Recent Advances in Seismic Design and Retrofit of Bridges

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This paper describes the seismic retrofit program implemented by the California Department of Transportation after the 1971 San Fernando Earthquake and accelerated after the 1989 Loma Prieta earthquake. The goal of the program is to reinforce most of the bridges designed and constructed prior to acquiring the current levels of knowledge of seismic loading and structure response (about 1978) to improve their structural ductility and resistance to the major factors which contributed to damage and collapse in the San Fernando and Loma Prieta events. The program has been executed in two phases. The initial phase, completed in 1988, provided reinforcement to superstructures of 1260 bridges by connecting all narrow expansion joint seats with hinge restrainers and anchoring girders and other superstructure elements to the substructure. The single and multiple column retrofit phase, now under active implementation, is designed to reinforce substructure elements and create ductile members by increasing confinement. A Risk Analysis procedure was, developed to prioritize the bridges for seismic upgrading so that highest risk bridges are retrofitted first. Legislation was recently enacted to require the Department of Transportation to also take the lead role in seismically retrofitting all locally owned bridges in the state. Research has been conducted, and is currently underway, at the University of California, San Diego to test and confirm the validity of several proposed design solutions for seismic retrofitting of existing bridge single column bent substructure elements. Since the Loma Prieta earthquake additional research is being conducted at the University of California at Berkeley, Irvine and Davis to develop and test retrofit techniques for multiple column bents and double level structures, including abutment and footing details. Some full scale testing was completed on a standing portion of the Cypress Street viaduct in Oakland to determine its fundamental response characteristics and to test some techniques which may be applied to the double deck structures in San Francisco and on complex structures with outrigger supports and other non standard support configurations throughout the state.

BACKGROUND

The 1971 San Fernando earthquake caused substantial damage to recent bridge construction and exposed a number of deficiencies in the bridge design specifications of that time. These deficiencies have the potential to impact dramatically on transportation life- lines and the traveling public today. Bridge design specifications were immediately modified to correct the identified deficiencies on newly designed bridges. Structures in-place however, have served to be a substantially more challenging problem. Research was undertaken both in the United States and overseas to improve analytical techniques, and to provide basic data on the strengths and deformation characteristics of lateral load resisting systems for bridges.

The initial phase of the Bridge Seismic Retrofit Program involved installation of hinge and joint restrainers to prevent deck joints from separating. This was the major cause of bridge collapse during the San Fernando earthquake and was judged to be the highest risk to the traveling public. Included in this phase was the installation of devices to fasten the superstructure elements to the substructure to resist vertical accelerations and also to prevent superstructure elements from falling off their supports. This phase is now essentially complete after approximately 1,260 bridges on the State Highway System have been retrofitted at a cost of over 55 million dollars.

While the hinge and joint restrainers performed well, shear failure of columns on the I-605/I-5 separation bridge in the moderate Whittier 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 bridges. The research program was initiated in 1987 and is currently being conducted at the University of California at San Diego.

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 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 an outrigger column-cap confinement detail, those bridges using the post-1971 design specifications and confinement detail changes performed well. The effect of the response of deep soft soils in the structure foundations proved to be a contributing factor which must be analyzed and included in future design procedures, especially for long, tall structures with relatively high periods of vibration.

PRE AND POST 1971 COLUMN DESIGN

Bridge columns designed before the 1971 San Fernando earthquake typically contain very little transverse reinforcement. A common detail for both circular and rectangular columns consisted of #4 (12.7 mm diam.) transverse peripheral hoops at 12 inch to 18 inch (300 mm to 450 mm) centers, regardless of column size and area of main reinforcement. As a consequence of these details, the ultimate curvature capable of being developed within the potential plastic region is limited by the strain at which the cover concrete starts to spall. The result is flexural failure resulting from inadequate ductility capacity, or shear failure due to lack of adequate shear reinforcement. Tests conducted at UC San Diego confirm this theory. Several bridges suffered column shear failures due to the elastic design philosophy under which they were designed prior to 1971.

