A PROPOSED METHODOLOGY FOR SEISMIC RISK EVALUATION OF HIGHWAY BRIDGES

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SUMMARY

In recent years, it has become apparent that many structures in seismic zones are inadequate to resist seismic loading. During recent earthquakes, several bridges have collapsed in different places all over the world. Furthermore, some of these failures occurred at relatively low levels of ground motion. Seismic retrofitting of existing highway bridges is one method of mitigating the risk that currently exists. However, funding for bridge seismic upgrading is limited, thus the management and prioritisation of bridge retrofit is vital. The task of this paper is to develop an improved simplified analytical procedure for assessing the seismic performance of existing reinforced concrete highway bridges. This evaluation methodology aims to express quantitatively what is known only qualitatively such that it can deal in a simplified way and quantify its seismic risk. This paper presents a simple evaluation method capable to assess the vulnerability rating and risk level of the reinforced concrete highway bridges without complex calculations. The proposed methodology covers the most important dynamic characteristics of the bridge structure. It is developed depending on the available data and researches on the seismic performance of this type of structures.

INTRODUCTION

Recent earthquakes (1971 San Francisco, 1989 Loma Prieta, 1994 Northridge, and 1995 Kobe earthquakes) emphasised that bridges are often the weak links for seismic damage to road network. So, most of the transportation authorities, especially those located in active zones, are beginning seismic retrofitting programs for their bridges. However, funding for bridge seismic upgrading is limited, thus the management and prioritisation of bridge retrofit is vital.

The seismic vulnerability evaluation of existing highway bridges is a subject that has recently attracted researches to its importance for both recent and old existing highway bridges. The rapid progress of the seismic design methods of highway bridges, by both new researches and seismic codes, has enabled these structures to be designed with improved prospects of satisfactory behaviour during earthquakes. At the same time, these methods have left some doubts about the adequacy of these existing structures. The first seismic inspection was made in 1971 in order to strengthen and promote earthquake disaster prevention measures in Japan [Kubo, 1977]. The damage experiences of highway bridges caused by the San Fernando Earthquake (Magnitude = 6.6) close to Los Angels, USA, in February, 1971 was a turning point of the initiation of the inspection. The attention was paid to detect deterioration such as cracks of reinforced concrete structures, tilting, sliding, settlement and scouring of foundations, etc.

Seismic inspection methods to detect highway bridges vulnerability to earthquakes have been developed and amended several times to reflect progress of bridge earthquake engineering and lessons learned from the past seismic damage. The most important requirement for the inspection method was to be able to assess the vulnerability of a number of highway bridges at a site without complex calculations. Some of the many evaluation methodologies which have been presented to estimate the seismic vulnerability of existing highway

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bridges are simplified [Kubo 1977, Babaei 1991, Gilbert 1993, Kawashima 1990, Maffei 1994, Maroney 1991, ATC 1983, Cooling 1990, Pezeshk 1993], and others are very detailed and need more sophisticated analysis [Priestley 1991, Buckle, 1995].

The purpose of this paper is to develop a methodology for the evaluation of the seismic vulnerability of existing reinforced concrete highway bridges. This evaluation methodology aims to express quantitatively what is known only qualitatively such that it can deal with the complicated dynamic characteristics of the highway structure and quantify its seismic risk. The method is developed so that it takes the most important parameters affecting the structure seismic performance, and is programmed to be used and applied by engineers having minimum dynamic experience. The main parameters that are considered in the proposed methodology are: the seismicity, the site conditions, and the structure vulnerability. The structure vulnerability includes the actual present state of the bridge, its configurations in plan and elevation, type and material of structure, and structural details.

CURRENT METHODS FOR SEISMIC VULNERABILITY EVALUATION

Several seismic vulnerability evaluation procedures have been proposed. The task of the vulnerability evaluation can be divided into two main steps, a) collecting data on all of the bridges to be considered, and b) mathematically (or subjectively) weighing and assessing the data to arrive at a relative priority for each bridge.

The available current prioritisation procedures are:

1- The United States prioritisation schemes:
   - One) ATC-6-2/FHWA-RD83/007 screening process developed by the Applied Technology Council (ATC, 1983), and The Federal Highway Administration (FHWA) [Bucle et al., 1987], and the modified established procedure developed by (FHWA) [Bucle, 1990].
   - Two) The California Department of Transportation (CALTRANS) procedure described in [Gates and Maroney, 1990], and the advanced established Procedure by Gilbert [Gilbert, 1993] and,
   - Three) The other five States of America: Nevada and Missouri described in [Maffei, 1994], Washington [Babaei, 1991], Illinois [Cooling, 1990], New York [Buckle, 1990 and Priestley, 1991] and Tennessee [Pezeshk, 1993], procedures.

