Seismic Vulnerability Assessment of RC Structures: A Review

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Abstract— **Earthquake induced damage has been increased over the last few years. Gujrat (2001), Sumatra (2004) & Haiti (2010) are burning example of devastating damage due to earthquake. The collapse of engineered and non-engineered buildings during an earthquake is the chief contributor to the loss of lives and injuries to people. A state-of-the-art review of the seismic vulnerability assessment of RC structures is presented in this paper. The review includes the history of vulnerability assessment, basic concept of vulnerability assessment, various screening procedure, development of screening techniques, advancement of technology etc. This paper also focuses on some recent vulnerability assessment techniques that would lead to identify buildings which might pose in case of an earthquake. Based on the scope, the future work on the topic is outlined.**

Index Terms— RC structures, vulnerability, discriminant analysis, Index, Review.

I. Introduction

Earthquakes occur when energy stored within the earth, usually in the form of strain in rocks, suddenly releases. This energy is transmitted to the surface of the earth by earthquake waves. Most of the earthquakes are minor tremors, while larger earthquakes usually begin with slight tremors, rapidly take the form of one or more violent socks and end in vibrations of gradually diminishing force called aftershocks. With the rapid development of urbanization, the urban areas are growing with high rise structures. Risk is high in those urban areas having built environments rather than rural areas. If possible damage caused by earthquake can be predicted and disseminated, and then the responsible authorities will be careful about preventive measures, disaster preparedness, response and mitigation.

The earthquake risk at any location depends on the seismic hazard as well as the vulnerability of its structures. The seismic hazard evaluation considers the likelihood of earthquake of a particular magnitude or intensity affecting a site, and the evaluation of seismic risk in any city requires proper consideration of the strength of likely earthquakes in future. The seismic vulnerability, on the other hand, depends on the construction practice in the city and is related to quality of building stock **[1]**. The local construction practice has also a very strong bearing on the seismic vulnerability since the use of inherently strong building materials will result in structures showing better resistance to earthquakes.

Every damaging earthquake reaffirms the importance of seismic hazard and risk analysis for estimating the consequences of an earthquake **[2]**. Here hazard means a threatening event, or the probability of occurrence of a potentially damaging phenomenon within a given time period and area. And “risk” means expected loss (such as lives, injury, property damage etc) due to a particular hazard for a given area and reference period. Based on mathematical calculations, risk is the product of hazard and vulnerability **[2]**. Although some progress in the area of seismic prediction has been made, earthquakes cannot be accurately predicted in time, magnitude or location. Even if an accurate prediction were possible, the earthquake occurrence and consequent damage potential could not be prevented. Seismic hazard and risk cannot be eliminated, but it can be effectively analyzed and possibly reduced by combining the available regional geologic and geographic information with recent technological developments **[3]**.

II. Seismic Vulnerability Evaluation

Seismic vulnerability is a measure of the seismic strength or capacity of a structure. Hence it is found to be the main component of seismic risk assessment. The review of the built environment for seismic vulnerability estimation is normally carried out in the light of earthquake resistance of buildings, past earthquake damage history, building type, seismic zoning and creation of database and its quantitative analysis. Seismic design provision has been incorporated in almost all design codes only a few years before. As the seismic design criteria advances continuously, the existing buildings can become seismically deficient **[4]**. In most developing countries, seismic design criteria are not added yet to their building codes **[5]**. Thus seismic vulnerability estimation is pre-requisite for disaster mitigation and management. Vulnerability assessment is a complex process, which has considered design of buildings as well as deterioration of the material and damage caused to the building **[6]**. Various

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vulnerability assessment techniques are described in the following sections.