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Columns designed since 1971 contain approximately eight times the confinement reinforcing steel than pre-1971 designs. All new columns, regardless of geometric shape, are reinforced with one or a series of spiral wound circular cages. The typical transverse reinforcement detail now consists of #6 (19 mm diam.) hoops or spiral at three inch (76 mm) pitch. All main column reinforcing is continuous into the footings and superstructure. Splices are mostly welded or mechanical, both in the main and transverse reinforcing. Transverse reinforcing steel is designed to produce a ductile column by confining the plastic hinge areas at the top and bottom of columns.

RETROFIT PHILOSOPHY

There are some 25,000 highway structures for which the State of California is responsible in some capacity. It is economically unrealistic to suggest that every structure be immediately retrofitted to withstand maximum magnitude earthquakes without some damage. The retrofit philosophy adopted at the start of the Restrainer Retrofit Phase of the program offers reasonable direction to the remaining phases of the Retrofit Program.

It was and still is Caltrans philosophy to first retrofit those structures which pose the greatest risk to the public and are the most vital to the transportation system. The ultimate goal is to see that all of the bridges in the state will be capable of surviving maximum credible earthquakes without collapse. Some damage is inevitable but, with proper retrofitting, it is believed that collapse is preventable and, further, it is believed that damage can be held to a minimum, to the extent that the transportation system can remain open and functioning during repair. As we get into the actual analysis and design it is becoming apparent that retrofitting many older structures to this standard may not be cost effective. It is highly probable that we may have to accept some period of closure on many structures to effect repairs. Time and further analysis will bring this problem to the decision makers. As a direct result of the one month loss of the San Francisco-Oakland Bay Bridge during the Loma Prieta earthquake, it has been recommended that major transportation structures be designed for higher elastic seismic force levels and longer shaking periods to reduce the damage to non structural type. To accomplish this goal a new "importance factor" will be introduced into the design and retrofit criteria. This represents a major change in the seismic design criteria for bridges.

PRIORITIZATION PROCEDURE

Identification of bridges likely to sustain damage during an earthquake was an essential first step in the Bridge Seismic Retrofit Program. Damage analysis after the San Fernando earthquake led the bridge engineers to the conclusion that unconnected joints at hinges, bents and abutments posed the highest threat to collapse. It was also determined that single column supported bents posed the next highest threat. These judgements have been confirmed by performance of both retrofitted and non-retrofitted bridges in several subsequent earthquakes. The overwhelming evidence from Loma Prieta supports the priority of retrofit that had been established in 1973 after analysis of bridge damage caused by the San Fernando earthquake.

After the hinge restrainer phase of the retrofit program was completed, the department began to prioritize the single and multiple supported structures for sequence of upgrading. What can be classified as a level one risk analysis was employed as the framework of the process which led to a consensus list of risk prioritized bridges.

A conventional risk analysis produces a probability of failure or survival. This probability is derived from a relationship between the load and resistance sides of a design equation. Not only is an approximate value for the absolute risk determined, but relative risks can be obtained by comparing determined risks of a number of structures. Such analyses generally require vast collections of data to define statistical distributions for all or at least the most important elements of some form of analysis, design and/or decision equations. The acquisition of this information can be costly if obtainable at all. Basically, what is done is to execute an analysis, evaluate both sides of the relevant design equation, and define and evaluate a failure or survival function. All of the calculations are carried out taking into account the statistical distribution of every equation component designated as a variable throughout the entire procedure.

To avoid such a large time consuming investment in resources and to obtain results which could be applied quickly as part of the Single Column Phase of the Retrofit Program, an alternative was recognized.

What can be called a level one risk analysis procedure was used. The difference between a conventional and level one risk analysis is that in a level one analysis judgements take the place of massive data supported statistical distributions.

The level one risk analysis procedure used can be summarized in the following steps:

1. Identify major faults with high event probabilities (priority one faults).

This step was carried out by consulting the California Division of Mines and Geology and recent US Geological Survey studies. A team of seismologists and engineers identified seismic faults believed to be the sources of future significant events. Selection criteria included location, geologic age, time of last displacement (late quarternary and younger), and length of fault (10 km min.). Each fault recognized in step 1 was evaluated for style, length, dip and area of faulting in order to estimate potential earthquake magnitude. Known faults were placed in one of three categories; minor (ignored for the purposes of this project), priority two (mapped and evaluated but unused for this project), or priority one (mapped, evaluated, and recognized as immediately threatening). After identification of single column supported bridges close to priority one faults, all remaining structures were evaluated equally affected by priority one and priority two faults.

