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Seismic Retrofitting of Highway Bridges

Renforcement de ponts routiers en vue de séismes

Verstärkung von Strassenbrücken im Hinblick auf Erdbeben

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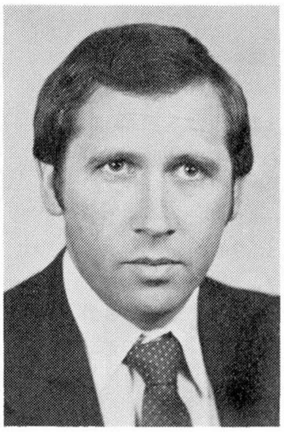

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SUMMARY

The paper presents a progress report on the Applied Technology Council ATC-6-2 project to develop guidelines for the seismic retrofitting of existing highway bridges. The guidelines will be applicable for all regions of the United States and for bridges of conventional steel and concrete girder and box girder construction with spans not exceding 180 m. The guidelines will provide a preliminary screening procedure to develop a priority rating for bridges in a particular region. Once a decision has been made to retrofit a particular bridge the guidelines provide a detailed evaluation procedure to determine seismic demand/capacity rations for all seismically vulnerable components of a bridge. The procedure can also be used to evaluate the effectiveness of any retrofit scheme contemplated by the engineer.

RESUME

L'article présente un rapport intermédiaire du projet de l',,Applied Technology Council'' sur les directives pour le renforcement des ponts routiers en vue de séismes. Les directives sont applicables dans toutes les régions des Etats-Unis, pour des ponts métalliques et en béton ainsi que pour des ponts caisson dont les portées ne dépassent pas 180 m. Les directives proposent une procédure préliminaire permettant d'établir des priorités parmi les ponts à renforcer dans une région particulière. Une fois la décision prise de renforcer un pont, les directives présentent une procédure d'évaluation détaillée afin de déterminer les rapports résistance au séisme-charge pour tous les éléments du pont vulnérables au séisme. La procédure pourra être également utilisée pour évaluer la valeur de tout projet de renforcement.

ZUSAMMENFASSUNG

Ein Zwischenbericht des Projektes des ,,Applied Technology Council'' über die Richtlinien zur Verstärkung von Strassenbrücken gegenüber Erdbeben wird vorgestellt. Die Richtlinien sollen auf dem ganzen Gebiet der Vereinigten Staaten anwendbar sein, für Stahl- und Betonbrücken, sowie Hohlkastenbrücken, deren Spannweite 180 m nicht übersteigt. Die Richtlinien schlagen ein Vorverfahren vor, welches Prioritäten unter den zu verstärkenden Brücken in einem gegebenen Gebiet erfassen lässt. Nach dem Entscheid, eine Brücke zu verstärken, erlauben die Richtlinien, mittels einem detaillierten Schätzungsverfahren das Verhältnis Erdbebenlasten zu Tragfähigkeiten für alle erdbebengefährdeten Brückenbauteile zu bestimmen. Das Verfahren kann auch für die Bewertung der Wirksamkeit eines beliebigen Verstärkungsprojektes benützt werden.

1. INTRODUCTION

The collapse of a highway bridge during an earthquake will in many cases sever vital transportation routes at a time when they are most needed to provide emergency services to or facilitate evacuation from a stricken area. The loss of the bridge as a transportation link may potentially result in a greater loss of life than the immediate effects of collapse.

The San Fernando Earthquake of 1971 taught engineers a great deal about the seismic resistance of bridge structures and resulted in the development of improved provisions for the design of new highway bridges.(1,2) This earthquake also demonstrated the potential inadequacy of past design procedures in providing seismically resistant bridges. Since most existing bridges in service today were designed using pre-1971 design procedures, it follows that many of the nations highway bridges in seismically active areas may have insufficient strength to resist seismic loading.

The problem of the seismic safety of our existing highway bridges is widespread and of sufficient magnitude to warrant national attention. Although bridge failures due to earthquakes have been confined to Alaska and California, many of these failures occurred at relatively low levels of ground motion. Seismologists have estimated that 37 of the 50 states and Puerto Rico have the potential for ground motion of a magnitude greater than or equal to that which has resulted in serious bridge damage in past earthquakes. Comparatively high levels of ground shaking can be expected in fifteen of these states and Puerto Rico. The potential for bridge failure in many states may also be aggravated by a previous lack of emphasis on seismic design. Certain structural details, especially at bearings, have proved extremely vulnerable to damage in past earthquakes.

To deal with this seismic safety problem it is necessary that an effort be made to identify deficient bridges, evaluate the risk and consequences of serious damage, and initiate a program to mitigate the risk of seismic failure. One method for dealing with the risk of failure, first initiated by the California Department of Transportation following the San Fernando Earthquake, is to strengthen seismically deficient bridges. This process is commonly referred to as seismic retrofitting.

Applied Technology Council is currently engaged in a project funded by the Federal Highway Administration to develop comprehensive guidelines for seismic retrofitting of bridges. These guidelines will include methods of identifying seismically vulnerable bridges, procedures for evaluating the existing seismic capacity, and methods and design details to improve the seismic resistance of bridges. This paper describes the background to the project, and the progress to date toward the development of the guidelines.

2. BACKGROUND

Applied Technology Council has recently completed a project (ATC-6) to develop "Seismic Design Guidelines for Highway Bridges".(1) These guidelines are intended for use in the seismic design of new structures. They are the result of a concerted effort by the members of an ATC Project Engineering Panel (PEP). The PEP was composed of representatives from bridge design firms, state highway departments, universities, the Federal Highway Administration and Applied Technology Council.

The current project, which is directed toward seismic retrofitting of existing bridges, is an extension of the effort to develop guidelines for the seismic design of new structures. Many of the principles being considered for use in retrofitting were first developed as part of the seismic design guidelines. A review of these principles follows.

2.1 Seismic Design Guidelines for Highway New Bridges

The seismic design guidelines for new bridges were developed for national use, and therefore contain provisions for considering the variable levels of expected seismic activity in the United States. This is primarily done through the use of an acceleration coefficient, A, which is the effective horizontal ground acceleration at the bridge site. An earthquake producing this acceleration has a ten percent chance of being equaled or exceeded at a given site within a 50 year period. A contour map of acceleration coefficients is shown in Figure 1. This map was developed by a team of seismologists using both historical and geological data.