2- The Japanese prioritisation schemes described by [Kubo, 1977 and Kawashima, 1990], and

3- The New Zealand procedure developed by [Maffei, 1994].

It has been found from the previous review of the current schemes of seismic evaluation of bridges that there are two forms of schemes can be identified. Those where the score for a number of perceived critical factors are added to give the total score used in ranking bridges for retrofit needs, and those where at least some of the factors are multiplicative. It would seem that the later approach has a sounder logical base, particularly when one of the factors is seismicity. It should also be noted that the age, the condition and maintenance history of a bridge were not covered in addition to the above shortfalls.

THE PROPOSED METHODOLOGY

Some of the current evaluation methodologies are very simple and give rough estimation of the bridge vulnerability and risk levels, while others are very complicated and depend on advanced methods of analyses. The proposed methodology accounts for the most important dynamic characteristics and bridge seismic performance. It is developed depending on the available data and researches on the seismic performance of these type of structures. Also the performance of bridges during past earthquakes and the potential of bridge seismic deficiencies are considered in the development of this procedure. The proposed methodology is presented and programmed in a simple form, so it can be systematically applied by engineers having minimum dynamic experience. In the following subsections a presentation of the basis and description of the proposed methodology are summarised [Gabr, 1996].

3.1 Basis of the Proposed Methodology

The proposed approach for assessing the vulnerability rating of the reinforced concrete highway bridges is based on:

a. Structural response during past earthquakes:

One of the important basis of the evaluation procedure, is the bridge seismic performance during past earthquakes and the frequently observed causes of damage, and related bridge seismic deficiencies. These observed damages have helped in the assessment of the importance of the different dynamic characteristics on the bridge seismic performance. Considerations have been taken of the bridge deficiencies and their contributions to the degree of damage detected by the bridge during previous earthquakes. Higher values are assigned for factors responsible on the severe damage.

b. Previously developed seismic evaluation methods

As it was described, there are several established methodologies to evaluate the seismic vulnerability of highway bridges. These methodologies introduce different ways of dealing with such a problem, and provide important information regarding the main topics that must be considered in the seismic vulnerability evaluation of existing highway bridges.

c. Previous research work

Many research works have been performed to study the effect of bridge deficiencies and the bridge characteristics, (i.e. geometry, structural elements, site effect,… etc.), on its seismic performance and vulnerability. These researches are of great importance in assessing the weights of the different factors considered in the proposed methodology.

d. Seismic codes

The minimum requirements for seismic design and construction of highway bridges are set out in current codes. The ranges of these requirements reflect, to some extent, the importance of each parameter in the bridge seismic performance.

3.2 Bridge Investigation

The determination of the bridge seismic risk need to compile the following basic information:

- The structural characteristics needed to determine the vulnerability.
- The seismicity and soil conditions at the bridge site needed to determine the seismic hazard.

The most important information required in the evaluation procedure, may be obtained from the owner's records, maintenance records, as-built drawings, on-site bridge inspection records, and other sources. This information may be obtained from:

3.2.1 Bridge site visit

The bridge site visit may help the inspector(s) to investigate many important aspects that may not be available in the as-built drawings, such as bridge actual state, and the condition of the bridge elements. These information along with data obtained from the as-built drawings and those obtained from the site tests, will be used in the seismic inventory data sheet, to perform the evaluation.

3.2.2 As-built drawings

The most important source of the needed information is the as-built drawing. Details of the design calculations, material properties, bridge configuration in plan and elevation, span lengths and heights, section dimensions, reinforcement details, and many other useful information could be obtained from the as-built drawings.

Site tests

It may be useful to perform some site tests to assure some of the basic requirements of the structural material properties. Also, other tests may be needed to obtain some soil properties that may be needed in the evaluation procedure. Site tests should be performed by trained technicians and the results should be interpreted carefully.

3.3 Evaluation Procedure

The evaluation procedure is performed by quantifying the most important dynamic characteristics of the bridge and its effect on the overall seismic response of the bridge. The proposed methodology is performed through assigning numerical values for each factor. These numerical values are chosen to account for the following:

- Parameter importance on the overall response.
- Parameter sensitivity on the overall response.
- Conformity to suggested criteria.