III. Rapid Visual Screening

Rapid visual screening (RVS) was first proposed in the US in 1988, which was further modified in 2002 to incorporate latest technological advancements and lessons from earthquake disasters **[7]**. These screening procedures have been widely used in many countries over the world even though it was developed for typical constructions in the US. The most important feature of this procedure is that it permits vulnerability assessment based on walk-around of the building by a trained evaluator. The evaluation procedure and system is compatible with GIS-based database and also permits use of the collected building information for a variety of other planning and mitigation purposes. The screening method is performed without any structural analysis. The inspection, data collection and decision making occurs generally on site and takes little time to complete the operation. RVS techniques can be implemented in both rural and urban areas. The RVS technology is only acceptable for the buildings not for the bridges or lifeline structures.

Basic structural hazard scores for various building types are provided on the RVS form. The screener modifies the basic structural hazard score by identifying and circling score modifiers which are then added to the basic structural hazard score to arrive at a final structural score, S. The basic structural hazard score, score modifiers, the final structural scores(S), all relate to the probability of building collapse. The result of the screening procedure is a final score that may range above 10 or below 0, with a high score indicating good expected seismic performance and a low score indicating a potentially hazardous structure. If the score is 2 or less, a detailed evaluation is recommended. On the basis of detailed evaluation, engineering analysis and other detailed procedures, a final determination of seismic adequacy and need for rehabilitations can be made.

IV. Damage Probability Matrices

Usually when an earthquake has happened, it is possible to get a distribution of the building damage with surveys. After that, we can derive an empirical vulnerability curve with this information. Therefore, in the curve derivation, we are assuming that damage due to past earthquakes observed in the structures classified by type, will be the same in future earthquakes in that region and it will representative of the vulnerability for areas with similar building stocks when subjected to similar size future events. The format of this types of curves also depend on the parameter used to define the hazard. If the intensity, which is a discrete scale, is chosen the the most widely used form is the damage probability matrix (DPM) **[8]**. Whitman et al. first proposed the use of damage probability matrices for the probabilistic prediction of damage to buildings from earthquakes. The format of the DPM is presented in the following table:

Table 1. Damage Probability Matrix format **[8]**

Damage State	Structural Damage	Non-structural Damage	Damage Ratio (%)	Intensity of Earthquakes				
				V	VI	VII	VIII	IX
0	None	None	0-0.05	10.4	-	-	-	-
1	None	Minor	0.05-0.3	16.4	0.5	-	-	-
2	None	Localised	0.3-1.25	40.0	22.5	-	-	-
3	Not noticeable	Widespread	1.25-3.5	20.0	30.0	2.7	-	-
4	Minor	Substantial	3.5-4.5	13.2	47.1	92.3	58.8	14.7
5	Substantial	Extensive	7.5-20	-	0.2	5.0	41.2	83.0
6	Major	Nearly total	20-65	-	-	-	-	2.3
7	Building condemned		100	-	-	-	-	-
8	Collapse		100	-	-	-	-	-

ATC-13 essentially derived damage probability matrices for 78 different earthquake engineering facility classes, 40 of which refer to buildings, by asking 58 experts (noted structural engineers, builder etc) to estimate the expected percentage of damage that would result to a specific structural type subjected to a given intensity. Based on their personal knowledge and experience, the experts had to fill in a formal questionnaire with their best estimates of damage ratios defined as dollar loss as a ratio of replacement value. In some case, however, only a few felt themselves sufficiently expert with respect to a particular structural type to venture an opinion. Clearly , the primary drawback of the ATC-13 approach is its subjectivity as the damage probability matrices are based exclusively on the subjective opinion of the experts. Hence, in addition to the uncertainties inherent to any estimation of damage due to the variability in actual building performance, there are uncertainties related to the opinion of the experts. The damage probability matrices based on expert opinions are also difficult to calibrate or modify in order to incorporate new data or technologies. Also it is difficult to extend ATC-13 to other building types and other regions, as well as to individual building characteristics. Nevertheless, it was the first relatively thorough study on earthquake damage and loss estimation and became the standard reference for many seismic vulnerability assessments until mid 1990’s.

