Impact of Loma Prieta Earthquake on Seismic Design of Concrete Bridges— California Perspective

by J. E. Roberts

Synopsis: Almost nine years have passed since the disastrous Loma Prieta earthquake of October 17, 1989 and eight years have passed since the Governor's Board of Inquiry into the cause of highway structure failures during that earthquake issued its final report with the warning title "Competing Against Time". The California Department of Transportation has developed improved Seismic Performance Criteria, Seismic Design Specifications, seismic design procedures, and construction details based on lessons learned from the 1971 San Fernando earthquake and subsequent seismic events. The success of the Bridge Seismic Design and Retrofit program and the success of future seismic design for California bridges is based, to a large degree, on an unprecedented accelerated and "problem-focused" seismic research program. The Department has spent over $40 million on this research and physical testing of details. This research has provided the bridge design community the assurance that the new specifications and design details perform reliably and meet the performance criteria. Caltrans staff engineers, consulting firms, independent Peer Review Teams, and university researchers have cooperated in this program of Bridge Seismic Design and Retrofit Strengthening to meet the challenge presented in the June, 1990 Board of Inquiry report. The eight year old Seismic Advisory Board has been an invaluable asset in reviewing the performance criteria, design specifications, design procedures, and construction details for both new design and retrofit strengthening of older, non-ductile bridges.

Keywords: confinement; displacements; ductility; nonlinear analysis; retrofit; seismic design

Director-Engineering Services, Calif. Dept. of Transportation. BS in Civil Engineering, University of California, MS in Structural Engineering University of Southern California. Forty Five years experience including 10 years Bridge Resident Engineer; 2 years Bridge Designer; 4 years Bridge Design Section Supervisor, 5 years Chief Engineer-Equipment Division, 6 years Project Director- Major Light Rail Transit project, 2 years Chief-Structure Design Office,7 years Chief-Division of Structures; 1 year Deputy Director-Transportation Engineering.

INTRODUCTION

Prior to the 1933 Long Beach earthquake there was no special consideration for seismic design of buildings or bridges in California. The severe damage to schools that resulted from that seismic event resulted in creation of the Structural Engineer license and a requirement for special consideration of seismic forces in the design of public schools in California. After the 1940 El Centro earthquake the bridge design office of the California Division of Highways developed minimal seismic design factors for bridges. The 1940 El Centro record was digitized and used as the seismic design spectra for over 30 years before an earthquake of greater magnitude occurred in California. The 1971 San Fernando earthquake caused severe damage to hospitals, public utilities, and freeway bridges, recording a peak ground acceleration of 1.0g and large ground displacements. This earthquake caused both building and bridge designers to revise their design criteria and structural details to provide better resistance to the forces and displacements of major seismic events. The American Association of State Highway and Transportation Officials (AASHTO) is the agency responsible for development of bridge design specifications for nationwide use. AASHTO has typically adopted seismic design criteria modeled after those developed in California, and the initial adoption is only as a guide specification. Until the 1989 Loma Prieta earthquake most other states in the United States had not been concerned with seismic design for bridges, considering it a California or West Coast problem. For example, the 1940 California seismic design specifications were not adopted by AASHTO until 1961, and the 1973 California seismic design specifications were not adopted nationally until 1983. In May, 1990, responding to the disastrous 1989 Loma Prieta earthquake in California, AASHTO finally adopted the 1983 "Guide Specifications For Seismic Design of Highway Bridges" as a mandatory requirement for those states which have a seismic hazard. Interestingly, some 37 states in the US have some level of seismic hazard. Understandably, there are hundreds of bridges in these other states which have been designed to seismic criteria that are not adequate for seismic forces and displacements that we know today. The seismic retrofit details designed by the California bridge engineers can be of great benefit to those states who are faced with seismic threats of lesser magnitude, and with little financial support for seismic retrofitting, and much less for research and seismic detail development.

