Comparison of U.S. and Japanese Highway Bridge Seismic Retrofitting Measures

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ABSTRACT

This paper presents comparisons between the philosophy and methods used for seismic retrofitting of highway bridges in Japan and United States. Similarities and differences between the fundamental philosophies, retrofitting process and retrofitting measures in different bridge components are discussed, including a comparison of the fundamental retrofitting procedure and design criteria.

KEYWORDS: Earthquake Engineering, Seismic Retrofitting, Highway Bridges.

1. INTRODUCTION

1.1 Background

There are about 596,000 bridges in the U.S., of which 70 percent were constructed prior to 1971 with little or no consideration given to seismic resistance. Japanese bridge design specifications first included seismic design provisions following the 1923 Kanto earthquake. Similarly Ministry of Construction of Japan (MOC) of Japan made several seismic inspections of highway bridges through out the country since 1971, and successfully retrofitted and strengthened many bridges. In the 1991's national-wide inspection, about 18,000 out of 60,000 bridges were subjected to seismic retrofitting. [Unjoh, et al. 1997]. Recently, three large destructive earthquakes have occurred in the United States and Japan. These earthquakes, the Loma Prieta earthquake in 1989, the Northridge earthquake in 1994, and the Kobe earthquake in 1995, have severely damaged a number of highway bridges, and have cost many lives and billions of dollars. Among those damaged bridges, most of them were designed and constructed prior to the implementation of modern seismic design codes, significant damage also occurred in some bridges built to more recent codes. Most of these damaged or collapsed bridges were due to inadequate seat width for the superstructure, insufficient ductility and shear reinforcement for bridge piers, or foundation failure caused by soil liquefaction or large movement. Seismic retrofitting of vulnerable bridges to reduce their hazards to earthquake damage becomes an important issue. In lieu of the new findings on highway bridge performance under earthquakes, the Public Works Research Institute (PWRI) of Japan and the Federal Highway Administration (FHWA) of US initiated a cooperative research to further investigate the current seismic retrofitting methods, and to develop a more efficient and cost-effective method(s).

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been mandatory until the Hyogo-ken Nanbu earthquake took place. But now, very strong earthquake should be considered in the design of very important structures. Major researches that need to be focused on would be development of the new design procedure based on the allowable deformation, improvement of the conventional pseudo-static analysis procedure and development of cost-effective countermeasures.

REFERENCES

Seismic Retrofitting Manual for Highway Bridges, U.S. DOT, Federal Highway Administration, May 1995

VISION 2000 - Performance Based Seismic Engineering of Buildings, Structural Engineers Association of California Vision 2000 Committee, April 1995

Tamura, K. and Nakao, Y.: Strong ground motion estimation based on source modeling and semi-empirical Green's function technique, 14th U.S.-Japan Bridge Engineering Workshop, UJNR, 1998.

Miranda, E. and Bertero, V. V.: Evaluation of strength reduction factors for earthquake-resistant design, Earthquake Spectra, Vol. 10, 357-379, 1994.

M.J.N. Priestley, F. Seible, G.M. Calvi: Seismic Design and Retrofit of Bridges, 1996

CALTRANS: Bridges Design Specifications, 1990

Transit New Zealand: Bridge Manual, 1995

P. E. Pinto: Eurocode 8, Part 2, Earthquake Resistant Design of Bridges, Proc. of the First Japan-Italy Workshop on Seismic Design of Bridges, 1995

Matsuo, M. and T. Tsutsumi: Evaluation of Cone Penetration Testing as an in situ Liquefaction Resistance Measurement, Proc. 1st Intl. Conf. On Site Characterization-ISC'98/ Atlanta/ Georgia/ USA/ 19-22 April 1998, pp. 1309-1315.

This initiation was agreed at the 7th FHWA/MOC Bridge Engineering Workshop in Pittsburgh, PA in November, 1998.