2. Develop attenuation relationships at faults identified in step 1.

An average attenuation model was developed by Mualchin of the California Division of Mines and Geology to be used throughout the state. It is the average of several published models. Mualchin, a well known seismologist, is now a member of the Caltrans Office of Earthquake Engineering

3. Define the minimum ground acceleration capable of causing severe damage to bridge structures.

The critical (i.e., damage causing) level of ground acceleration was determined by performing nonlinear analyses on a typical highly susceptible structure (single column connector ramp) under varying maximum ground acceleration loads. The lowest maximum ground acceleration that demanded the columns to yield (provide a ductility ratio of 1.3) was defined as the critical level of ground acceleration. That level of ground acceleration was 0.5 g. Loma Prieta proved this assumption to be wrong and adjustments have been made in current evaluations. Based on input from our Geologists and the type of material over the bedrock, an acceleration level as low as 0.25 g could be critical.

4. Identify all the bridges within high risk zones defined by the attenuation model of step 2 and the critical acceleration boundary of step 3.

The shortest distance from every bridge in California to the two closest priority one faults was calculated. Each distance was compared to the distance from each respective level of magnitude fault to a 0.5 g decremented acceleration boundary. If the distance from the fault to the bridge was less than the distance from the fault to the 0.5 g boundary, the bridge was determined to lie in the high risk zone and was added to the screening list for prioritization. The prioritization procedure is described below.

The Caltrans Division of Structures has developed a computerized data base which has the coordinates of all 25,000 State, County and City bridges stored. We can produce a map of the entire state or any portion of the state showing the bridges, the major faults and an overlay of the combinations. These maps can be viewed on the computer screen or printed for use by designers in screening to identify high risk bridges. The procedure is quite simple, using the computer data base.

a) Locate all Highway Bridges on the State System
b) Locate all Earthquake Faults
c) Determine those structures that are in a high risk zone.

5. Prioritize the threatened bridges by summing weighted bridge structural and transportation characteristic scores.

This step constitutes the process used to prioritize the bridges within the high risk zones to establish the order of bridges to be investigated for retrofitting. It is in this step that a risk value is assigned to each bridge. A specifically selected subset of bridge structural and transportation characteristics of seismically threatened bridges was drawn from the California Department of Transportation structures computer database. Those characteristics were:

Ground Acceleration
Route Type-Major or Minor
Average Daily Traffic(ADT)
Column Design-Single or Multiple Bents
Confinement Details of Column(relates to age)
Length of Bridge
Skew of Bridge
Availability of Detour

After evaluating the results of the 1989 Loma Prieta earthquake, Caltrans engineers modified the Risk Analysis Algorithm by adjusting the weights of the original characteristics and adding the following new characteristics to the list. A total of 18 different characteristics are now evaluated.

Soil Type
Hinges, Type and Number
Exposure (Combination of Length, Height & ADT)
Abutment Type
Type of Facility Crossed

All of the components listed above were considered in the Caltrans risk evaluation. A team of experts representing hundreds of years of experience in the fields of bridge design, construction and maintenance engineering and geotechnical and geological sciences were employed to identify and weight appropriate risk components. Normalized preweight characteristic scores from 0.0 to 1.0 were assigned based on the information stored in the database for each bridge. Scores close to 1.0 represent "high risk structural" characteristics or "high cost of loss" transportation characteristics. The preweight scores were multiplied by prioritization weights. Postweight scores were summed to produce the assigned prioritization risk value.

In summary, an evaluated risk number is calculated respecting source, distance, local geologic site conditions, bridge structural components and what is at risk in addition to the bridge.

