SEISMIC RETROFITTING GUIDELINES FOR HIGHWAY BRIDGES

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SUMMARY

This paper describes guidelines for the seismic retrofitting of highway bridges within the United States. The guidelines, which are the recommendations of a team of nationally recognized experts, are comprehensive in nature and embody several new concepts that are significant departures from existing retrofitting practice. They include a preliminary screening procedure, methods for evaluating an existing bridge in detail, and potential retrofitting measures for the most common seismic deficiencies. The guidelines utilize many of the concepts presented in the "Seismic Design Guidelines for Highway Bridges" (ATC-6) and are intended to be used in conjunction with that document.

INTRODUCTION

It has become apparent in recent years that many bridges within the United States cannot adequately resist earthquakes. This has been dramatically demonstrated by several bridge failures during recent U.S. earthquakes. Many of these failures occurred due to the types of structural deficiencies that are present in a large number of existing U.S. bridges designed and constructed in accordance with standard practices that existed prior to recent advancements in the state-of-knowledge of seismic behavior. Some of these deficiencies may lead to serious bridge failures even at moderate levels of ground shaking. Because such ground shaking is likely to occur in a large portion of the United States, there is a clear need to conduct a nationwide effort to identify seismically deficient bridges, to evaluate the risk and consequence of seismic damage, and to initiate a program for reducing the risk of seismic failure.

Seismic retrofitting of existing bridges is one method of mitigating the risk that currently exists. The goals and economics of retrofitting, however, differ from those of new construction. A bridge owner may elect to accept the risk of seismic failure and/or damage if the risk of damage is low or the cost of reducing the risk is too high. Abandonment or replacement of the bridge may also be considered. A decision on which course of action to follow requires that both the importance and degree of vulnerability of the structure be evaluated. The most important bridges and those that are highly vulnerable to seismic damage will be the most likely candidates for seismic retrofitting.

It is usually difficult and costly to strengthen an existing bridge to comply with the current earthquake design standards for new construction. For this reason, retrofitting is directed towards preventing damage that is likely to have unacceptable consequences. This approach allows for a considerable amount of structural damage during a major earthquake. The threshold of damage

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that will be unacceptable must be defined by taking into account the overall configuration of the bridge, it's importance as a lifeline following an earthquake, the ease of repair, and the relationship of the bridge to other structures on the highway system. A decision to retrofit should be based in part on an evaluation of the likelihood of unacceptable damage due to an earthquake. Retrofitting decisions must also consider several non-engineering factors and can become very complex. For these reasons such decisions generally require a considerable amount of judgement.

BACKGROUND

Following the 1971 San Fernando earthquake in Southern California there was a significant effort to improve seismic design criteria for bridges. Within California there was also an effort to improve the seismic resistance of existing state highway bridges (Ref. 1). This effort was directed toward preventing the spectacular types of failures that had occurred during the San Fernando earthquake.

In 1977, in recognition of the considerable advance in the state-of-knowledge of the seismic behavior of bridges that occurred after the San Fernando earthquake, the Federal Highway Administration (FHWA) awarded a contract to Applied Technology Council (ATC) to evaluate then current seismic design criteria and research findings, with the objective of developing new and improved seismic design guidelines for highway bridges (Ref. 2). The guidelines developed as part of this project have recently been adopted by the American Association of State Highway and Transportation Officials (AASHTO) as a guide specification for seismic design.

Following the completion of the Seismic Design Guidelines (ATC-6), the FHWA asked ATC to extend their findings to the problem of seismic retrofitting of existing bridges. This work has now been completed (Ref. 3). This paper describes these retrofitting guidelines.

THE RETROFITTING GUIDELINES

The retrofitting guidelines, which are based on the recommendations of a team of nationally recognized experts composed of consulting engineers, academicians, state highway engineers, and Federal Highway Administration representatives from throughout the United States, offer procedures for evaluating and upgrading the seismic resistance of existing highway bridges. Specifically the guidelines contain:

- A preliminary screening procedure to identify and rate bridges that need to be evaluated for seismic retrofitting.
- A methodology for quantitatively evaluating the seismic capacity of an existing bridge and determining the overall effectiveness, including cost and ease of installation, of alternate seismic retrofitting measures.
- Retrofit schemes and design requirements for increasing the seismic resistance of existing bridges.

The retrofitting guidelines, like the ATC-6 Guidelines, were developed for national use and contain provisions for considering the variable levels of expected seismic activity in the United States. A concept that is common to both guidelines is that of the Seismic Performance Category. The Seismic Performance Category of a bridge is based on its importance and the design acceleration coefficient at the bridge site. It is a crude measure of the seismic risk of a bridge and is used as a means for determining the analysis, design, or retrofitting requirements. Figure 1 shows a flowchart of the seismic retrofitting process as described in the guidelines. The applicable chapters are indicated in this flow chart.