The main three steps of the evaluation procedure are explained here-in-after.

3.3.1 Preliminary evaluation

The preliminary evaluation is the first step in the proposed methodology. It accounts for the effect of the most important parameters on the bridge seismic performance.

i. Bridge present state rating

Bridge present state rating is of particular importance for the evaluation of bridge seismic vulnerability. Deteriorated and poor quality concrete, cracked bridge elements, corrosion of reinforcements, bridge history, age, maintenance records, and bridge upgrading, are examples of factors that affect the present state of the bridge. The evaluation of the bridge present state mainly depends on the judgement of the inspector engineer(s). The actual present state of a structure reflects its ability to achieve the expected theoretical capacity. Cracks, maintenance, age, seismic exposure, and retrofit history are the factors considered in this parameter. The bridge present state parameter is obtained by summing up the previous five factors.

ii. Bridge geometry rating

Seismic performance is affected by the structural form, which in turn is a function of the bridge geometry. To study structural form effects on the overall seismic performance, several comparative analysis are reported for different bridges. Several variations are analysed in which pier heights, and span lengths are changed, skew, curvature, and slope are introduced, abutment restraint is adopted, and monolithic and non monolithic bridges are analysed. Bridge geometry rating represents the effect of individual parameter defects on the bridge seismic performance. Bridge type, skew, slope, curvature, and bridge irregularity are the factors considered in this parameter. The final bridge geometry rating factor is obtained by summing up these five factors.

iii. Bridge element rating

Bridge element rating factor reflects its effects on the bridge seismic performance. Design specification, superstructure, bearings, joints, substructure, and abutment are the factors considered in this parameter. The final bridge element rating factor is obtained by summing up the previous six factors.

vi. Aggregate factor of the preliminary evaluation:

The aggregate factor of the preliminary evaluation is obtained as the sum of the above three contributions, the bridge actual state, the bridge geometry, and the bridge elements, The structural vulnerability inversely proportional to the preliminary evaluation factor. This factor is then compared with the recommended limits, leading to the determination of the appropriate level of vulnerability.

Detailed evaluation

The detailed evaluation accounts for the reinforcement detailing and the ability of the bridge structure to response in a ductile manner. One of the aims of detailing is to ensure that the full strength of reinforcing bars serving either as principal flexural or as transverse reinforcement can be developed under the most adverse conditions that an earthquake may impose. In general, good reinforcement detailing improves the structural behaviour under seismic loading. This section is concerned with the effect of detailing of the individual structural elements on the overall bridge seismic performance. Each characteristic of reinforcement detailing under investigation is allotted a numerical value dependent on its effect on the bridge seismic performance.

The detailing of longitudinal, transversal reinforcement and lap splices for axially loaded elements (Piers), joints, and foundation elements are considered in this evaluation step. In proportional manner, the final detailing factor reflects the level of ductility of the bridge elements. This factor is then compared to the recommended limits, to define the level of bridge vulnerability and risk.

Seismic hazard evaluation

Seismic hazard evaluation accounts for the effect of seismicity, and site conditions at which the bridge is located on the bridge seismic performance. The parameters considered in this evaluation step are the site seismicity, the site effects, and the liquefaction potential. Also, the bridge span length is of particular importance for the prediction of the bridge seismic performance. The asynchronous motion is one of the most important parameters affecting the bridge seismic performance.

3.3.4 Assessment of bridge seismic vulnerability and risk

The above evaluation steps are performed by assigning a numerical value for each of the factors considered. The allocated values are lower for vulnerable conditions and vice versa. The sum of the numerical values is then compared with the pre-defined ranges to determine the vulnerability, hazard, and the risk level. It is worthy of mention that the allocation of numerical levels to evaluate the very complicated response of bridges under seismic loading is highly subjective. Extensive analysis and statistical studies are still needed to correlate the values recommended in this methodology. It is through calibration and application that the fine-tuning of this technique may be achieved. Seismicity and the site condition in which the structure is located are of great importance.

According to the values of the factors considered in the evaluation methodology and the limits recommended for each factor, the bridge seismic vulnerability and risk levels could be assessed. According to possible available combination of the three levels obtained above for the preliminary evaluation factor, detailed evaluation factor, and the overall bridge score, the bridge seismic vulnerability and risk could be evaluated. The possible vulnerability and risk levels are: 1) Low vulnerability and risk, 2) Medium vulnerability and low risk, 3) High vulnerability and low risk, 4) Low vulnerability and high risk, 5) Medium vulnerability and high risk, and 6) High vulnerability and risk. If the bridge seismic risk is low, it means that the bridge seismic capacity is deemed to be adequate to resist the expected seismic event. Otherwise, if the bridge seismic risk is high, additional analytical investigations are needed and appropriate analytical techniques must be used.