Determined risk values are not to be considered exact. Due to the approximations inherent in the judgements adopted, the risks are no more accurate than the judgements themselves. The exact risk is not important. Prioritization list qualification is determined by fault proximity and empirical attenuation data and not so much judgement. Therefore, a relatively high level of confidence is associated with the risk ranking and identified bridges on the initial list of threatened bridges. Relative risk is then used to establish the order of bridges to be investigated in detail for possible need of retrofit by the designers. The risk analysis offers consistency in applying the judgements adopted to all bridges in the state.

A number of assumptions were made in the process of developing the prioritized list of seismically threatened bridges. This is typical of most engineering projects. These assumptions are based on what is believed to be the best engineering judgement available. It seems reasonable to pursue verification of these assumptions some time in the future to insure that we have not missed anything. Two steps seem obvious: (1) monitoring the results of the design engineer's retrofit analyses, and (2) executing a higher level risk analysis where necessary and better data are available.

Important features of the prioritization procedure are the ease and minimal cost with which it was carried out and the database, highlighting bridge characteristics, to identify structures in need of retrofit. This database will serve as part of the statistical support for the current risk analysis and of any future conventional risk analysis. The additional accuracy inherent in a higher order risk analysis will serve to verify previous assumptions, provide very good approximations of actual structural risk, and develop or evaluate postulated scenarios for emergency responses. It is reasonable to analyze only selected structures at this level. A manual screening process was used here which included review of "AS-Built" plans by three engineers to identify bridges with column and footing details that appeared to need upgrading.

DESIGN

The California Department of Transportation implemented the single column phase in 1986 and the multiple column phase (covering all remaining bridges) of the Bridge Seismic Retrofit Program in 1990, in which entire structures may be subject to modification to reduce the likelihood of catastrophic failure during a large earthquake. The main goal of the program is to prevent collapse, but a secondary goal is to increase serviceability by reducing damage to a level that can be repaired without closing the structure to traffic. This is a goal that may have to be modified as cost- benefit considerations are evaluated. Special attention is being focused on overall structure response. Two key items are recognized as being primary in achieving this goal: (1) providing continuity in superstructures at joints to prevent supported elements from collapsing, and (2) increasing ductility at certain locations throughout the structure and specifically in columns. The key to the column retrofit phase is ductility provided by the supplemental external confinement and improvements to foundations and abutments. Currently, that external confinement consists of steel shells designed to resist the column shear forces and provide confinement of main column reinforcing at the plastic hinge location. Other techniques for wrapping with cables or fiber reinforcing are also being tested. Foundations and abutments are being reinforced with additional piles, confinement reinforcement, soil anchors, pile shaft retainers, bolster walls and other details to improve seismic resistance.

Design engineers have been assigned the final task of verifying or discrediting the prioritized bridges' need for retrofitting and then, if necessary, developing retrofit contract plans. Verification of the need for retrofit is necessary due to the possibility of prioritized bridges already being capable of withstanding the maximum credible earthquake. This can only be determined by additional analysis and will be the case when judgements made in the prioritization process prove to be too conservative. Emphasis is being placed on evaluation of the total bridge during this design phase. In most cases a dynamic analysis is necessary before the final decision to retrofit or not can be made.

A number of structure modification schemes are under consideration in the bridge seismic retrofit program (since the Loma Prieta earthquake the Single and Multiple Column phases of the program have been combined with the old superstructure phase into the single, "Bridge Seismic Retrofit Program with no phases). Restrainer and superstructure retrofit techniques which have proven to be successful during recent earthquakes will continue to be used to effectively force superstructures to act more like single units. The problems associated with preventing the type of substructure failures seen at San Fernando, Whittier and Loma Prieta are complicated. If all columns are made to carry earthquake loads, then so must the footings and the pile groups. This is not an acceptable solution economically. Some columns may be allowed to pin at a point of contraflexure under dynamic loading while selected retrofitted columns and the abutments absorb the seismic energy and continue to hold the damaged bridge up, preventing bridge collapse. Substructure modifications are currently being evaluated by researchers at the University of California, Berkeley and San Diego. The conclusions drawn from their work will be used to standardize retrofit design schemes.