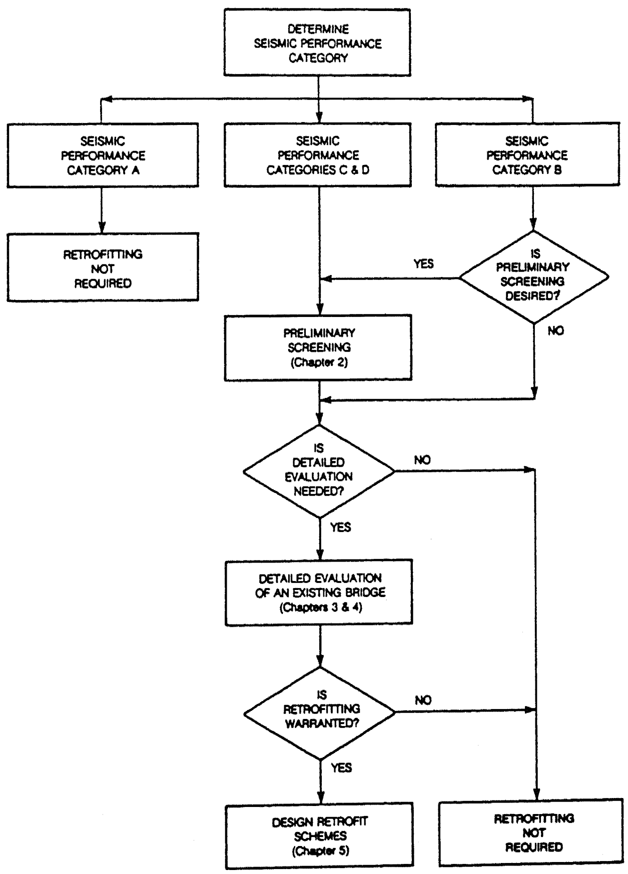

Figure 1.- SEISMIC RETROFITTING PROCESS.

Preliminary Screening

Preliminary screening of seismically deficient bridges is necessary to identify bridges that are potentially in the greatest need of retrofitting. To assist in the preliminary screening process, a Seismic Rating System was developed that considers only the technical aspects of the problem and does not include administrative, economic, or political considerations. In cases where these other considerations are important, the Seismic Rating System provides useful information but does not necessarily dictate the order in which bridges should be selected for evaluation and possible retrofitting.

To calculate the seismic rating of a bridge, consideration is given to structural vulnerability, seimicity of the bridge site, and the bridge's importance as a vital transportation link. This is accomplished by assigning a rating, weight, and score in each of these three areas in accordance with the following procedure:

Vulnerability Rating (rating 0 to 10) x weight	=	score
Seismicity Rating (rating 0 to 10) x weight	=	score
Importance Rating (rating 0 to 10) x weight	=	score
Seismic Rating (100 maximum)	=	Total Score

The higher the seismic rating score, the greater the need for the bridge to be evaluated for seismic retrofitting. It is recommended that each weight be taken as 3.33 unless different weights, which must total 10, are assigned by the engineer to reflect regional and jurisdictional needs.

Detailed Evaluation of an Existing Bridge

One of the most innovative features of the retrofitting guidelines are the procedures for evaluating an existing bridge. A flowchart for the detailed evaluation of a bridge is shown in Figure 2. At the heart of bridge evaluation are the methods for determining capacity/demand ratios for selected bridge components. An overall assessment of capacity/demand ratios and identification and assessment of retrofit measures are also part of the evaluation process.

Capacity/demand ratios may be calculated for any bridge component, but the guidelines describe detailed methods for the components most likely to be damaged during an earthquake. These include:

- Expansion Joints and Bearings.
- Reinforced Concrete Columns, Piers, and Footings
- Abutments
- Foundations

In major earthquakes the loss of support at bearings has been responsible for several bridge failures. Although many of these failures resulted from permanent ground displacements, several were caused by vibration effects alone. The San Fernando, California earthquake of 1971 (Ref. 4), the Guatemala earthquake of 1976 (Ref. 5), and the Eureka, California earthquake of 1980 (Ref. 6) are some recent examples of earthquakes in which bridge collapse resulted from bearing failure. Even relatively minor earthquakes have caused failure of anchor bolts, keeper bar bolts or welds, and nonductile concrete shear keys. In many of these cases the collapse of the superstructure would have been imminent had the ground motion been slightly more intense or longer in duration. Therefore, capacity/demand ratios for bridge expansion joints and bearings are calculated for displacement at restrained or unrestrained expansion joints and for force in bearings that are restrained against movement.