The guidelines also consider the importance of the structure in social/survival and security/defense terms. Essential bridges are assigned a high importance signified by an Importance Classification I. All other bridges are placed in Importance Classification II. The Importance Classification is used along with the acceleration coefficient to assign a bridge to one of four seismic performance categories, A through D, as shown in Table 1. The analysis and design requirements vary depending on the seismic performance category.

TABLE 1: SEISMIC PERFORMANCE CATEGORY

Acceleration Coefficient	Importance Classification	
	I	II
$A \leq .09$	A	A
$.09 < A \leq .19$	B	B
$.19 < A \leq .29$	C	C
$.29 < A$	D	C

The seismic design guidelines utilize one of two elastic response spectrum analysis procedures to determine the seismic displacements and elastic member forces due to the design earthquake in each of two perpendicular horizontal directions. Provisions are given for combining forces resulting from earthquakes in the two horizontal directions to account for directional uncertainty of the earthquake. The response spectra to be used vary based on acceleration coefficient and the soil profile at the bridge site.

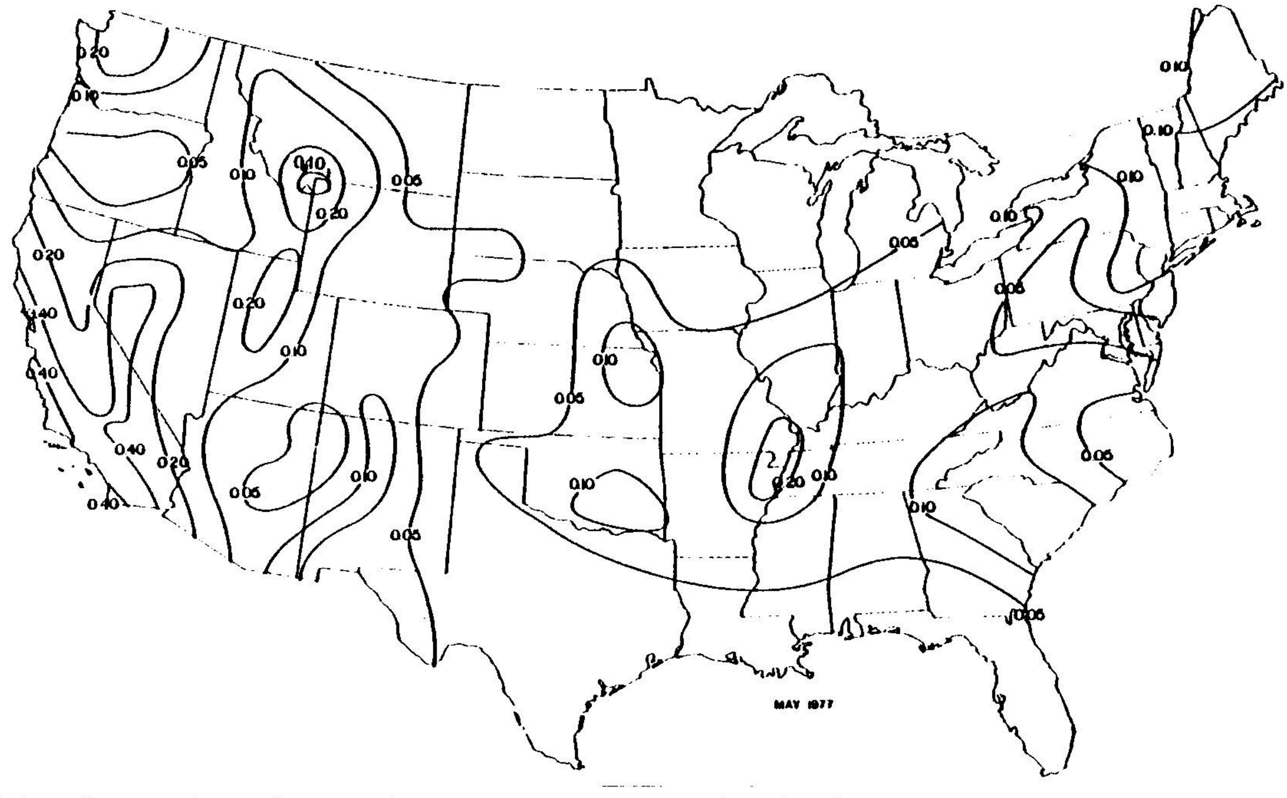

Fig. 1 Acceleration coefficient - Continental United States

The elastic member forces obtained from the analysis are divided by response modification factors to obtain component design forces. Use of a response modification factor greater than one implies the acceptance of yielding in the member. Use of factors less than one are used for non-ductile components that may be subjected to higher forces due to yielding elsewhere in the structure. The guidelines also allow for a reduction in certain design forces when it can be shown that column yielding will limit these forces to certain maximum values.

Elastic displacements form a lower bound on the expected structure displacements. To account for larger relative displacements at expansion joints, the guidelines specify minimum support lengths. These support lengths are intended to account for the overall inelastic response of the bridge structure, possible independent movement of different parts of the substructure, and out-of-phase rotation of abutments and columns resulting from traveling surface wave motions.

Special design requirements are provided for foundations and abutments, structural steel, and reinforced concrete. Particular attention is given to the reinforcement details of concrete bridge columns. These details are directed toward providing greater ductility in columns which are assumed to undergo inelastic yielding.

3. RETROFIT GUIDELINES

A Project Engineering Panel is also being used to develop the seismic retrofit guidelines for highway bridges. The panel for this project is composed of consulting engineers, academicians, state highway engineers, and representatives from the Federal Highway Administration and Applied Technology Council. The project is expected to be completed in early 1983.

The retrofit guidelines will recommend procedures for evaluating and upgrading the seismic resistance of existing highway bridges. Methods of evaluation will assist engineers in identifying and assessing bridges which could be hazardous to life safety during earthquakes. Evaluation results may be used with engineering judgement to decide if, how and to what degree a bridge should be retrofitted.

Methods of retrofitting various vulnerable bridge components will also be presented in the guidelines. Since seismic retrofitting is a relatively new concept, only a few retrofitting schemes have been tried in practice. At present, seismic retrofitting is an art requiring considerable engineering judgement. Although the guidelines will present accepted retrofitting techniques, they are not intended to restrict innovative designs.

The guidelines will not prescribe rigid requirements dictating when and how every bridge is to be strengthened. Retrofitting decisions depend on several factors, many of which are economic and are outside the realm of engineering. The guidelines are intended to provide a guide for rationally assessing the engineering factors involved.