The California State Department of Transportation (Caltrans) owns and maintains over 12,000 bridges (spans over 20 feet). There are an equal number on the City and County system. The bridge office maintains the condition data for all these and some 6,000 other highway structures such as culverts (spans under 20 feet), pumping plants, tunnels, tubes, Highway Patrol inspection facilities, maintenance stations, toll plazas and other transportation related structures. Structural details and the current condition data are maintained in the department's bridge maintenance files as part of the National Bridge Inventory System (NBIS) required by the US Congress and administered by the Federal Highway Administration (FHWA). This data is updated and submitted annually to the FHWA and is the basis upon which some of the Federal gas tax funds are allocated and returned to the states. The maintenance, rehabilitation and replacement needs for bridges are prorated against the total national needs. Seismic retrofit strengthening is eligible for use of those funds.

The two most significant earthquakes in California in recent history that produced the best information for bridge designers were the 1989 Loma Prieta and the 1994 Northridge events. While the experts consider these to be only moderate earthquakes, it is important to note the good performance of the many bridges that had been designed for the improved seismic criteria or retrofitted with the early era seismic retrofit details. This reasonable performance of properly designed newer and retrofitted older bridges in a moderate earthquake is significant for the rest of the United States because that knowledge can assist engineers in designing new bridges and in designing an appropriate seismic retrofit program for their older structures. Although there is a necessary concern for the "Big One" in California, especially for the performance of important structures, it must be noted that many structures which vehicle traffic can bypass need not be designed or retrofitted to the highest standards. It is also important to note that there will be many moderate earthquakes that will not produce the damage associated with a maximum event. These are the earthquake levels that should be addressed first in a multi phased retrofit strengthening program, given the limited resources that are available. Cost benefit analysis of retrofit details is essential to measure and insure the effectiveness of a program. It has been the California experience that a great deal of insurance against collapse can be achieved for a reasonable cost, typically ten percent of replacement cost for normal highway bridges. It is also obvious that designing for a performance criteria that provides full service immediately after a major earthquake may not be economically feasible. The expected condition of the bridge approach roadways after a major seismic event must be evaluated before large investments are made in seismic retrofitting the bridges to a full service criteria. There is little value to the infrastructure in investing large sums to retrofit a bridge if the approaches are not functioning after a seismic event. Roadways in the soft muds around most harbors and rivers are potentially liquefiable and will require repair before the bridges can be used.

Approximately 2,200 of California's 12,000 bridges are located in the Los Angeles area so it is significant to examine the damage and performance of bridges in the Northridge earthquake of January 17, 1994. About 1,200 of these bridges were in an area that experienced ground accelerations greater than 0.25g and several hundred were in the area that experienced ground accelerations of 0.50g or greater. There were 132 bridges in this area with post San Fernando retrofit details completed (Hinge and Joint restrainer cables) and 63 with post Loma Prieta retrofit details completed (Additional joint restrainers and column strengthening). All of these retrofitted bridges performed extremely well (not closed to public traffic) and most of the other bridges performed well during the earthquake; newer bridges designed and constructed to Caltrans' current seismic specifications survived the earthquake with very little damage. Seven older bridges, designed for a smallerearthquake force or without the ductility of caltrans' current design, sustained severe damage during the earthquake. Another 230 bridges suffered some damage ranging from serious problems of column and hinge damage to cracks, bearing damage and approach settlements, but these bridges were not closed to traffic during repairs.

SEISMIC DESIGN PHILOSOPHY

Performance Criteria--An agency or designer must have a seismic performance criteria established. How do you want the structure to perform in an earthquake? How much damage can you accept? What are the reasonable alternate routes? How do you define various levels of damage? How long do you expect for repair of various levels of damage? A bridge seismic performance criteria was developed by Caltrans' Engineering staff for state owned bridges and was approved by the Seismic Advisory Board in September, 1992. That current Performance Criteria is **"No Collapse", "No Major Damage", "No Secondary Injuries or Fatalities Because Emergency Equipment Cannot Get Through", "Major Important Structures and Lifeline Routes Must**

Remain Operational". This criteria is generally attainable but the Lifeline Route structure performance criteria can be expensive if structures are expected to withstand severe earthquakes such as a 45 second duration shake due to large earthquakes on a major fault. That is what is expected of major important structures in California and the 45 second duration shake is what the experts predict when the "Big One" comes.