3.4 Case Studies

To calibrate and investigate the sensitivity of the proposed evaluation methodology and the implemented computer program, to be more confident with its results of evaluation, and make it applicable for use, four different bridges located in different sites are considered, the bridge details are given in [Gabr, 1996]. The above considered bridge sample of population are evaluated by the following considered methodologies: 1) The FHWA-95 methodology, 2) The CALTRANS 1993 methodology, 3) The Tennessee methodology, 4) The New Zealand methodology, 5) The Kawashima methodology, 6) The proposed evaluation methodology.

A summary and comparison of the evaluation results obtained by the mentioned evaluation methodologies are presented in Table 1. Ratings given in this table are subjective since all current methods (except Kawashima method) do not prescribe limits for risk levels. It should be noted that the proposed methodology covers most of the important bridge seismic characteristics. However it can be applied in simple and systematic manner without any complications of the analytical solutions.

3.5 Discussion and Comments

From the results obtained from the evaluation of the above four bridges by the proposed and the different considered evaluation methodologies, it can be noticed that:

1. The Tennessee, New Zealand, and Kawashima evaluation methods omitting the seismicity effect because they assumed that all of the considered bridges are located in the same seismic risk zone. This will not affect the order of the ranking of the bridges, that will be used for prioritisation.
2. The results obtained by CALTRANS, and Tennessee methods are used just for prioritising the evaluated bridges.
3. The CALTRANS, and Tennessee methods give some weight to the bridge importance which in tern are omitted from the others and as well the proposed methodology. In order to develop retrofit priorities consideration should be given to structural vulnerability, seismic and geotechnical hazards, and the socio-economic factors affecting importance, while the task of the FHWA-95, New Zealand, Kawashima, and the proposed methodologies are the assessment of the structure vulnerability and the seismic risk levels.
4. The results obtained by the proposed methodology are in good agreement with those obtained by the considered evaluation methods for the first three samples. While the proposed methodology result for the fourth one is different with the results obtained by most of the current evaluation methodologies, it is in good agreement with the bridge performance during the 1994 Northridge earthquake. This is attributed to the lack in the evaluation characteristics of some of these methodologies.

4 CONCLUSIONS

To evaluate the seismic vulnerability and risk levels of existing reinforced concrete highway bridges, a new methodology that has been developed and implemented into a computer program is presented in this paper. The main advantages of the developed methodology could be summarized as follows:

1. Accounts for the most salient bridge seismic characteristics that affect the bridge seismic capacity.
2. It considers parameters that are not considered in all the previous evaluation methodologies, which have pronounced effect on the bridge seismic performance. Yet it maintains simplicity required by engineers involved in damage assessment.

3. Identifies the potential of seismic deficiencies and weakness in the structural system, which helps in retrofitting processes.
4. By using the developed methodology, it is easy to establish a system for bridge prioritisation inventory and database.
5. Again, it is simple, useful, and easy for use by engineers having minimum dynamic experience.

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Table 1: Comparison between the results obtained by the current and the proposed methodology

	FHWA-95 Method	CALTRANS Method	Tennessee Method	New Zealand Method	Kawashima method	Proposed Method	Comments
Bridge I	Low Vulnerability and Risk	Low Vulnerability and Risk	Low Vulnerability and Risk	Low Vulnerability and Risk	Safe	Low Vulnerability and Risk	All methods give similar results
Bridge II	High Vulnerability and Risk	High Vulnerability and Risk	High Vulnerability and Risk	High Vulnerability and Risk	Vulnerable	High Vulnerability and Risk	All methods give similar results
Bridge III	Low Vulnerability and Risk	Low Vulnerability and Risk	Low Vulnerability and Risk	Low Vulnerability and Risk	Safe	Low Vulnerability and Risk	All methods give similar results
Bridge IV	High Vulnerability and Risk	High Vulnerability and Risk	Low Vulnerability and Risk	Low Vulnerability and Risk	Safe	Medium Vulnerability and High Risk	FHWA-95, and CALTRANS, give results similar to those obtained by the proposed method