The retofit process involves identification of the bridges which pose the greatest threat to life safety due to earthquakes; a procedure for the detailed evaluation of individual bridges so identified; determination of the need for retrofitting; identification of appropriate retrofit measures; an economic assessment of the benefits of retrofitting; and a decision to retrofit or not to retrofit. This process is depicted in the flow chart shown in Figure 2. The guidelines are intended for use throughout this retrofitting process. Specifically, the guidelines will provide:

- A preliminary screening process for determining which bridges present the greatest hazard due to earthquakes
- A methodology for quantitatively evaluating the seismic capacity of an existing bridge
- Retrofit measures that can be used to increase the seismic resistance of bridges

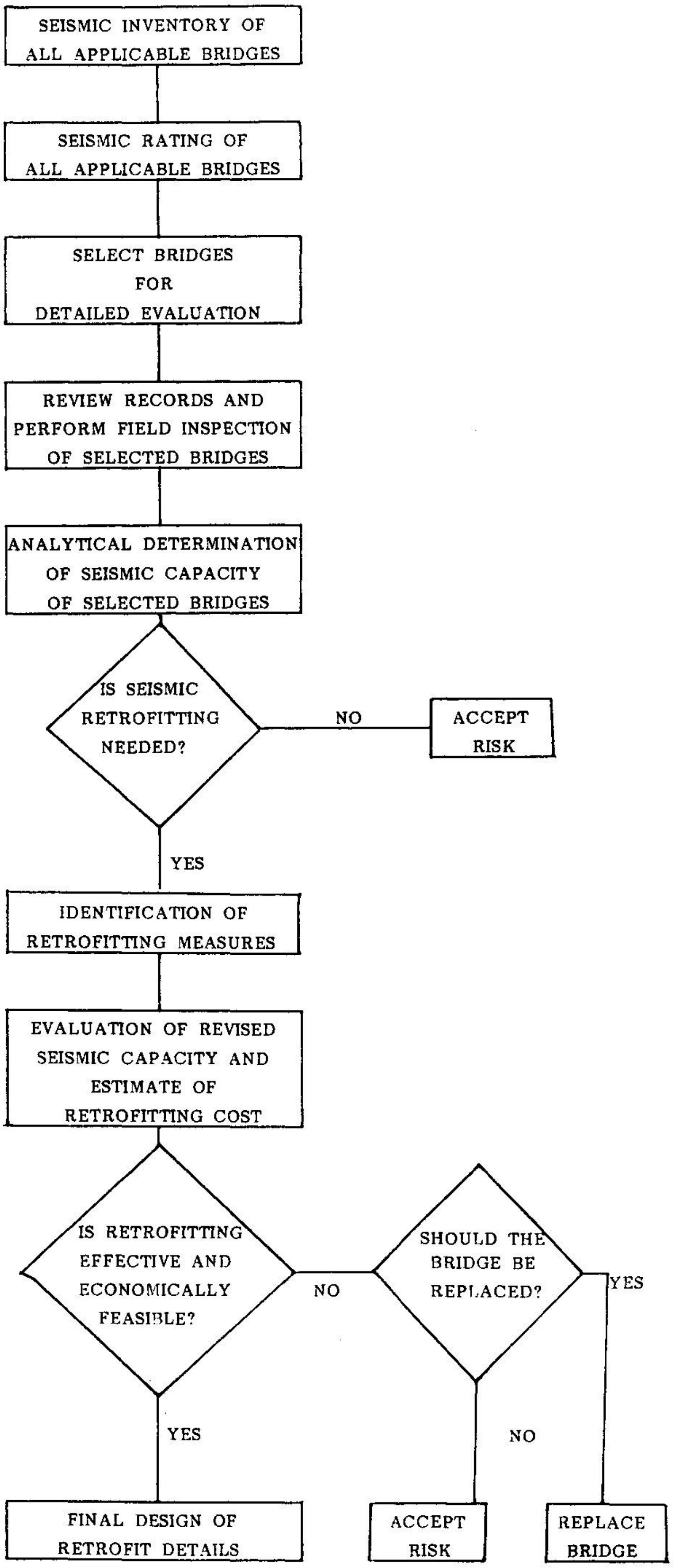

Fig. 2 Seismic retrofitting process for bridges

Each of these features of the guidelines will be discussed in greater detail in the sections that follow.

3.1 Preliminary Screening Process

The first problem facing an engineer contemplating a seismic retrofitting program is to determine which bridges should be retrofitted first. If a large number of bridges are being considered, this determination must be accomplished with a minimum of effort for each bridge. The retrofit guidelines will establish a framework for addressing this problem through the use of a seismic rating system. This system will help the engineer establish a priority in which bridges should be investigated for retrofitting by a more detailed evaluation.

The seismic rating system will be subjective by design. This will allow the engineer to consider regional and jurisdictional needs in assigning priorities.

To enhance consistancy it is recommended that rating of all bridges in one geographical area be performed by the same personnel.

The seismic rating of a bridge will consider structural vulnerability, seismicity and structure importance. Each of these three areas will be assigned an independent rating, weight and score. The scores will be added to arrive at an overall seismic rating according to the following procedure:

1. Vulnerability Rating (rating 0 to 10) x weight = score
2. Seismicity Rating (rating 0 to 10) x weight = score
3. Importance Rating (rating 0 to 10) x weight = score

Seismic Rating (100 maximum) = Total Score

Although the ratings in each of the three areas will be established by procedures described in the guidelines, the weights to be used, which must total 10, will be left to the discretion of the engineer. This will allow the engineer the flexibility to emphasize the seismic aspects most important to him. For example, in an area with uniform seismicity, the seismicity rating may be deemphasized by using a low weight. This will minimize the effect of seismicity and emphasize vulnerability and importance in the overall rating. Conversely, in an area of variable seismicity, it will be desirable to place more emphasis on seismicity. In this case a greater weight should be applied to the seismicity rating.

Other more scientific methods for combining the affects of vulnerability, seismicity and importance were considered. The objective of the rating system was limited, however, to providing the engineer with a framework for systematically considering the three most important engineering aspects of the retrofitting problem. In light of this objective, the proposed method of seismic rating was selected because of its simplicity, flexibility and ability to yield reasonable results.