Reinforced concrete columns or piers and their supporting footings form a group of interacting components that are among the most vulnerable to earthquake damage. During high levels of ground shaking it is likely that one of these components will be subjected to yielding. Because of the interaction between yielding in one component and the response of the remaining components, the columns, piers, and footings should be considered as a group. The weakest of these components will govern the type of failure that is likely to occur.

The procedure for evaluating columns, piers, and footings includes a systematic method for locating plastic hinges and evaluating the capacity of the columns and/or footings to withstand this plastic hinging. In quantitatively evaluating the strength of the columns and piers, pullout of main reinforcement, splice failures in the main reinforcement, shear failure, and loss of flexural capacity due to insufficient confinement are each considered separately. Each of these failure modes are a function of the level of column yielding that takes place in the column and depend on the amount of transverse reinforcing steel. Although some useful research has been performed with respect to the behavior of bridge columns under cyclic loading, the state-of-the-art is such that column evaluation must rely heavily on engineering judgement, especially in the case of existing columns that may have vulnerable reinforcing details. The methods proposed for evaluating the capacity/demand ratios are based on the latest research related to the behavior of reinforced concrete columns but still reflect considerable judgement on the part of those performing the research.

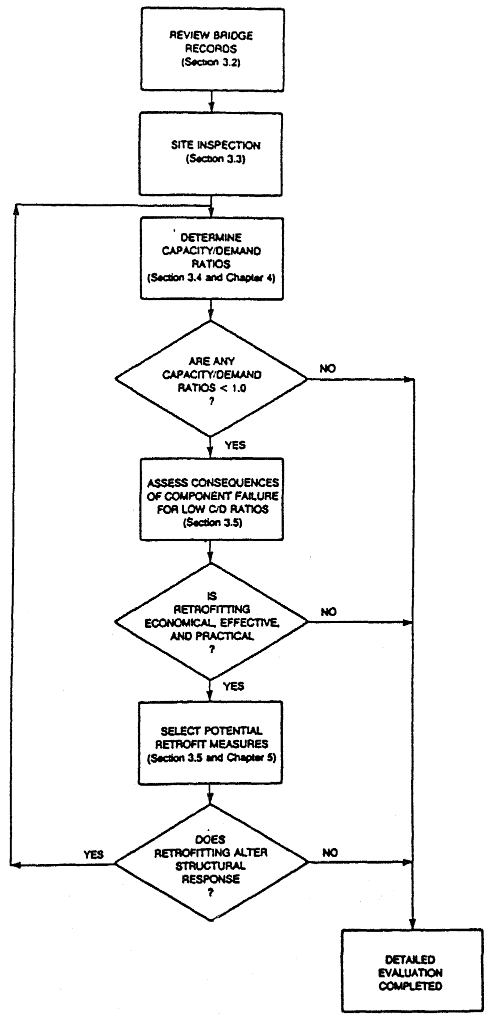

Figure 2.- SEISMIC EVALUATION PROCEDURE

Footing failures, which must be evaluated in conjunction with column failures, involve the yielding or rupture of foundation elements due to excessive seismic forces transmitted from the structure itself. This would include yielding of footing reinforcing, fracture of footing concrete, excessive soil pressures, sliding or overturning of the footing, and/or pile failure. These failures may result in ductile behavior or in sudden brittle failure depending on the failure mechanism. The footing failure mechanism is considered in the calculation of capacity/demand ratios.

Failure of abutments during earthquakes usually involves tilting or shifting of the abutment, either due to inertia forces transmitted from the bridge superstructure or seismic earth pressures. Usually these types of failures alone do not result in collapse or impairment of the ability of the structure to carry emergency traffic loadings. These failures, however, often result in loss of bridge access, which can be critical in certain important structures. Large horizontal movement at the abutments can also cause large approach fill settlements that can prevent access to the bridge. Therefore, when required, abutment capacity/demand ratios are based on the horizontal abutment displacement.

Many foundation failures during earthquakes are the result of loss of foundation support occurring as a result of liquefaction. The preliminary screening procedure in the retrofitting guidelines provide simple methods for determining the potential for liquefaction damage at a bridge site. When the screening procedures indicate the possibility of liquefaction, the capacity/demand ratio for liquefaction should be calculated. This capacity/demand ratio is given as the acceleration level at which unacceptable liquefaction damage will occur, divided by the design acceleration coefficient. The acceleration level at which unacceptable liquefaction damage occurs is difficult to determine precisely because the ability of the structure to withstand liquefaction movement must be factored into such a determination. Therefore, determination of this acceleration level will require considerable engineering judgement and should involve geotechnical as well as structural expertise.