In the United States, *Seismic Retrofitting Guidelines for Highway Bridges* was first issued in 1983, and was refined in 1987 as a national manual, *Seismic Design and Retrofitting for Highway Bridges.* In 1995, FHWA updated this manual with more currently knowledge and practical technology. This revision is to reflect recent changes in seismic design philosophy and performance criteria that was proposed to American Association of State Highway and Transportation Officials (AASHTO) in 1995. The guidance (or specification) of Japanese seismic retrofitting are most covered in Japan Road Association's (JRA) seismic design specifications, and are generally updated while codes are revised. The other important reference, *JRA's Manual for Earthquake Disaster Prevention of Road Facilities,* was published in 1988 [Note: this is also called as *Pre-earthquake Countermeasures*]. In 1996, the latest JRA seismic design code was issued. This revision has taken in consideration of the findings from the Kobe earthquake. A new guideline, *Reference Manual of Seismic Retrofitting for Existing Highway Bridges,* was also published which including new retrofitting requirements for reinforced concrete (RC) bridges piers and steel piers.

Seismic design and retrofitting philosophy and specification in both countries have become more rigorous and rational over time, as subsequent damaging earthquakes have occurred and educated bridge engineers worldwide. It seems that every earthquake provides an opportunity to improve the understanding of the performance and behavior of structures of all kinds, both through reconnaissance studies and research. In the latter case, observed behavior is often used to calibrate and/or refine theoretical models, which in turn may lead to changes in construction details and analysis methods.

1.2 Objective

The objective of this paper is to review and study those comparisons between the seismic retrofitting philosophies and design criteria for highway bridges as contained in the Japanese and United States' retrofitting specifications and manuals. This review is based on current seismic retrofitting manuals or codes being used in the two countries: In US, the FHWA's Seismic Retrofitting Manual for Highway Bridges published in 1995: In Japan, JRA Bridge Design Specification, Vol. V (Seismic), published in 1996; and Reference Manual of Seismic Retrofitting for Existing Highway Bridges of JRA, issued in 1997. Several technical papers [Kawashima, et al, 1993 and Zelinski 1996] were also reviewed. This review will present the different approaches used for seismic design through a comparison of fundamental philosophies, retrofitting process and retrofitting measures.

2. RETROFITTING PHILOSOPHIES

In order to understand the application and intent of a seismic retrofitting manual or specifications, it is important to have an understanding of the underlying philosophy on which the manual is based. In both the United States and Japan, because of the difficulty and cost involved in strengthening an existing bridge to new design standards, it is usually not economically justifiable to do so. The general goal of retrofitting is to prevent unacceptable failure. However, the interpretation of the "unacceptable" failure may not be the same in both countries. In the US, this implies that a considerable amount of structural damage during a major earthquake is acceptable as long as bridge collapsed is prevented. However, for important bridges such as lifeline system, the capability of the bridges to carry out emergency transportation immediately following an earthquake may require a higher level of performance with less structural damage. Thus, the threshold of damage that will constitute unacceptable failure may therefore be defined by the engineer by taking into overall configuration of the structure. In general, the unacceptable damages are the following:

- Serious injury or loss of life
- Collapse of all or part of the bridge.
- Loss of use of a vital transportation route.

In Japan, existing bridges had been expected to prevent critical damage as unseating of the superstrucutres against the maximum creditable events such as 1923 Kanto Earthquake in the past. The existing bridges have been evaluated and retrofitted to meet the criteria through the several inspection and retrofit programs.

However, due to the considerable interruption and damage restoration in the Kobe earthquake, higher level seismic safety requirement for critical bridges are needed to prevent large direct and indirect cost. In the new seismic design specifications [JRA 1996], the bridges are classified into two different categories based on the importance factor. The categories include Type B: important bridges and Type A: standards bridge. The design target for Type B bridges is to recover the transportation function of the bridge as soon as possible after the large earthquake. That of the Type A bridges is to prevent the critical damage such as unseating of the superstructure. This is very similar as US design and retrofitting classification. Performance based design will be the future basis for seismic design and retrofitting criteria. However, the determination of the importance factors and what kind of damage level in terms of immediate function or repairable structures are still debatable in the earthquake communities.

Seismic retrofitting philosophies are very similar in both countries. However, the implementation of this fundamental philosophy is somewhat different in the specifications and manuals of the respective countries, and some of these differences are explored in this paper. In the US, the Retrofitting Manual recommends low-to-moderate seismic zone that retrofitting be considered whenever non-seismic rehabilitation of bridge is planned or when bearing deficiencies exist in structure. But in Japan, since the most of area in the country is in high seismic zone, most of bridges are required for evaluation to meet the new design requirement.