The vulnerability rating for a bridge must be performed with a minimum of computation, and with data readily available to the engineer. Two separate vulnerability ratings are currently proposed; the first for the bearings and the second for the remainder of the structure; namely columns, piers, footings, abutments and liquefaction potential. The greater of these two ratings will be the vulnerability rating for the structure. In areas of lower seismicity, only the vulnerabilty rating for the bearings needs to be considered.

Although, the engineer is allowed to used his judgement in performing vulnerability ratings, the guidelines do provide a suggested step-by-step procedure for arriving at each of the two proposed ratings. This procedure has its basis in the observations of the performance of bridge structures during past earthquakes. Structural configurations and details which have resulted in failure in the past are identified, and assigned vulnerability ratings between 1 and 10.

The seismicity rating will be based on the acceleration coefficient taken from the map shown in Figure 1.

The importance rating will be based on the social/survival and security/defense requirements used to establish the importance classification in ATC-6.(1) Essential bridges will be rated between 6 and 10 and all other bridges will receive a rating of 5 or below. Selection of the final importance rating from within this range of ratings will be based on the number of people likely to be on or under the bridge at any one time, and the relative importance of the bridge as a vital transportation link.

3.2 Detailed Seismic Evaluation

The detailed seismic evaluation of a bridge will be performed in two phases. The first phase will be a quantitative evaluation of individual bridge components using the results from one of the two analysis procedures developed for the ATC-6. The analysis will be performed using the design earthquake loading. The resulting force and displacement results, which are referred to as demands, will be compared with the ultimate capacities of each of the components to resist these forces and displacements. The ability of columns to resist post elastic deformations will be considered. A capacity/demand ratio will be calculated for each potential mode of failure in the critical components. This ratio is designed to represent the portion of the design earthquake that each of the components is capable of resisting.

The second phase of evaluation is an assessment of the consequences of failure in each of the components with insufficient capacity to resist the design earthquake. Consideration will be given to retrofitting substandard components if their failure results in a bridge collapse. In the case of certain essential bridges, the loss of function may also warrant the consideration of retrofitting. A procedure for selecting retrofit methods is shown in Figure 3.

There are four areas where local failure has a high potential of occurring and where component capacity/demand ratios will be calculated. These are:

- Bearings and Expansion Joints
- Columns, Piers and Footings
- Abutments
- Liquefaction of Foundation Soil

Aspects of the evaluation process relating to each of these areas are discussed in the following paragraphs.

3.2.1 Bearings and Expansion Joints

Bridge superstructures are often constructed discontinuously to accommodate anticipated superstructure movements such as those caused by temperature variation or to allow for the use of incompatible materials. Discontinuities necessitate the use of bearings which provide for rotational and/or translational movement. During earthquakes certain types of bridge bearings have proved to be among the most vulnerable of all bridge components.

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(3), the Guatamala earthquake of 1976(4), and the Eureka, California earthquake of 1980(5) 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 if the ground motion were slightly more intense or longer in duration.

Capacity/Demand ratios for bearings will be calculated for both displacement and force. Displacements are investigated in the longitudinal direction at expansion joints or "fixed" bearings where the force capacity is inadequate. The force capacity/demand ratio is calculated for bearings designed to resist lateral loads.

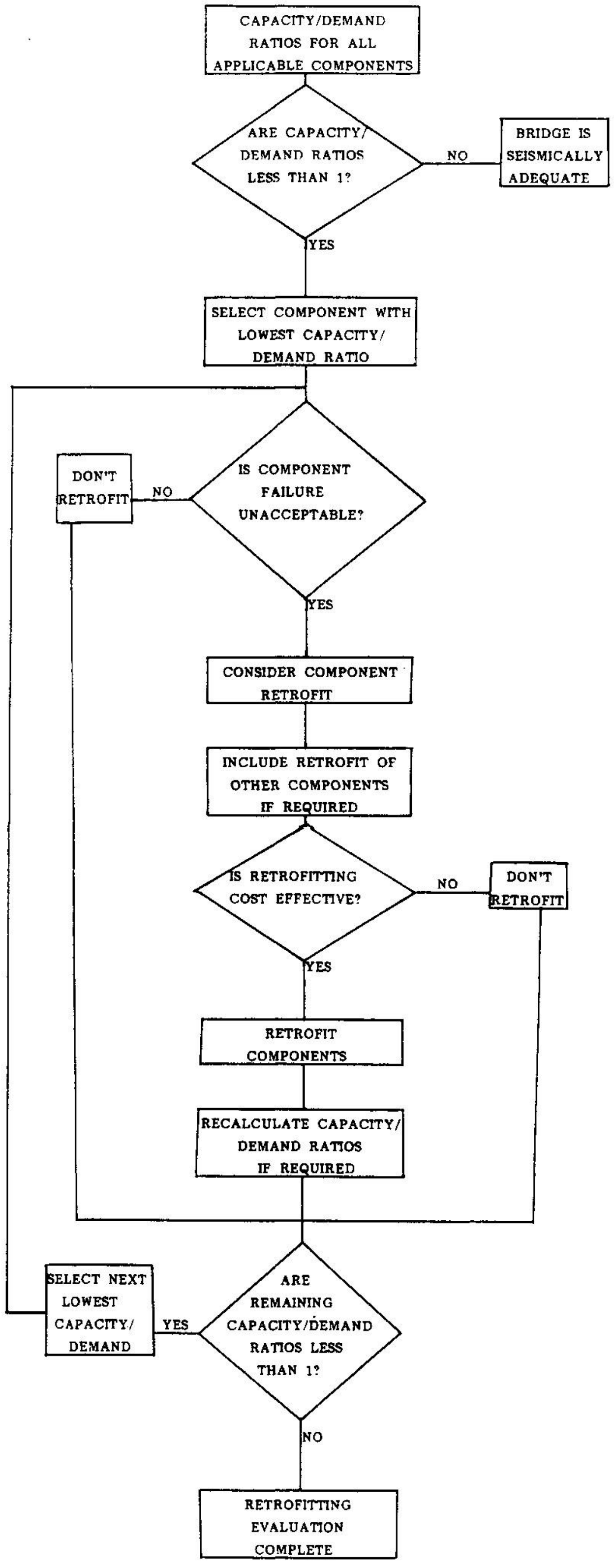

Fig. 3 Procedure for selecting retrofit methods

In the case of the differential displacements at expansion joints, elastic response spectrum analysis results yield displacements that are often below those intuitively expected based on observed bridge behavior during past earthquakes. In addition to the nonlinear behavior of expansion joints, possible independent movement of different parts of the substructure and out-of-phase movement of abutments and columns resulting from travelling surface wave motions also tend to result in larger displacements. For this reason, two methods for calculating the displacement capacity/demand ratio are proposed. The first method is based on a comparison of the nominal support length at the bearing (capacity) and the required design support length (demand) from the ATC-6. The second method compares the effective seat width (capacity) with the differential displacements obtained from an analysis (demand). Except in the case of restrained expansion joints where only the second method can be used, the lesser of the two capacity/demand ratios obtained from these two methods will govern.