Once a seismic performance criteria is adopted the important issue then is to guarantee that the design criteria and construction details will provide a structure that meets that adopted performance criteria. In California a major seismic research program was financed to physically test large scale and full sized models of bridge components to provide reasonable assurance to the engineering community that those details will perform as expected in a major seismic event. The current phase of that testing program involves real time dynamic shaking on large shake tables. In addition the Caltrans bridge seismic design specifications have been thoroughly reviewed in the Applied Tecnology Council, ATC-32 project to insure that they are the most up to date with state of the art technology. On major projects a project specific design manual has been produced to provide guidance to the various design team members on what must be done to structural elements to insure the expected performance.

Seismic Design Principles--**Continuity** is extremely important and is the easiest and cheapest insurance to obtain. Well designed monolithic structures also have the added advantage of low maintenance. Joints and bearings are some of the major maintenance problems on bridges today. If structures are not continuous and monolithic, they must be tied together at deck joints, supports and abutments. This will prevent them from pulling apart and collapsing during an earthquake. **Ductility** in the substructure elements is the second key design consideration. It is important that when you design for ductility you must be willing to accept some damage during an earthquake. The secret to good seismic design is to balance acceptable damage levels with the economics of preventing or limiting the damage. Properly designed ductile structures will perform well during an earthquake as long as the designer has accounted for the displacements and controlled them or provided for them at discontinuities such as abutments and hinges. For a large majority of bridges displacement criteria controls overstrength criteria in the design for seismic resistance.

Nonlinear Analysis Procedures--Prior to the Loma Prieta event there was little use of nonlinear analysis in the design of bridges. In order to correctly analyze bridge performance in a major earthquake of long duration, the use of nonlinear analysis techniques is mandatory. Ample research has been completed in this area to give designers the necessary tools to conduct reasonable nonlinear analysis and design structures that will perform in a ductile manner during a major earthquake with long duration. Additional work in this area will continue to improve the expertise of bridge designers and build confidence in non-linear analysis techniques.

Steel versus Concrete--While it can be argued that steel is inherently more ductile than concrete, it must also be noted that steel members have a high potential to buckle after reaching the yield point. Concrete members, being substantially larger in cross section, have a much better chance for survival without buckling, even after exceeding the yield point. This is due in part to the larger distance the concrete column must be displaced to cause buckling. Most damage in California during the Loma Prieta and Northridge earthquakes occurred on structures that had been designed 30 to 60 years ago to comply with codes that required seismic design forces of only 0.06g to 0.08 g. Today most of those structures would be designed for 8 to 10 times those seismic forces. The forces are derived from the acceleration coefficients multiplied by the weight of the contributing mass at any supporting member or joint. A quick survey of most bridges in this country will confirm that almost all have reinforced concrete substructures, regardless of the superstructure type. And the substructures are where most of the earthquake damage occurs. Since we rely on internal strain energy to dissipate the external work (energy) caused by the earthquake forces, concrete substructure elements are preferable. As long as they are properly confined they will remain intact and sustain the gravity loads after the event. Internal damage can be repaired after a seismic event.

Seismic Design Research Program--The Governor's Board of Inquiry recommended that Caltrans "Fund a continuing program of basic and problem-focused research on earthquake engineering issues pertinent to Caltrans responsibilities." The initial Legislative investment in bridge seismic research was $8 million. Subsequently, the Department management has agreed to a problem-focused seismic research program at an annual expenditure level of $5 million (approximately 1% of the Caltrans annual bridge capital expenditure program). It is this last recommendation that gave impetus to the major seismic research work which is being supported by the Department today and through which we are supporting the annual seismic research workshops. The workshops serve a major goal of technology transfer to the user community. All bridge seismic details for new design and retrofit have been proof tested in the university laboratories before being implemented in the final structures. Over $40 million has been spent on bridge problem focused seismic research since the 1989 Loma Prieta earthquake.