3. RETROFITTING PROCESS

Seismic retrofitting is one solution for mitigating the hazard of existing bridges that are vulnerable to serious damage during an earthquake. Because not all bridges can be retrofitted simultaneously, the most critical bridges should be retrofitted first. The selection of bridges for retrofitting requires an overall evaluation of the whole structure system including seismic risk, economics and social impacts. Thus, the process of the retrofitting bridges involves an assessment of a multiple of variables and requires the use of considerable judgment.

In the US, the process is divided into three different stages:

- Preliminary Screening.
- Detailed Evaluation.
- Design of Retrofitting Measures.

Figure 1 shows the flow chart of the US seismic retrofitting process.

The new JRA seismic design specifications issued in December, 1996 has changed the seismic design criteria in accordance with ground motion characteristics recorded in the Kobe earthquake. The bridge inspection procedure to identify vulnerable bridge is based on the damage experiences during the Kobe earthquake. In the determination of the priority for the retrofitting of the existing bridges, bridge conditions including construction year, ground condition, material, structural member characteristics, etc., and the importance of highway network are considered as shown in Figure 2.

4. RETROFITTING MEASURES

4.1 Retrofitting Strategies

In general, there are two alternative strategies that will allow a design engineer to choose while design in retrofitting a bridge. One is based on conventional strengthening techniques that increase the capacity of structure to meet the demand. The other one is based on reducing the demand on the structure so that the capacity of the existing structure is sufficient to resist earthquake forces. Both countries' retrofitting design guidelines include both strategies to retrofit bridges. The latter approach involves the use of an earthquake protective system, such as base isolation bearing (or called Menshin design) was proven successfully reducing earthquake forces in the Kobe earthquake. Although this approach may not be applicable to all bridge sites, earthquake protective system has been shown to be a cost-effective approach as well.

4.2 Superstructures

Superstructures loss supports at their bearings, seats or expansion joints was found one of the major factors to cause bridge failure in the past earthquakes. Although frequently amazing the results, these failure are relatively simple and inexpensive to prevent by retrofitting. Because of this, most retrofitting efforts to date have been directed toward tying bridges together at their bearings and expansion joints. To prevent this kind of failure, bridge superstructures are tying together at their bearings and expansion joints with restrainers. Restrainers in the US are used in three different purposes when tying the various parts of a bridge together:

- Longitudinal joint restraint.
- Transverse bearing restraint.
- Vertical restraint.

Bearing seat extension, adding shear keys and replacing vulnerable bearings are also used to reduce the seismic vulnerability of bridge superstructures from earthquake damages. After 1971 San Fernando earthquake, US California DOT immediately started to a retrofit program. As a result of that program, seismic resistance of 1260 bridges was improved by the addition of hinge restrainers, seat extensions, and shear keys [Zelinski, 1996].

Superstructures retrofitting are similar in Japan. After the Kobe earthquake 1995, simple supported bridge are tied together to prevent superstructures from falling off their supports in Hanshin Expressway. Generally, steel girders are made continuous up to two or three spans by installing shear and moment plates. The end girders are strengthened with redundant elements such as restrainers, isolation bearings, stoppers, and extended seats.

In comparison with both countries' retrofitting methods in superstructures, restrainers are used very common in both US and Japan. Nevertheless, in Japan more different materials and types of restrainers, such as *Znaidal Flexible Link Restrainer* and *Steel Plate Connector Restrainer* (as shown in Figure 3.) are installed..

4.3 Substructures

Recent destructive earthquakes have re-emphasized the needs to increase seismic resistance of bridge substructures including columns and cap beams. Bridge column failure due to insufficient ductility and inadequate shear reinforcement was found to be the most important factor causing bridge collapse or failure.