V. Analytical Methods

The methods for the assessment of the vulnerability of buildings based on score assignments are rather detailed and therefore time-consuming. More sophisticated methods, implying a more detailed analysis and more refined models, take even more time and serve therefore for the evaluation of individual buildings only, possibly as a further step after the rapid screening of potential hazardous buildings in a multi-phase procedure **[9]**. They are not suitable for earthquake scenario projects where a large number of buildings have to be evaluated. Nevertheless, the concepts behind those methods can be valuable for the development of new simple methods and hence, the main analysis procedures shall be briefly outlined. The analysis procedures can be divided into linear procedures (linear static and linear dynamic) and nonlinear procedures (nonlinear static and nonlinear dynamic) **[10]**.In a linear static procedure the building is modeled as an equivalent single-degree of-freedom (SDOF) system with a linear elastic stiffness and an equivalent viscous damping. The seismic input is modeled by an equivalent lateral force with the objective to produce the same stresses and strains as the earthquake it represents. Based on an estimation of the first fundamental frequency of the building using empirical relationships or Rayleigh's method, the spectral acceleration is determined from the appropriate response spectrum which, multiplied by the mass of the building, results in the equivalent lateral force. The lateral force is then distributed over the height of the building and the corresponding internal forces and displacements are determined using linear elastic analysis. These linear static procedures are used primarily for design purposes and are incorporated in most codes. Their expenditure is rather small. However, their applicability is restricted to regular buildings for which the first mode of vibration is predominant **[11]**.

In a linear dynamic procedure the building is modeled as a multi-degree-of-freedom (MDOF) system with a linear elastic stiffness matrix and an equivalent viscous damping matrix. The seismic input is modeled using either modal spectral analysis or time history analysis. Modal spectral analysis assumes that the dynamic response of a building can be found by considering the independent response of each natural mode of vibration using linear elastic response spectra. Only the modes contributing considerably to the response need to be considered. The modal responses are combined using schemes such as the square-root-sum-of-squares. Time-history analysis involves a time-step-by-time-step evaluation of building response, using recorded or synthetic earthquake records as base motion input. In both cases the corresponding internal forces and displacements are determined using again linear elastic analysis. The advantage of these linear dynamic procedures with respect to linear static procedures is that higher modes can be considered which makes them suitable for irregular buildings. However, again they are based on linear elastic response and hence their applicability decreases with increasing nonlinear behavior which is approximated by global force reduction factors. In a nonlinear static procedure the building model incorporates directly the nonlinear force-deformation characteristics of individual components and elements due to inelastic material response. In a nonlinear dynamic procedure the building model is similar to the one used in nonlinear static procedures incorporating directly the inelastic material response using in general finite elements. The main difference is that the seismic input is modeled using a time-history analysis which involves time-step-by-time-step evaluation of the building response

VI. Evaluation Method in Japan

Ohkubo and Otani et al. describe Japanese standard for the evaluation of the seismic vulnerability of the existing low-rise reinforced concrete buildings **[12]**. Japanese design code requires large dimensions of columns and shear walls in order to provide substantial lateral load resistance. Since the estimation of deformation capacities of such large columns and shear walls are more difficult than the estimation of their strength capacities, the screening procedure in Japanese standard is mainly based on examination of story shear of columns and structural walls. The Japanese seismic evaluation standard named as "Standard and Commentary for Evaluation of Seismic Capacity of Existing Reinforced Concrete Buildings", follows three levels of screening procedures with different phases.

These procedures are applicable for low rise reinforced concrete buildings less than six stories with or without structural walls. For all of three screening levels, a structural index, IS, is defined with three sub-indices; namely basic structural performance sub-index, E0, structural design sub-index, SD, and sub-index on time dependent deterioration of the building. Then, the structural index is compared with the required seismic performance index, IS0, based on the estimation of equivalent static earthquake force. In case the structural index is greater than the required seismic performance index, the building is found to be adequate and no further analysis is required. On the other hand, lower value of structural index requires additional study as a next level of screening.