The displacement capacity/demand ratio is intended to reflect the reduced level of loading at which a loss of support type of failure will occur. Usually the consequences of a support failure is the collapse of the span. In certain bridges with continuous superstructures, however, the bridge may still be capable of resisting the dead load moments and shears resulting from a loss of support at the expansion joint. This is often the case in long reinforced concrete slab bridges. Although a structure which has failed in this manner is not capable of carrying traffic loadings, it is likely that following a major earthquake it will be inspected and the expansion joint failure discovered. Traffic can then be diverted or measures taken to shore up the unseated bearings.

Conversely, certain structural configurations are exceptionally vulnerable to collapse in the event of a loss of support at the bearings. Such structures would be prime candidates for retrofitting. Simple or suspended spans in which no redundancy exists are particularly vulnerable. This is also true to a lesser degree in the case of a structure with a small redundancy, such as continuous bridges in which only one support occurs between expansion joints.

Elastic bearing forces obtained from a conventional analysis are likely to be lower than those actually experienced by bearings during an earthquake. This is because bearings, which are nonductile components, often do not resist loads simultaneously. This has been demonstrated in past earthquakes by the failure of anchor bolts or keeper bars on some, but not all of the bearings at a support. In addition, the yielding of ductile members such as columns can transfer load to the bearings. This phenomenon was observed in the results from nonlinear analytical case studies of three bridge structures(6). For these reasons it is necessary to increase elastic analysis force results through the use of a response modification factor when evaluating the force demand on nonductile motion-restraining components.

The force capacity of bearings must be carefully calculated. Anchor bolts are often subjected to combined bending and shear or high stresses at the threads. Spalling of edge concrete at anchor bolts is also possible. In addition, bearings may not be what they are represented to be on "As Built" plans or maintenance records.

By itself, the failure of bearing anchor bolts, keeper bars or shear keys will not constitute a situation that warrants retrofitting. When such a failure can result in relative displacements sufficient to cause collapse, however, then retrofitting should be considered. This determination should be made at the time that the consequences of component failure are assessed. For example, the loss of support of an edge girder due to transverse movement may render a portion of the superstructure unuseable but will not result in a structure collapse except possibly in a two girder bridge. It would still be possible to utilize the remaining portion of the superstructure. In this case retrofitting would not be warranted based on bearing force failure alone.

3.2.2 Columns, Piers and Footings

During an earthquake, the interaction of the columns and piers with their footings will determine the probable mode of failure for these components. The first step in evaluating these components is to determine if and where plastic hinging will occur. Plastic hinges may occur in the column end regions or at the footing. Piers can develop plastic hinges in the end regions about the weak axis only. The location of plastic hinging will dictate the modes of failure that should be investigated.

It is not uncommon for bridge columns to yield during strong seismic shaking. This is expected and provided for in the design of new structures. Existing columns however may not be capable of withstanding as much yielding as newly designed columns. Column failure may also occur prior to yielding in columns designed by pre-1971 standards. Column failures that result in a sudden loss of flexural or shear strength have the potential for causing collapse. The force levels at which these local failures occur will be reflected in the capacity/demand ratios for the various column failure modes. Each of these failures must be assessed in terms of its effect on the global stability of the structure. The cummulative effect of column failures elsewhere in the structure should also be considered in making this assessment.

Four modes of column failure are considered in evaluating columns. These include:

- Shear failure in the column
- Anchorage failure in the main longitudinal reinforcement
- Flexural failure in the column due to inadequate transverse confinement
- Failure of the splices in main longitudinal reinforcement

Detailed procedures are included in the guidelines for calculating the capacity/demand ratios for each of these modes of failure.

Column shear failures occur suddenly and can result in the rapid disintegration of the column. This happened to several bridges during the San Fernando earthquake. Flexural yielding of the column has the effect of limiting the shear force, but it also results in a degradation of shear capacity. The guidelines provide a technique for determining the level of yielding at which the danger of a shear failure is large. The level of yielding is represented by a ductility indicator which is applied to the flexural capacity. The capacity/demand ratio for column shear is then determined by comparing the modified flexural capacity with the elastic flexural demand.

In order to visualize this method, it is useful to look at the schematic relationship between shear capacity and shear demand as shown in Figure 4 for various levels of yielding. In this graph the level of yielding is indicated by the Ductility Indictor (D Factor). The shear capacity is shown as being constant up to a D factor of 2 where concrete spalling is assumed to begin. Between a D factor of 2 and a D factor of 5, the shear capacity is assumed to decrease linearly until it has reached the capacity of the effective transverse steel and the concrete core.

The applied shear force (demand) is proportional to the elastic moment up to flexural yielding (D=1). Beyond initial flexural yielding the shear force is assumed constant. To account for column overstrength, the maximum shear force is increased by a factor of 1.3. The point at which the shear capacity is equal to the shear force is the point representing the degree of flexural yielding at which shear failure may occur. If this occurs between a D value of 1 and a D value of 5, a reduced ductility capacity due to shear degradation in the column is indicated. This reduced ductility capacity is represented by the D value at which the shear capacity and shear force are equal in Figure 4. Therefore by evaluating the seismic capacity/demand ratio for flexure at this D factor the ratio of acceleration causing shear failure to design acceleration can be found.