In both countries, reinforced concrete (RC) columns are usually retrofitted by adding steel jackets. Although in some cases, columns might be retrofitted with concrete jackets. Composite fiberglass wrapping methods have also been using in certain cases, such as limited working spaces (as shown in the Figure 4). For the rectangular columns, the recommended procedure in the US is to use oval shape jackets (as shown in the Figure 5), which provides a continuous confining action similar to that for a circular column. But in Japan, rectangular columns are retrofitted with steel jackets, and steel plates are welded together around columns. The plastic hinge zone at the bottom of column is confined by H-shaped beams to increase the ductility. The concept to increase the confinement using oval shape jacketing or confined members is similar between US and Japan, the oval shape construction increasing more spaces, which are usually difficult to be applied in most viaduct highways in the urban area of Japan.

In most cases, column retrofitting with steel jackets would not only increase ductility but also enhance certain level of strength capacity to resist earthquake loads in Japan. As recommended by the *Reference Retrofitting Manual* [JRA, 1997], retrofitting for RC column is to enhance ductility as much as possible but not to increase load capacity excessively. So that the foundation would be less effected. However, if the load capacity is not sufficient, enhancing ductility only may cause large residual displacement after earthquake. Thus, it is essential to check the foundation's capacity before retrofitting so that the column strength will not stronger than its foundation. Clearly, the increasing ductility and load capacity should be balanced.

Japan has more steel bridge columns than US has in the high seismicity area due to different soil profiles. They are commonly retrofitted to prevent buckling. In the current *JRA's Seismic Design Specification*, hollow steel columns are recommended to fill with low-strength concrete up to the height where the column's lateral capacity exceeds the earthquake demands. If column is unable to be filled with concrete, welding vertical stiffeners and diaphragms at corners of rectangular tubes is recommended.

Cap beams provide the link in force transfer between superstructure and columns. The US general philosophy is to increase the cap beam flexural strength sufficiently to force plastic hinge into columns. Retrofitting are generally adding vertical and horizontal special joint shear reinforcement and covered by concrete to integrate the joint connections. The other alternative way is to alleviate cap beam problems by adding a new link cap beam below the existing cap beam. However, this method may not be favorable in Japan due to the space underneath the highway might be occupied or used as secondary traffic route.

4.4 Soil and Foundations

Retrofitting of footings or piles may be the most expensive aspect of bridge seismic upgrading. During the past earthquake events, bridge foundations performed fairly well in comparison with bridge columns in both countries. However, the deficiencies may be found in footing flexural and shear strength, pile capacity and overturning resistance. Retrofitting measures are very alike in both countries. For liquefiable soils, stabilization for site soils such as:

- Lowering of groundwater table.
- Densification of soil by vibro-compaction, vibro-replacement, or compacting grouting
- Vertical network of drains.
- Placement of permeable overburden.
- Particulate or Chemical grouting.

are recommended in the FHWA's retrofitting manual. Structural improvement is the other option to accommodate site soil problem. Foundations are usually retrofitted by enlarging footings or increasing number of piles/ adding batter piles. The new design codes of JRA is using the *Ductility Design Method* for foundation design and the similar retrofitting methods have been studied and developed for vulnerable pile foundations, caisson foundations, footings, and soil liquefaction.

5. SUMMARY AND CONCLUDING REMARKS

This paper has presented a comparison of the philosophies and practical retrofitting measures of seismic retrofitting on highway bridges in both US and Japan. In which the FHWA's *Seismic Retrofitting Manual for Highway Bridges* and JRA new *Seismic Design Codes* and *Reference Manual for Seismic Retrofitting* are based. In comparing with retrofitting measures, the fundamental philosophies and basis are essentially similar. However, due to the different environments and restraints, practical retrofitting methods applied in the site are not the same. For example, although rectangular RC columns retrofitted with oval shapes steel jackets are recognized more efficient than rectangular steel jackets. Applying this measure to a limited-space area, such as an urban area of Japan, may not be practical. Bridge RC column retrofitting in Japan is usually designed for both increasing ductility and strength capacity but not to exceed the limit from foundation's capacity. Other than Japan, column retrofitting are focused on increasing ductility, and retrofitting design criteria are lower than Japan in the low-to-moderate seismicity area. This difference may due to the expectation of the large earthquake occurrence.