The capacity/demand ratios calculated according to the procedures outlined above indicate the reduced load levels at which individual components may fail. Values greater than one indicate that the corresponding component is not likely to fail during the design earthquake, whereas values less than one indicate a possible failure. Each value less than one should be investigated to assess the consequences of local component failure on the overall performance of the bridge, to identify retrofit measures and to determine the effectiveness of retrofitting. Component failure is always considered unacceptable if it results in the collapse of the structure. If component failure results in a loss of access or loss of function, this may also be unacceptable if the bridge serves a vital transportation route. If component failure does not result in unacceptable consequences, then retrofitting is usually not justified for the component in question. If an improvement in overall bridge performance will result from the component retrofit and this can be accomplished at a reasonable cost, then the bridge should be retrofitted. In those cases where retrofitting will affect the response of the remainder of the structure, new capacity/demand ratios should be calculated.

Retrofitting Schemes

The guidelines present retrofitting schemes for each of the components for which capacity/demand ratios are calculated. Retrofit measures should be selected with the goal of minimizing the probability of total collapse and/or severe structural damage of the bridge. If practical, important bridges should be retrofitted so emergency vehicles can use the bridge following an earthquake.

Several bridges have failured during past earthquakes due to a loss of support at the bearings. These failures are sometimes spectacular, but are also relatively simple and inexpensive to prevent by retrofitting. Because of this, most retrofitting efforts to date have been directed toward tying the bridge together at bearings and expansion joints. Several bearing retrofitt methods have been used extensively, while other more exotic methods have been used only on a trial basis. These methods include:

- Longitudinal Joint Restrainers
- Transverse Bearings Restrainers
- Vertical Motion Restrainers
- Bearing Seat Extensions
- Replacement of Bearings
- Special Earthquake Resistant Bearings and Devices

Reinforced concrete columns, piers, and footings may fail in any of several ways during an earthquake. In general it is more difficult and less cost effective to retrofit these components than it is bearings. To date very few retrofit methods have been used on seismically defiecient bridge columns. Some column, pier, and footing retrofit measures that have been suggested include:

- Force Limiting Devices
- Increased Transverse Confinement
- Reduced Flexural Reinforcement
- Increased Flexural Reinforcement
- Infill Shear Wall
- Strengthening of Footing

Abutment failure very rarely results in the collapse of the structure unless associated with liquefaction failure. Lateral movement of an earth-retaining abutment or consolidation of the abutment fill, however, may result in a loss of accessibility to the bridge, which may be unacceptable for a particularly important bridge. In addition, the use of restrainers to limit relative displacement at the abutment bearings may result in much larger abutment forces. Therefore, situations will exist in which abutment retrofitting should be considered. The guidelines suggest settlement slabs and soil anchors as two possible retrofit measures for abutments.

Liquefaction and/or excessive movement have been the cause of the majority of bridge failures in some areas during past earthquakes. There are two suggested approaches to retrofitting that will mitigate these types of failure. The first approach is to eliminate or improve the soil conditions that tend to be responsible for liquefaction. The second approach is to increase the ability of the bridge to withstand large relative displacements similar to those caused by liquefaction.

Although site stabilization would only be used in exceptional cases, several methods are available for stabilizing the soil at the site of the bridge. Some of these methods may not be suitable or environmentally acceptable, and may even be detrimental in certain cases unless provisions are made to minimize the effects of soil settlement during retrofitting. Therefore, careful planning and design are necessary before employing any site-stabilization methods.

Any method that will tend to prevent loss of support at the bearings will be useful in preventing structure collapse due to excessive soil movement. Therefore, most of the methods for retrofitting bearings should be considered in a structure subjected to excessive soil movements. In addition, the ability of the substructure to absorb differential movements is important. Usually retrofitting of the structure alone will not prevent severe damage in the event of large soil movements. Retrofitting is intended to prevent collapse and provide for some restricted use of the structure immediately following an earthquake.

CONCLUDING REMARKS

Seismic retrofitting and the evaluation of structures for retrofitting is still very much an art. The seismic retrofitting guidelines developed by Applied Technology Council provide information that will be of value to bridge engineers engaged in seismic retrofitting. The guidelines described in this paper reflect the collective judgement of several highly qualified bridge engineers who are familiar with current retrofitting practices. Although current retrofitting practice is directed primarily toward expansion joints and bearings, the retrofitting guidelines provide the needed information to extend retrofitting to other bridge components.

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