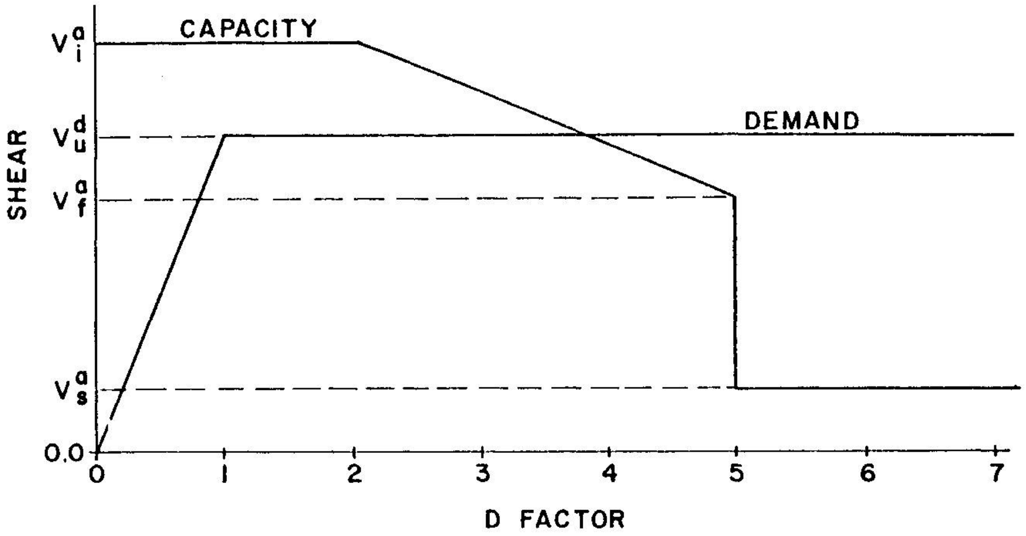

Fig. 4 Shear capacity and demand for reinforced concrete columns subjected to flexural yielding

If the initial shear capacity is less than the ultimate shear force, then the seismic capacity/demand ratio will be calculated as the ratio of the inital shear capacity to the elastic shear force caused by the design earthquake. If the final shear capacity is greater than the ultimate shear force resulting from plastic hinging of the column, then shear will not be considered a critical mode of failure. When yielding occurs in the footing, column shear capacity will not deteriorate, and shear failure may occur only if the ultimate shear force exceeds the initial shear capacity.

A sudden loss of flexural strength can result from an anchorage failure of the main reinforcement. This type of failure occurred at the Route 210/5 Separation and Overhead during the 1971 San Fernando Earthquake(3). When cracking occurs in the concrete where reinforcing steel is anchored, bond capacity is lost, and this type of failure is more likely. The procedures for calculating capacity/demand ratios for longitudinal steel anchorage will take this into consideration.

Sufficient transverse confining reinforcement is necessary to prevent strength degradation in flexure. In most existing columns the transverse reinforcement is not capable of preventing flexural degradation at the levels of yielding assumed in the design of new columns. Therefore, a method for determining the reduced levels of yielding at which existing columns will fail is proposed in the retrofit guidelines. This is also done through the determination of a ductility indicator that is applied to the ultimate flexural capacity of the column. This modified flexural capacity is divided by the elastic moment in the column to obtain the capacity/demand ratio.

The practice of splicing reinforcing bars at the bottom of the column was common in the past and may result in a high potential for failure during an earthquake. Flexural yielding of the column is likely to occur at this location, which will greatly reduce the capacity of the splices. The guidelines will consider this type of failure by limiting the amount of allowable yielding that can take place at a location where splices occur. Both anchorage and splice failures have the potential for limiting forces in the column. This may be critical in preventing column shear failures.

The capacity/demand ratio for the footing in flexure is calculated when yielding occurs in the footing. The allowable amount of flexural yielding will depend on the mode of footing failure. This is also represented by a ductility indicator that is applied to the ultimate footing flexural capacity.

3.2.3 Abutments

Failure of abutments during earthquakes usually involves tilting or shifting of the abutment either due to seismic earth pressures or inertia forces transmitted from the bridge superstructure. Usually these types of failures alone do not result in collapse or impairment of the structures capacity to carry emergency traffic loadings. They may result in loss of access, however, and can be critical in certain important structures.

Large horizontal movement at the abutments can result in approach fill settlements beyond acceptable limits. Abutment capacity/demand ratios therefore, are based on the abutment displacement. The displacement demand is assumed to be the elastic displacements at the abutments obtained by properly modeling the abutment stiffness. The displacement capacity is assumed to be three inches unless determined otherwise by a more detailed evaluation.

3.2.4 Liquefaction of Foundation Soil

Most foundation failures during earthquakes are the result of excessive soil movement such as occurs due to liquefaction. A capacity/demand ratio for liquefaction should be calculated when there is the potential for a severe liquefaction failure. This is obtained by dividing the ground acceleration at which liquefaction failure will occur by the design acceleration coefficient.

4. RETROFIT MEASURES

The guidelines will propose several conceptual details for retrofitting typical components that are known to be seismically deficient based on their past performance during earthquakes. These details are designed to prevent collapse or disabling structural damage due to the following modes of failure:

- Loss of support at the bearings which will result in a partial or total collapse of the bridge
- Excessive strength degradation of the supporting components
- Abutment and foundation failures resulting in loss of accessibility to the bridge

Once strengthening of a component has been decided upon, the guidelines will recommend that component retrofitting be designed to the standards for new construction. Reduced levels of seismic retrofitting may be considered when it is not cost effective to retrofit to new design standards and partial strengthening will greatly reduce the chances for structure collapse.

4.1 Bearing and Expansion Joint Retrofitting

Several techniques for retrofitting bearings are proposed. These include:

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

Longitudinal Joint Restrainers are used extensively by the California Department of Transportation(7). The primary function of these devices is to limit relative displacements at joints and thus decrease the chances for a loss of support at these locations. Restrainers are designed to resist force in the elastic range. Careful attention must be given to the methods used to attach restrainers to the superstructure so that existing components will not be damaged during an earthquake. The typical retrofit detail used by the California Department of Transportation on its concrete box girder bridges is shown in Figure 5.