Japan has had a long, active history of dealing with earthquakes and designing for them since the 1923 Kanto earthquake. Over the years, Japanese design codes have been upgraded in order to address deficiencies found due to damaging earthquakes (Iemura, 1995). This is also the situation for the United States, especially since 1971 (Buckle, 1995). The recent 1989 Loma Prieta, 1994 Northridge and 1995 Kobe earthquakes have demonstrated the importance of functionality of highway structures for the emergency restoration. Consequently, design criteria for a higher performance should be considered in the codes and manual. Although both countries' current bridge design codes has included bridge importance factor to classify them into a higher category's performance, a more specific performance-based design codes should be developed in the near future. Similar to the new design codes, retrofitting measures should also be moving toward these changes.

Another aspect of seismic retrofitting for the highway structures is to assess the whole impacts of highway system, including other modes of transportation systems, social impacts ... etc from destructive earthquakes. Starting in the fall of 1992, FHWA has been cooperating with the Multidisciplinary Center for Earthquake Engineering Research to work on a comprehensive research program to develop tools to evaluate the seismic vulnerability of the national highway system in the United States. An important end-product of this program is the development of a seismic evaluation and retrofitting manual for existing highway systems. This manual, which expected in year 2000, is being prepared in three volumes, where Volume I contains the methodologies, procedures, and examples for conducting a seismic risk assessment of highway networks and systems; and Volume II and Volume III contain guidance on seismic vulnerability screening, analysis, and retrofitting of highway bridges, retaining structures, slopes, tunnels, culverts, and pavements. PWRI has also enhanced their research area in the earthquake disaster prevention by adding earthquake information system after the Kobe earthquake.

With the common interests in developing a cost-effective and more efficient method for seismic retrofitting in highway bridges. FHWA and PWRI are looking forward to co-investigating smart device systems and materials that will better retrofit the existing vulnerable bridges.

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REFERENCES:

AASHTO, 1995, Interim Revisions to the AASHTO *Standard Specifications for Highway Bridges*, Division I-A: Seismic Design, American Association of State Highway and Transportation Officials, Washington, DC.

Applied Technology Council, 1994, Meeting notes of the ATC-*18 "Seismic Design Criteria Review"* project.

Buckle, I., 1995, *"Influence of Damaging Earthquakes on Bridge Design in the United States of America,"* Preprint from the International Bridge Seismic Design Workshop, Tsukuba, Japan.

Buckle, I. And Friedland, I., 1995 *"Seismic Retrofitting Manual for Highway Bridges"*, Federal Highway Administration (FHWA), FHWA-RD-94-052, Mclean, VA USA.

Iemura, H., 1995, *"Damage Characteristics of Bridges,"* Preprint from the International Bridge Seismic Design Workshop, Tsukuba, Japan.

Japan Road Association, 1996, *"Specifications for Highway Bridges,"* Part V: Seismic Design, Japan.

Japan Road Association, 1997, *"Seismic Retrofitting Reference Manual for Existing Highway Bridges"*. Japan.

Kawashima, K., 1994, *"Seismic Design Force of Bridges,"* Proceedings of the Second International Workshop on Seismic Design of Bridges, Queenstown, New Zealand.

Kawashima, K., and Hasegawa, K., 1994, *"New Design Specification for Highway Bridges in Japan,"* Earthquake Spectra, Vol. 10, No. 2.

Kawashima, K. and Unjoh, S., 1992 "*Seismic Strengthening and Retrofitting of Highway Bridges in Japan*", 5th US-Japan Workshop on Earthquake Disaster Prevention for Lifeline System, Tsukuba, Japan.

Kawashima, K., 1990, "*Seismic Strengthening and Repair of Highway Bridges in Japan*", US-Japan Workshop on Seismic Retrofit of Bridges, Tsukuba, Japan.

Unjoh, S., Terayama, T., Adachi, Y. and Hoshikuma, J., 1997, "*Seismic retrofit of Existing Highway Bridges in Japan*", Proceedings of the 29th Joint Meeting of US-Japan Panel on Wind and Seismic Effects, UJNR, May 13-16, Tsukuba, Japan.

Yashinski, M., 1998, "*Bridge Seismic Retrofits After the 1995 Kobe Earthquake*", Periodic of CALTRANS, What's Shakin'.