SEISMIC DESIGN SPECIFICATIONS AND PROCEDURES FOR BRIDGES

A major element of the improved seismic design specifications and procedures was the adoption of a site specific seismic design philosophy shortly after the 1971 San Fernando earthquake. The California Division of Mines and Geology (CDMG) was engaged for the development of an earthquake ground fault map. The maximum credible events (MCE) on seismic faults throughout the state define peak bedrock acceleration levels. Average energy attenuation relationships were developed by various seismologists and contours of these decreasing levels of expected peak rock acceleration are included on the map. The original map was produced in 1973 and included 225 known faults. The current version is CDMG Map Sheet 45. This document maps the 275 currently known faults and is updated periodically as new information becomes available. This approach, using the MCE, has been criticized as too conservative but our cost analyses show that the additional cost for an average bridge is less than one percent for the maximum credible event versus design for a probabilistically determined event. Considering the limited ability to determine a probabilistic earthquake with a high degree of confidence and the high cost for a site specific study, we feel that the maximum credible approach for the smaller typical state highway bridges is a reasonable approach, given the current state of seismological event predictions. Since the 1989 Loma Prieta earthquake Caltrans has utilized a site specific probabilistic hazard analysis to determine the most probable design earthquake for major structures. This event is incorporated into the seismic design procedure along with the maximum credible event.

In 1973 Caltrans, working with Professor Harry Bolton Seed at UC Berkeley, then developed a series of Acceleration Response Spectra (ARS) for alluvium and harder soils of various depths above bedrock. These spectra have been used for determining the appropriate seismic design force for typical freeway bridges in California. After the 1989 Loma Prieta earthquake the staff and consultants began developing a similar set of response spectra for deep, soft soils. These new spectra have been included in the ATC-32 project which was an effort to upgrade the Caltrans bridge seismic design specifications. It is apparent, however, that more site specific soil studies must be used for major bridges being built or retrofitted over softer soil foundations.

Earthquake of October 1, 1987 reemphasized the inadequacies of pre-1971 column designs. Even though there was no collapse, the extensive damage resulted in plans for basic research into practical methods of retrofitting bridge columns on the existing pre-1971 non-ductile bridges. That research program had already been initiated in early 1987 at the University of California at San Diego and the Whittier earthquake merely speeded its approval and execution. The continuing bridge seismic retrofit research is currently being conducted at the University of California at San Diego, the University of California at Berkeley, and over six other University research facilities. Funding levels for seismic retrofit program implementation were increased four fold after the Whittier earthquake to an annual program of $16 million. Even at that level it would have required nearly 300 years to complete the retrofitting program that was ultimately identified and implemented.

Most columns designed since 1971 contain a slight increase in the main column vertical reinforcing steel and a major increase in confinement and shear reinforcing steel over the pre-1971 designs. All new columns, regardless of geometric shape, are reinforced with one or a series of spiral wound interlocking circular cages. The typical transverse reinforcement detail now consists of #6 (3/4 inch, 18mm diam.) hoops or continuous spiral at approximately three inch (75mm) pitch over the full column height. This reinforcement detail provides approximately eight times the confinement and shear reinforcing steel in columns than what was used in the pre-1971 non-ductile designs. All main column reinforcing is continuous into the footings and superstructure. Splices are mostly welded or mechanical, both in the main and transverse reinforcing. Splices are not permitted in the plastic hinge zones. Transverse reinforcing steel is designed to produce a ductile column by confining the plastic hinge areas at the top and bottom of columns. The use of the more ductile ands weldable grade 60, A 706 reinforcing steel in bridges has been specified on all new projects since 1992.

The Loma Prieta earthquake of October 17, 1989 again proved the reliability of hinge and joint restrainers, but the tragic loss of life at the Cypress Street Viaduct on I-880 in Oakland emphasized the necessity to immediately accelerate the column retrofit phase of the bridge seismic retrofit program with a higher funding level for both research and implementation. Other structures in the earthquake affected counties performed well, suffering the expected column damage without collapse. With the exception of a single outrigger column-cap joint confinement detail, those bridges using the post 1971 design specifications and confinement details performed well. Damage to long, multiple level bridges showed the need to more carefully consider longitudinal resisting systems because earthquake forces cannot be carried into abutments and approach embankments as they can on short bridges.