RETROFIT DETAILS

Some typical superstructure retrofit methods used to date have been to add restraining cables or rods at piers and hinges and add shear keys at abutments. In some cases new, longer hinge and abutment bearing seats had to be installed. Where this was not practical heavy duty pipe hinge extenders were installed to resist both horizontal and vertical seismic forces. Additionally, these hinge extenders carry the supported portion of a bridge in the unlikely event it were to move off the narrow hinge bearing seat. The continuing Legislatively mandated Bridge Seismic Retrofit Program will include this type of retrofitting on all state and other publicly owned bridges (i.e. County, City, Transit Systems, Other State agencies).

Work is beginning on the multiple column structure retrofit as research results become available. The total program will consist of retrofitting approximately 4500 bridges on the state system and 1500 bridges on the local city and county systems. During this phase we will go back and look at all phase I bridges again to insure that none are missed by the initial screening processes.

RESEARCH AND PROOF TESTING

Work at the University of California at San Diego was funded in 1987 and consisted of half scale model testing of the various single column bent retrofit techniques. Theoretical calculations and research work previously conducted in New Zealand by Doctor Nigel Priestley showed that enclosing the columns in steel casings could significantly increase their shear strength and ductility by providing the additional confinement at the hinge areas. A series of tests have been completed on round columns with outstanding results. Based on this work, the first contracts for bridge column retrofit were advertised in January, 1990 and work is underway in the Los Angeles area. A second series of tests was begun in February, 1990 on rectangular single column bents and the results will be available this summer. Both series of tests include models of the prototype columns with the pre-1971 reinforcing details without retrofitting, retrofitted columns using the steel shell confinement and a post damage retrofitted column using the steel shell to determine whether a non-retrofitted damaged column can be salvaged after an earthquake. Typical displacement ductility factors on retrofitted undamaged columns are 6 to 8. On the post damage retrofitted column a ductility factor of 2 was achieved. Even though displacement ductility factors of 6 to 8 have been common in these first tests, our analysis procedure is based on moment ductility demand no greater than 4. Future tests are scheduled to be conducted on columns retrofitted by wrapping pre-stressing strand and fiber reinforced sheet wrapping similar to the technique used on large concrete tanks and industrial smoke stacks.

Work at the University of California at Berkeley is funded and was started in November, 1990 to test retrofit techniques on multiple column bents. These substructure configurations are more complex and difficult to retrofit but on the other hand they have not demonstrated as high a risk as do single columns. During the aftermath of the Cypress Street Viaduct cleanup efforts a three span segment of the standing portion of the viaduct was instrumented and tested by the University of California researchers to determine its fundamental period. Column jacketing retrofit techniques proposed for use on the double deck viaducts in San Francisco were tested to prove their theoretically calculated value and actual reliability in increasing column ductility and shear capacity. This was a unique opportunity to test full scale structure frames to yield, apply several retrofitting techniques and retest the upgraded structure. The results have been published by the University and offer some degree of confidence for use in very specific applications.

SUMMARY

The procedure used by the California Department of Transportation to identify and prioritize seismically threatened bridges to be investigated for possible retrofit has been presented. The original decision to retrofit deck joints first and columns later was based on experience from the 1971 San Fernando earthquake. Subsequent earthquakes, including the recent Loma Prieta event, have proved the validity of this decision. Several hundred bridges with only the deck joint restrainers in place have performed well during these earthquakes. The level one risk analysis used to prioritize the structures in the single column phase was discussed in which decisions were made based on reasonable judgement instead of massive statistical data. The level one risk analysis offers a procedure to consistently apply knowledge gained from past earthquakes and known characteristics of bridges throughout the state which can be carried out quickly without developing a large, more sophisticated statistical database. Steps will be taken to verify assumptions made in the risk analysis in an attempt to improve confidence in this analysis. A modification of this risk analysis procedure will be used to prioritize the more complex bridges remaining in the program as the candidate list is screened. Research on column retrofit techniques will be continued to refine and improve those techniques. Research on the effects of soft foundation materials and the effects of variable foundation material response on long structures will also be continued.

Finally, the legislative direction and funding is being made available to accelerate the California Bridge Seismic Retrofit program for all publicly owned bridges which require upgrading to modern seismic standards.