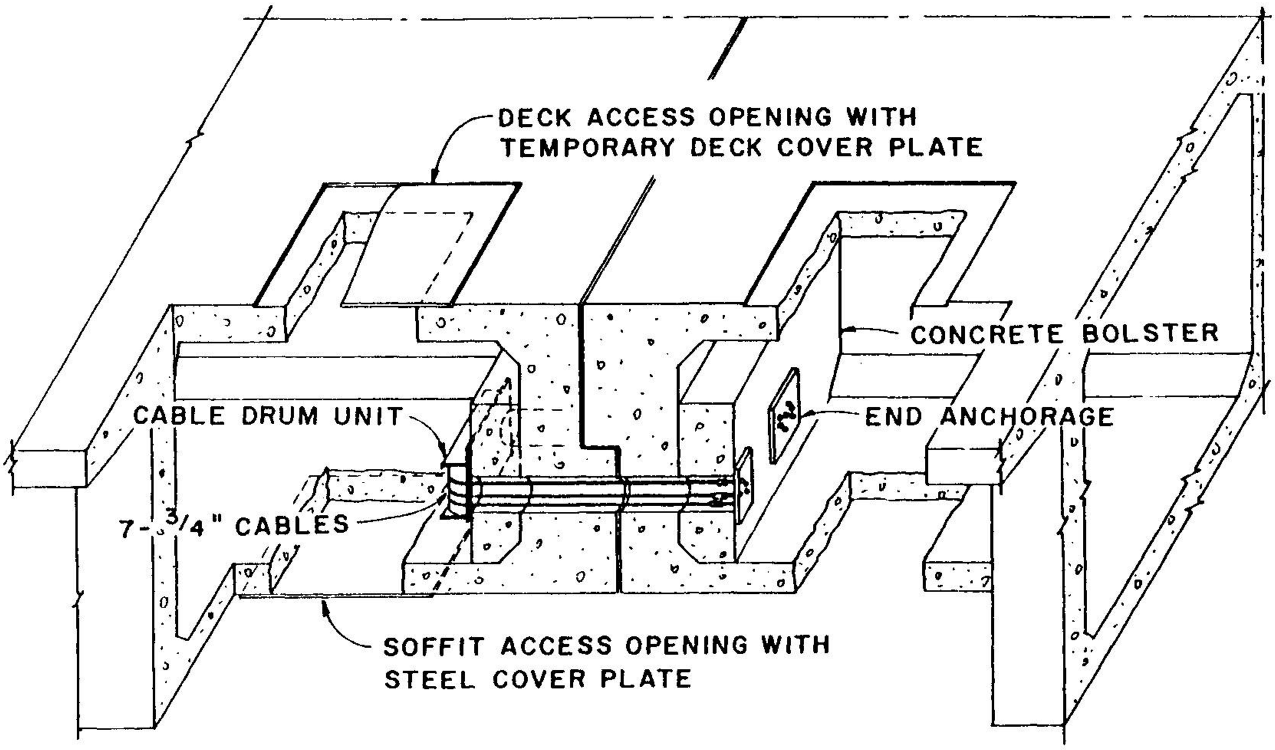

Fig. 5 Longitudinal joint restrainer for concrete box girder

Two other types of restrainers utilized at bearings and expansion joints are designed to restrict either transverse or vertical motion. Transverse bearing restrainers should be used when the existing anchor bolts, shear keys, or keeperbars are inadequate to resist transverse forces and when a loss of support due to transverse motion is likely due to the structure configuration or bearing support details.

The need for vertical motion restrainers will seldom be demonstrated by an analysis. However experience has shown that vertical movement can take place at the bearings. This can lead to the displacement of bearings and possibly increase the chances of a loss of support failure. The guidelines recommend that vertical restrainers be installed if feasible whenever longitudinal restrainers are considered as a retrofit measure and the seismic uplift force obtained from an analysis of longitudinal motion exceeds fifty percent of the deadload reaction.

Bearing seat extensions may be a feasible retrofit measure in certain situations. Extensions allow larger relative displacements to occur at the joints before support is lost and the span collapses. Since high forces may be imposed on these extensions, it is recommended that if feasible, such as at abutments, they be supported directly on the foundation. When this cannot be done, such as at columns or piers, bearing seat extensions should be designed using substantial overload factors.

Bearings which are damaged or malfunctioning can fail during an earthquake. In addition certain types of bearings, such as those shown in Figure 6, have performed poorly during past earthquakes. A possible retrofit measure in these cases is the replacement of the bearings with modern types such as elastromeric pads which, in conjunction with adequately designed restrainers, are more effective in resisting seismic loading.

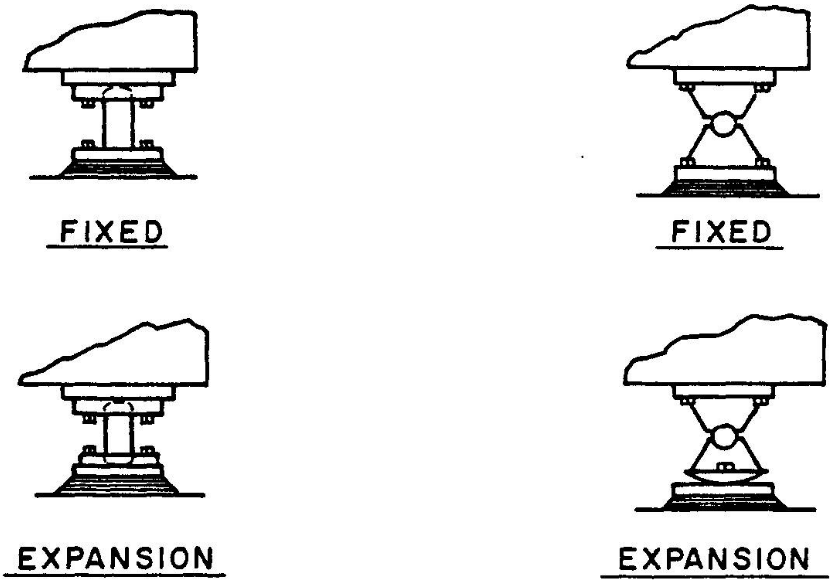

Fig. 6 Seismically vulnerable bridge bearings

Certain types of bearings and devices have special performance characteristics which will alter the seismic response of the entire structure. Some of these are designed to act as force limiting devices which minimize the force that can be transferred to supporting columns, piers or abutments. The behavior of these devices is usually highly non-linear. Some of the devices have been extensively tested but none of those currently installed in new bridges have been subjected to actual earthquakes. The guidelines recognize the complexity of these devices and recommend that a special design be performed if they are to be used as a retrofit measure.

4.2 Column, Pier and Footing Retrofitting

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 specifically retrofit these components than it is bearings. However, if force-limiting bearing devices can be added between the superstructure and columns, piers, or abutments, a cost-effective retrofit measure can be achieved without the necessity for retrofitting the substructure. This method of retrofit has been proposed for use in New Zealand(8).

To date there are very few retrofit methods that have actually been tried on seismically deficient bridge columns. Several methods have been proposed, however, and these are discussed in the following paragraphs.