Zelinski, R. 1996, "*Bridge Retrofit Concepts*", SAMPE Conference, Anaheim, CA.

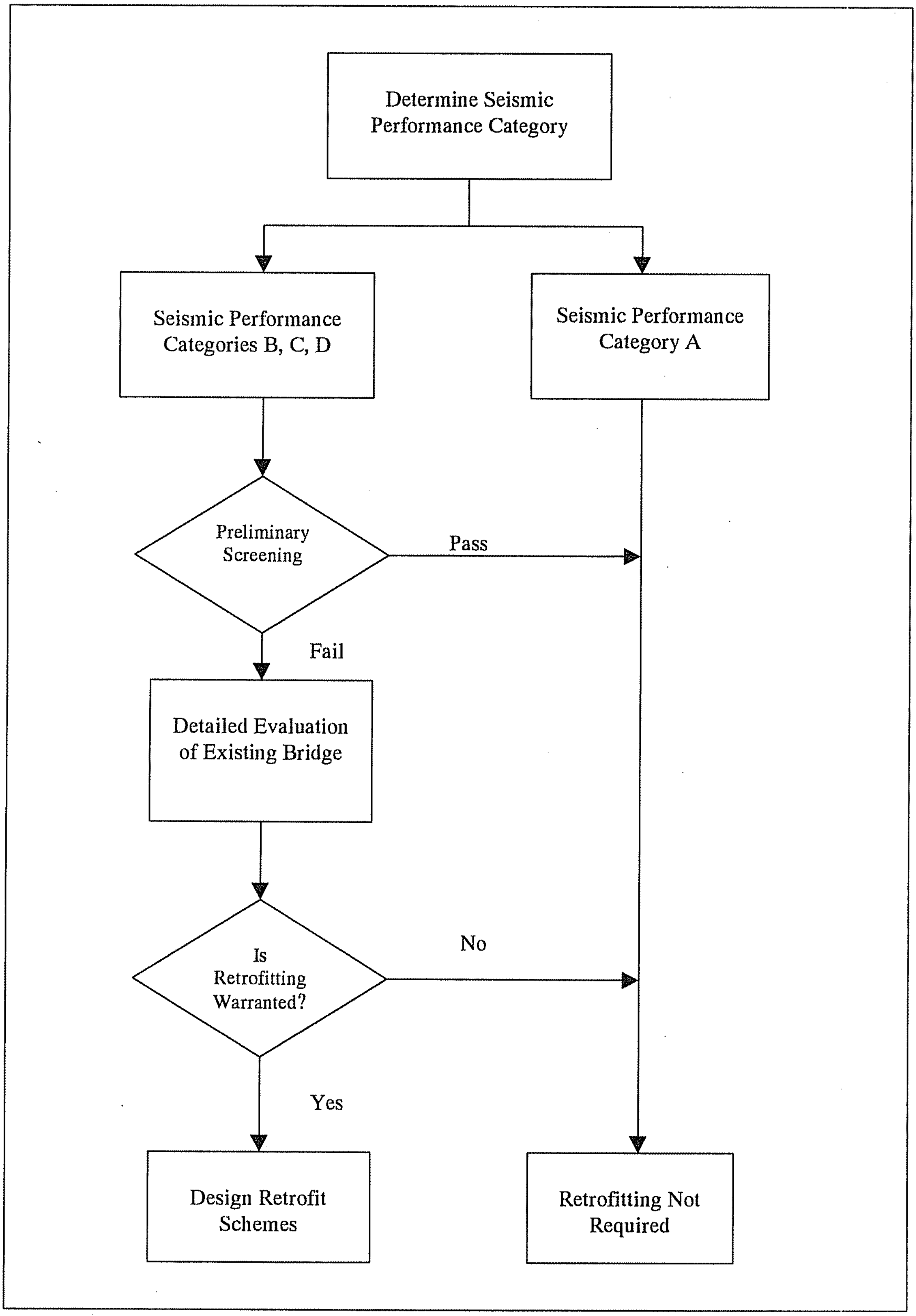

Figure 1 Seismic Retrofitting Process in US
(FHWA Seismic Retrofitting Manual)