VII. Evaluation Method in USA

Stepwise evaluation process, consisting three evaluation steps, is proposed by Applied Technology Council (ATC). The evaluation steps are namely rapid visual screening, evaluation in detail and engineering evaluation [13], [14], [15]. The stepwise evaluation may stop at any step in case the structure under assessment is found to be adequate at that step. If the safety level of the structure is not clear, the consideration of the next step is required. In the first stage named as rapid visual screening, rapid and easy identification of the building that might suffer severe damage and lead to the loss of human lives during a strong ground motion is aimed. The second stage, evaluation in detail, is performed in order to determine whether there are any weak links in the structure that can cause component or structural failure. In this evaluation stage, lateral load carrying capacity of the structure is appraised by utilizing shearing stress check and drift check. The shearing stress check is based on the quick estimation of shearing stress in columns and structural walls, while drift check is mainly based on quick estimation of story drift considering relative rigidity of frame elements. The final evaluation stage, named as engineering evaluation, is carried out by an experienced design engineer in case the building is marked as seismically deficient and inadequate in the first two stages. The current design code is utilized in order to perform the further detailed structural analyses of building from "as built drawings". Final evaluation of the structure may need several weeks for each structure.

VIII. RELEVANT PAST STUDIES

A. Hassan and Sozen

Hasan and Sozen **[16]** proposed a simplified method for the classification of low-rise monolithic reinforced concrete structures in a given region according to their seismic vulnerability. The main objective of the proposed method is to identify buildings that have high probability of severe damage during a strong ground motion. The ranking process basically depends on the total floor area of the building and cross sectional areas of the columns, shear walls and masonry walls. "Wall index" and "Column index" are calculated for both directions of a structure and the indices corresponding to the weaker direction are plotted such that x and y axes will represent column and wall indices, respectively. The plot indicates the relative seismic vulnerability of the buildings with respect to each other in a given region.

$$WI = A_{wt}/A_{ft} * 100 \quad (1)$$

$$WI = A_{wt}/A_{ft} * 100 \quad (2)$$

In which,

$$A_{wt} = A_{cw} + \left(\frac{A_{mw}}{10}\right) \quad (3)$$

$$A_{ce} = \frac{A_{col}}{2} \quad (4)$$

The wall and column indices are calculated for both directions of a structure. Then, the indices corresponding to the weaker direction are plotted such that x and y axes will represent column and wall indices, respectively. This plot indices their relative seismic vulnerability with respect to each other in a given region. Priority index is defined to identify the buildings that require immediate rehabilitation. The priority index is calculated using the following relationship:

$$PI = WI + CI \quad (5)$$

Structures with lowest priority index are considered to be candidates for severe damage in case of strong ground motion. If decisions are to be made for immediate renewal or strengthening of structures in a given region, priority index could be used as indicator. Since the method is designed to rank buildings in the same region, no additional factors are needed to reflect the relative seismic risk of those buildings.

B. Ersoy and Tankut

Ersoy and Tankut proposed a methodology for the seismic design of low-ris residential reinforced concrete buildings with less than seven stories **[1]**. Detailed structural analysis of buildings is not needed if the structure fulfills the minimum design requirements for the reinforcement ratios and the dimensions of members given in the "specifications for structures to be built in disaster areas" and the column and wall areas given in following Equations

$$(k \sum A_c + \sum A_w) \geq 0.003 \sum A_p \quad (6)$$

$$\sum A_w \geq 0.002 \sum A_p \geq 0.01 A_{pb} \quad (7)$$

The ratio of available column and shear wall areas of the buildings to the required area is denoted by R and computed using the equation …….. the ratios were calculated in both directions for each structure by using …………… Smaller R values of structures were plotted against the number of stories. If the ratio is greater than one, no severe damage is expected in case of a strong ground motion.

