provide information on structures performance during the seismic events. The data will be used to calibrate and refine the models used to predict bridge performance during seismic events. The information gained from these systems will improve the safety of California's bridges during earthquakes. Caltrans and University of California, Berkeley installed more sensitive down hole weak motion sensors for the Bay Area Toll Bridges. These sensors can record motions from the more common Magnitude 2 and 3 earthquakes. These weak motions reading can be used to accurately locate and map the fault structures. (El-Azazy, et al, 1999)

7- Ground Motion Investigation

Caltrans supports research that lead to better understanding of the ground motions, seismic loading and the effect of fault rupture on bridges built near or crossing faults.

8- Performance of Steel Bridges

Caltrans sponsored several research projects to study the performance of steel bridges.

The research findings were used to make decisions such as whether to retrofit the east crossing of the San Francisco Bay Bridge (SFOBB) or to construct a new bridge. The research also defined the scope of how to retrofit the latticed members on the west crossing of the SFOBB and on the Richmond San Rafael structure. The findings were used to help Caltrans engineers determine what allowable stress values to use on the existing steels and rivets and to better calibrate analytical modeling with testing results. The research work contributed to more accurate use of modeling parameters and the bridge boundaries during analysis stage.

LESSONS LEARNED THROUGH THE SEISMIC RESEARCH PROGRAM

- Caltrans adapted a seismic design philosophy based on displacement performance achieved through ductile details.(Mahan and El-Azazy,1999)
- Continuity in details or system enhances seismic performance of highways structures.
- Balanced design lead to uniform distribution of seismic forces results in better performance during seismic events.
- The overall performance of the structure depends on the soil characterization and the soil/foundation interaction.
- The retrofit of long spans on toll bridges requires innovative techniques using seismic response modification devices, SRMD to accommodate/control the high seismic demands.
- Research findings combined with engineering judgments are essential when selecting the type of the structure to achieve the best seismic performance during the seismic events.(El-Azazy, 1996), (Cooper, et al, 1999)

SUMMARY AND CONCLUSIONS

Development of a comprehensive Seismic Research Program positioned Caltrans as a leader in seismic bridge design. The program led to:

- Incorporation of research findings into the seismic design, resulting in improvements in performance and an increased safety level of highway structures.
- Validation of new and existing design concepts, new devices, and new materials introduced by industry.
- Improved design procedures accomplished by incorporating established design guidelines into the design of new highway structures.

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