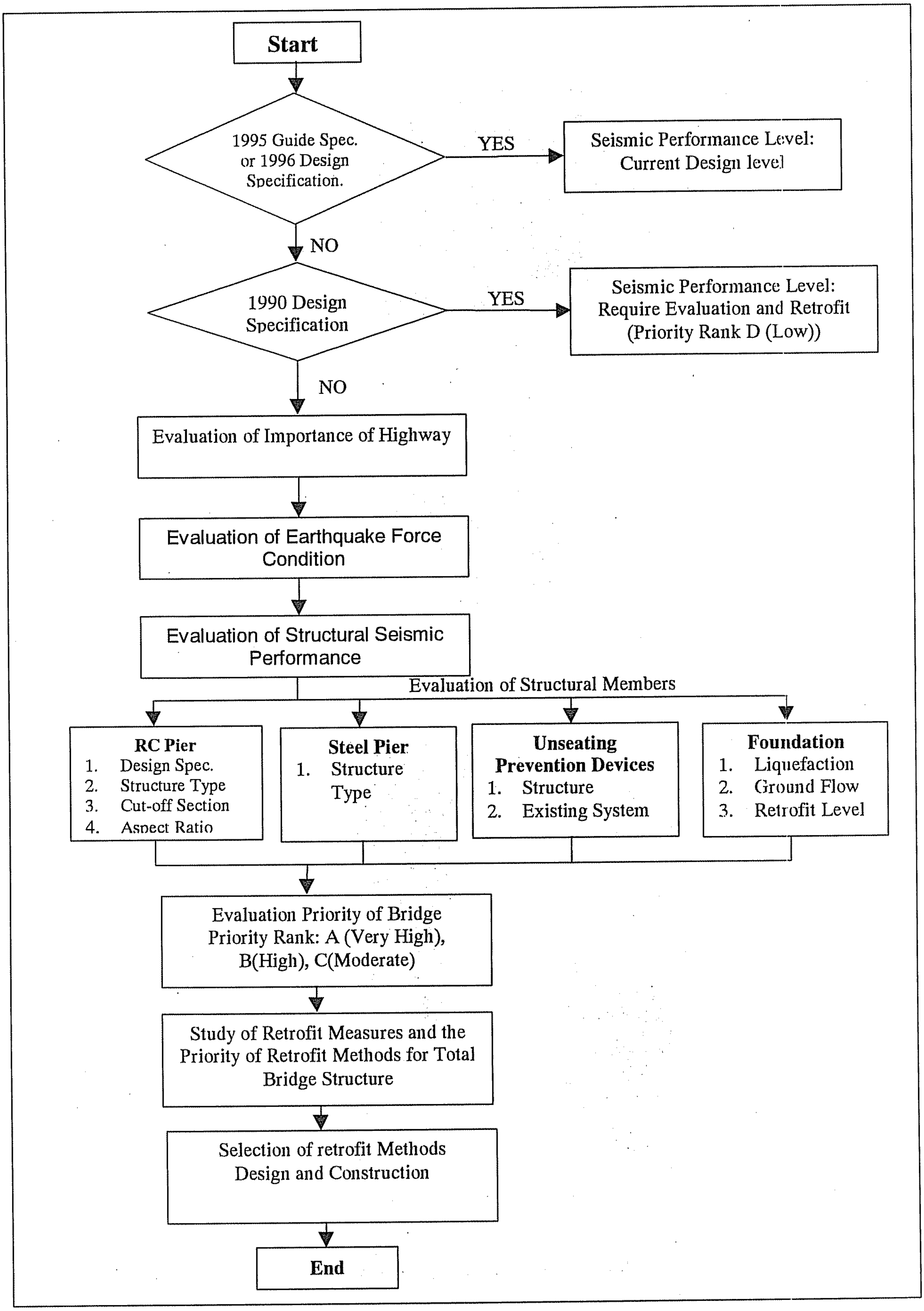

Figure 2 Prioritization Concept of Seismic Retrofit of Highway Bridges in Japan

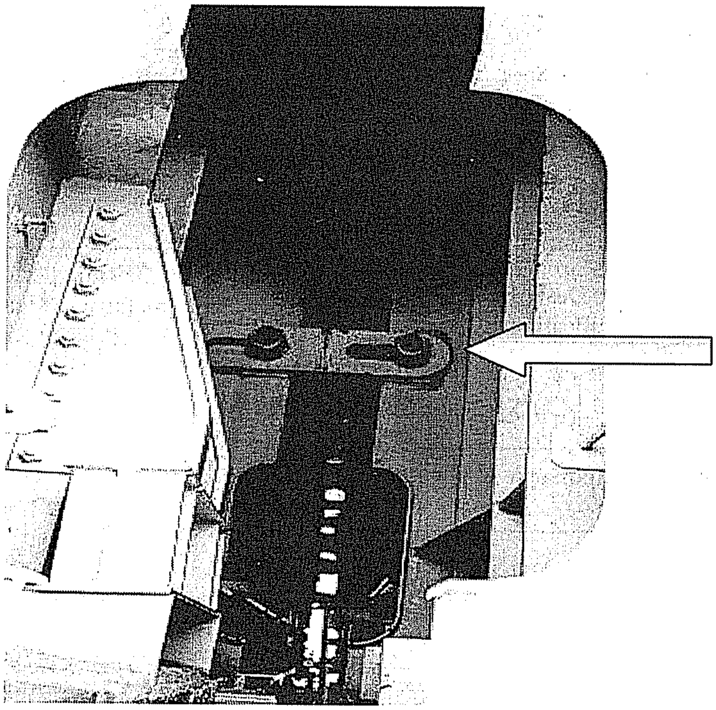

Figure 3　Steel Plate Connector Restrainer Used in Japan