$$R = {(k \sum A_c + \sum A_w)}\Big/{\left(0.003 * \sum A_p\right)} \quad (8)$$

C. Gulkan and Sozen

Gulkan and Sozen **[17]** proposed a methodology in order to estimate the seismic vulnerability of reinforced concrete frame buildings with masonry infill. The method requires only total floor area, cross-sectional dimensions of columns and masonry infill walls. It is mainly based on defining the ranking on a two – dimensional plot using column and wall ratios. Column ratio is defined as the ratio of the sum of column areas in a given direction at the base level of the structure to the total floor area. Similarly, the wall ratio is simply the ratio of the effective masonry infill wall area in a given direction at the base level to the floor area.

D. Pay

Pay **[18]** proposed a new methodology for the seismic vulnerability assessment of existing reinforced concrete buildings in Turkey. The proposed methodology was based on discriminant analysis technique and it was applied to the available seismic damage databases compiled from recent earthquakes in Turkey. Pay developed the method on the basis of the parameters that affect structural damage. The parameters included in the study were the number of stories, overhang ratio, soft story, redundancy, and square root of sum of squared moment of inertias. In the study, two parameters, overhang ratio and soft story, were found to be statically insignificant. Therefore, the statistical analysis was based on the remaining three parameters.

E. Askan

Askan developed three different stochastic approaches in order to estimate potential seismic damage to existing reinforced concrete building in Turkey **[1]**. First, damage probability matrices for each seismic zone were derived by considering the available damage databases and expert opinion. As a second methodology, Askan prposed a reliability based model, in which seismic demand and seismic capacity were taken as random variables. This model requires total floor area, cross sectional areas of columns and walls on the ground floor, an approximate estimation of the fundamental period of the structure and local soil conditions. Askan utilized a discriminant analysis technique as the third methodology in order to estimate the seismic vulnerability of reinforced concrete structures. The estimation parametes included in the study were number of stories, normalized square root of sum of squares of inertias (SRSSI), soft story, overhang, redundancy, density ratio and floor regularity factor. Finally, in order to compare the damage estimations obtained from those three methods, the results are expressed in terms of mean damage ratios and compared with each other. It is concluded that at any certain intensity level, the two empirical models, the damage probability matrices and the discriminant analysis method, gave mean damage ratios that are very close to each other. However, the reliability based model underestimated the damage rates at high intensities.

F. Turkish Method

In many instances statistical analysis based on the observed damage and significant building attributes would provide reliable and accurate results for regional assessments. Yucemen et al., Ozcebe et al Yakut et **[19]**, **[20]** alemployed the discriminant analysis technique to develop a preliminary evaluation methodology for assessing seismic vulnerability of existing low- to medium-rise RC buildings in Turkey. The main objective of the procedure is to identify the buildings that are highly vulnerable to damage. The procedure is applicable to RC frames and frame-wall structures, having up to seven stories. A survey of 477 damaged buildings affected by Duzce earthquake was carried out. This was then compiled to form a database of damaged buildings to be used for future research work. This database was employed for developing the performance score (PS) equation to determine the vulnerability of reinforced concrete building.

IX. CONCLUSION

A state-of-the-art review of the seismic vulnerability of RC structures is presented in this paper. The review does not include all the research work conducted in this field but most important and widely applied technology has been added in this review study. Based on the above discussed research work, some conclusion has been drawn by the authors and given in the following:

1. Vulnerability assessment method has been advanced with the technological development.
2. Selection of one of those models depends on the objective and reliability of the study.
3. Seismic vulnerability is a measure of seismic strength of structures.
4. All sources of uncertainty should be incorporated in all the analysis types.
5. A balance is required between the methodology and amount and types of data available for the analysis.

However, for the future needs, a combination of the above described methods incorporating the uncertainties and available data are needed. In other words, reliable vulnerability assessment method should be incorporated and accuracy can be checked with the aid of statistics.

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