After the Loma Prieta earthquake caused 44 fatalities on the State Highway System, capital funding for bridge seismic retrofitting was increased to $300 million per year. At the same time bridge seismic research funding was increased from $0.5 million annually to $5.0 million annually with an initial $8.0 million allocation from the special State Emergency Earthquake Recovery legislation of November, 1989 (Senate Bill 36X).

RESPONSE OF DEEP SOFT SOILS

The Acceleration Response Spectra (ARS) developed after the 1971 San Fernando earthquake were developed for harder soils and alluvium but were not accurate for prediction of the dynamic response of softer soils and bay muds. After the Loma Prieta earthquake Caltrans immediately engaged Professors John Lysmer and Raymond B. Seed at UC Berkeley to help develop a set of similar ARS curves for deep, soft soils and mud. Professors Lysmer & Seed and C.M. Mok & S.E. Dickenson of UC Berkeley have concluded that the deep, soft muds amplify the bedrock ground motions by factors of 2 to 3 and that amplification of the longer period components is especially pronounced, resulting in surface motions that are more damagingto the taller, longer period structures.

Seismic ground motions have been predicted in the deep, soft soils with an analytical procedure and those predictions have been confirmed with the actual recorded Loma Prieta motions at four sites around the San Francisco Bay. The Applied Technology Council project ATC-32 has provided a series of ARS curves for various soft soil conditions to augment those already in use.

Other geotechnical factors that contributed to structural damage in the Loma Prieta earthquake were non-uniform and out of phase response of the foundation materials and their affect on longer structures such as the 1.5 mile long viaducts and the San Francisco-Oakland Bay Bridge. The effect of non-coherent soil response is now being considered in the site specific response spectra that are developed for longer structures. While soil liquifaction was not a contributor to bridge damage, it was apparent near several major structures in the East Bay after the Loma Prieta earthquake and must be considered and dealt with in future seismic design for bridges. Results of studies by Lysmer, Seed, Idriss and other investigators clearly indicated the shortcomings of the 1989 provisions for dealing with the influence of deep, soft foundations on structure response. In addition to developing the new set of ARS curves for deep, soft soils, Caltrans has also initiated a program to identify and map the soft soil sites in the state. Caltrans has developed a set of generic ARS curves for several representative deep, soft soil site conditions for use on the more standard and smaller bridges but, upon the recommendation of Doctor Seed and other advisors, we will concentrate on site specific response analyses for all major structures at soft soil sites. These researchers have shown that the analysis techniques and the computer programs currently available can reliably predict the response of deep, soft soils, and therefore, justify site specific analyses. For the major Bridges crossing the Bays from San Diego in the South to Antioch at the extreme Northeast end of the San Francisco Bay we have engaged consultants to conduct site specific complete hazard analyses using a probabilistic approach to provide the design earthquake for bridge seismic design purposes.

Working with in-house Engineering Geologists & Geotechnical Engineers and several Consultants, Caltrans is also identifying and mapping the sites which could potentially liquefy and working with Professor Geoffrey Martin at the University of Southern California and others to develop design mitigation procedures for those sites. For one site north of San Diego at Del Mar Heights, adjacent to the Pacific Ocean, Caltrans is using 16 inch diameter stone columns to stiffen the soil around the bridge piers. For the major Mission Valley interchange between Interstate Routes 8 and 805 in San Diego extensive substructure modifications are being incorporated to overcome the foundation strength loss due to liquefaction in a major seismic event. Jackura and Abghari of Caltrans have reported on the mitigation of liquefaction hazards at three California bridge sites, including the two in San Diego. On the relocation project for IS 880 in Oakland extensive foundation stiffening measures were incorporated to resist liquifaction impacts.

SEISMIC DESIGN PROCEDURES FOR BRIDGE STRUCTURE/ FOUNDATION INTERACTION

The two major considerations in seismic design of foundations are ground motion and foundation-substructure interaction. Caltrans adopted a site specific seismic design philosophy shortly after the 1971 San Fernando earthquake. For the average smaller freeway structures we use the Maximum Credible Earthquake (MCE) for determining the seismic design forces. For major structures we use a site specific probabilistic hazard analysis to determine the