Figure 4　Composite Material (FRP) Wrapping Used in Limited

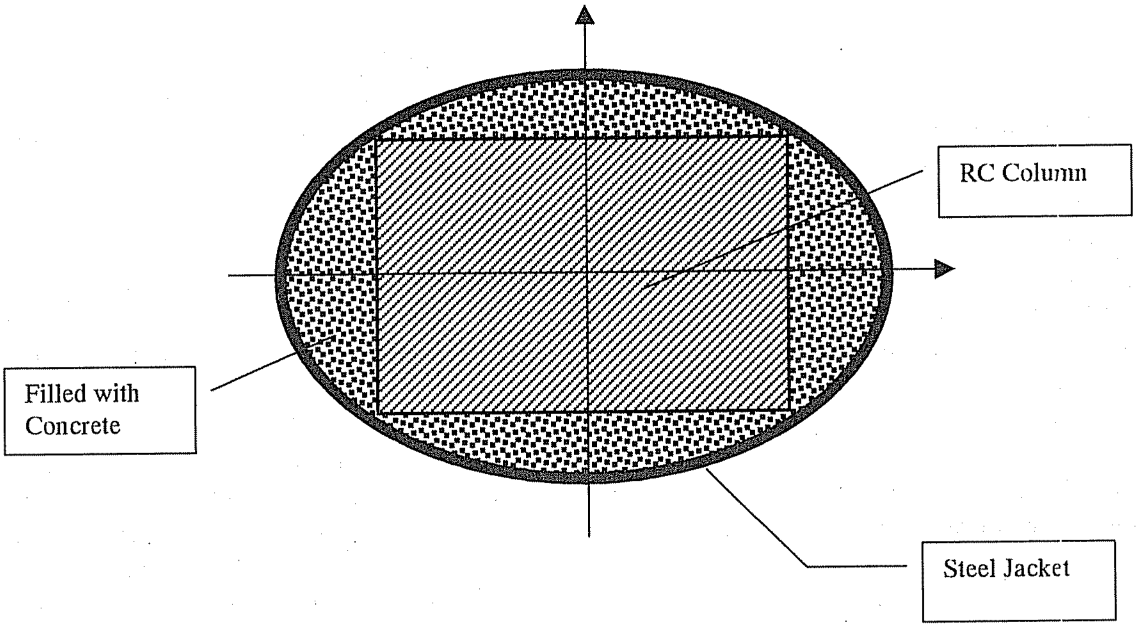

Figure 5 Elliptical (or Oval Shape) Jacket for Rectangular RC Column Retrofit