Improved confinement will increase the ability of a column to withstand repeated cycles of loading beyond the elastic limit and tend to prevent column failure due to shear, pullout of longitudinal reinforcement, and degradation of flexural capacity. The ATC "Seismic Design Guidelines for Highway Bridges" have requirements for the spacing, amount and anchorage of conventional transverse reinforcement. The use of conventional transverse reinforcement for retrofitting, however, would present construction difficulties and would be of questionable effectiveness. Several methods of increasing the transverse confinement of columns through retrofitting have been proposed.

The first method utilizes conventional half inch steel reinforcing that is prestressed on the outer face of the column through the use of a specially designed turnbuckle. The steel bars would be spaced at 3½ inches on center which would provide confinement equivalent to new construction in most cases. The steel would be protected with a layer of pneumatically applied concrete.

A second method is similar to the first except that quarter inch prestressing wire is wrapped under tension around the column. A method of anchoring the wire would be required. The wire and anchorages would be protected by the same technique used for the first method.

The third method would employ a solid steel shell that would be welded in place around an existing column. A small space would be left between the column and the shell that would be grouted solid. The steel could be of a weathering type or it could be ordinary painted steel.

Other methods of increasing the confinement of concrete members have been tested in the laboratory at the Georgia Institute of Technology(9). In one of these methods, steel banding of the type used for packaging materials was applied to the outside of the concrete member. This method made a definite improvement in the ability of the concrete member to withstand repeated cycles of yielding. Because of the limited sizes of available banding, it is questionable if this method would be effective for the larger sizes of bridge columns, but tests have proved its effectiveness for the smaller sizes.

The Japanese have also proposed several methods for increasing the transverse confinement of reinforced concrete building columns which could be used for many smaller bridge columns. It should be stressed that retrofitting to increase transverse confinement has not been tried on an actual structure and with the exception of methods tested at the Georgia Institute of Technology and the Japanese methods, no physical tests have been performed. The advantages of confinement are well established by physical testing, however, and any method that can increase the confinement should be considered as a potential retrofit measure.

The maximum shear force on a column can be reduced by decreasing the yield moment at one or both ends of the column. This can be done by cutting the longitudindal reinforcing bars. Since this will increase the ductility demand at the points of flexural yielding, this retrofitting technique must be employed with caution. An essential prerequisite to using this retrofit method is that loss of flexural capacity at the location of cut bars not result in an overall structure instability, since any uncut bars at this location can be expected to yield in the early stages of seismic shaking.

This retrofit method should be considered when columns are overreinforced for flexure resulting in little or no flexural yielding during an earthquake. The resulting high yield moments could produce shear forces above the capacity of the column. By cutting bars an increased amount of yielding is accepted in exchange for a reduced shear force. The net result could be an improvement in the overall earthquake resistance of the structure.

The use of increased flexural reinforcement has also been proposed(10). The retrofit technique will increase the flexural capacity of the column. Increased flexural capacity will increase the forces transferred to the foundation and the superstructure/column connections and will also result in an increased column shear force. In addition the strengthened column will be stiffer and thus may attract more seismic force. If increased flexural reinforcement is being considered, care should be taken that all other components are able to resist the forces developed by the strengthened column. Since failure of the footings or failure of the columns in shear is usually more critical than excessive flexural yielding, this retrofit technique should be used with care. This technique should only be considered when loss of flexural strength would result in a collapse mechanism being formed and when levels of yielding in the column are exceptionally high.

In many cases the column footing will fail before the column or pier yields. This is often due to the absence of a top layer of footing reinforcement capable of resisting uplift forces on the footing. During an earthquake this can result in the fracturing of the concrete and the loss of anchorage for the longitudinal bars. This condition is usually most critical in single column bents.

One suggested method of retrofitting columns with this type of deficiency involves a concrete cap of constant thickness and the same horizontal dimensions as the footing which would be cast directly on top of the footing. Continuity with the existing footing would be provided by steel dowels cast in drilled holes. Negative moment capacity would be provided by a top layer of conventional reinforcement and prestress tendons. The collar would strengthen the footing for uplift and provide an extra measure of confinement at the base of the column and the top of the footing.

4.3 Abutment Retrofitting

Abutment retrofitting tehniques are suggested which tend to prevent loss of access to the bridge. These techniques are usually justified for structures which serve a critical function. Abutment tie back systems and settlement slabs are the only two abutment retrofit measures discussed in the guidelines.

4.4 Retrofitting for Liquefaction

Liquefaction or excessive soil movement has been the cause of many bridge failures during past earthquakes(11,12). 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 seismic liquefaction. The second approach is to increase the ability of the structure to withstand large relative displacements similar to those caused by liquefaction or large soil movement. The first approach has been tried on dams, power plants and other structures but to date has not been used as a retrofit measure for bridges. The second approach will utilize many of the retrofitting techniques discussed previously.

Several methods are available for stabilizing the soil at the site of the structure. Each method should be individually designed using established principles of soil mechanics to insure that the design is effective and that construction procedures will not damage the existing bridge. Some possible methods for site stabilization include:

1. Lowering of Groundwater Table
2. Consolidation of Soil by Vibrofloatation or Sand Compaction
3. Vertical Network of Drains
4. Placement of Permeable Overburden
5. Soil Grouting or chemical injection

Some of these methods may not be suitable and may even be detrimental in certain cases. Therefore, careful planning and design is necessary before employing any of the above 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 movement. In addition, the ability of the substructure to absorb differential movements is important. If, for example, column shear is the critical failure mode, retrofitting methods such as cutting longitudinal reinforcing steel that will tend to make flexure the dominant failure mode should be considered. Usually retrofitting of the structures alone will not prevent severe damage. Retrofitting is intended to prevent collapse and possibly provide for some restricted use of the structure immediately following an earthquake.

At a site subjected to excessive liquefaction, methods to improve the structure may be ineffective unless coupled with methods to stabilize the site.

5. CONCLUSIONS

The seismic retrofitting of bridges is still very much an art. Because of the variety of bridge configurations and details it is difficult to specifically cover all cases by a guideline. The guidelines are being developed to insure that engineers contemplating bridge seismic retrofitting have the benefit of the experience gained to date. In addition, the guidelines are being written to encourage innovative thinking and to aid in advancing the state of the art. They are written in a rational framework so that new ideas can be easily incorporated in future updates.

The development of the guidelines is still in progress and it is likely that modifications and additions will still be made. When completed, it is hoped that the guidelines will provide engineers with the information needed to solve the problem posed by our seismically deficient bridges.

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