

Minireview Article

A review of studies on the seismic vulnerability of structures

Abstract:

The performance-based seismic vulnerability analysis of structures is the basis for assessing the seismic reliability of structures. It is of great significance for the prediction of seismic damage of building structures, and even the establishment of seismic design codes based on reliability theory. In this paper, the structural earthquake fragility analysis methods, research status, and existing problems in this field are comprehensively reviewed. First, the structural seismic fragility analysis methods are classified, and the applicable characteristics and advantages and disadvantages of each method are summarized, and discussed the research progress in this field in detail; finally, combined with the existing problems in the field of seismic vulnerability research in China, the further research directions in the future were proposed.

Keywords: structure; seismic vulnerability analysis; reliability.

INTRODUCTION

Earthquakes are sudden-onset natural disasters with great randomness and uncertainty. In the past few decades, earthquakes have been occurring frequently around the world, and the damage caused by them has increased dramatically. Seismic vulnerability refers to the probability of various damage states occurring in the structure under the action of earthquakes of different intensities, which embodies the seismic performance of engineering structures in a probabilistic sense, describes the relationship between the intensity of ground shaking and the degree of damage to the structure from a macroscopic point of view, and has become a research hotspot in the field of earthquake engineering and structural engineering. The purpose of structural seismic vulnerability assessment is to calculate the damage probability of a structure by selecting a set of ground shaking records for a given structure type with selected damage criteria [1].

The analysis of seismic vulnerability of building structures is the basis for evaluating the seismic reliability of building structures, and the improvement of the theory of seismic vulnerability of building structures is of great significance to the seismic design of building structures, the prediction of seismic damages, the maintenance and reinforcement of building structures in the later stage and even the establishment of the seismic design code based on the theory of reliability. The paper summarizes various methods of analyzing the seismic vulnerability of structures, and discusses in detail the current research progress in this field at home and abroad.

1 Basic theory of seismic vulnerability analysis of structures

Seismic vulnerability refers to the probability of different damage states of structures and the specific damage state of structures under the action of different ground motion intensities (such as peak ground acceleration, spectral acceleration or spectral displacement). The conditional probability of the structure can predict the probability of damage at all levels of the structure.

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Earthquake vulnerability analysis can be aimed at one or a type of building structure in a certain area, and can also be aimed at building groups in a certain area. The analysis results are usually expressed in terms of a vulnerability probability matrix or vulnerability. It is represented by a damage function. It was originally used for seismic risk assessment of nuclear power plants, and later it was gradually developed and applied to earthquake damage prediction of various civil infrastructure and engineering structures. The vulnerability analysis is a probability-based structural seismic performance assessment method. Its vulnerability analysis results are usually described by a vulnerability curve, and the vulnerability curve which usually takes the ground motion intensity parameter as an independent variable, and on the basis of selecting the damage index and formulating the limit value of the damage state, the structural earthquake requirement reaches (what?), or the probability of exceeding a certain damage state limit is the dependent variable. The probability formula, when the structure reaches a certain damage state under a certain earthquake intensity, can be expressed as:

$$P_f = P[DI \geq C | IM] \quad (1-1)$$

In the formula, IM is the ground motion parameter; C is the structural capacity; DI is the damage index, corresponding to the structural requirements.

In seismic vulnerability analysis, the theoretical analysis method is a mature technology with a wide range of applications and is suitable for analyzing complex special structures. In this paper, the silo structure is a high-rise special structure, which is suitable to be analyzed by the theoretical seismic vulnerability analysis method and adopts the capacity to demand ratio model. It has been mentioned that the expression for a structure to reach a certain damage state under a certain seismic intensity is shown in the above equation, and the relationship between the ground vibration parameters and the structural demand parameter (EDP) samples is satisfied as follows[2]:

$$EDP = \alpha(IM)^\beta \quad (1-2)$$

Assuming that the median value and the ground-shaking parameters obey an exponential relationship then:

$$\hat{D} = \alpha(IM)^\beta \quad (1-3)$$

Taking the logarithm of both sides of the above equation:

$$\ln \hat{D} = a + b(IM) \quad (1-4)$$

The probability function D of the structural response is represented by a lognormal distribution function with the statistical parameter:

$$\lambda_d = \ln \hat{D} \quad (1-5)$$

$$\beta_d = \sqrt{\frac{1}{N-2} \sum_{i=1}^N (\ln D - \ln \hat{D})^2} \quad (1-6)$$

where λ_d is the logarithmic mean of D and β_d is the logarithmic standard deviation of D.

Define the probability function of the structural capacity parameter as C, assuming that it can also be represented by a lognormal distribution function and defined by λ_c and β_c .

In Eq. (1-4), $a = \ln \alpha$ and $b = \beta$, where a and b are obtained by statistical regression of data from

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a large number of incremental dynamic analyses of the structure, then the values of α and β are easily derived.

The probability that the structural response D reaches or exceeds a certain damage state limit C under different intensity of ground shaking forms a susceptibility curve. This probability can be expressed by the following equation:

$$P_f = P(C/D < 1) \rightarrow P_f = P(C - D < 0) \quad (1-7)$$

Let $Z = C - D$, since C , and D are independent random variables, and they all obey the normal distribution, then $Z = C - D$ also obey the normal distribution, and its average value $\lambda_z = \lambda_c - \lambda_d$, standard deviation $\beta_z = (\beta_c^2 + \beta_d^2)^{1/2}$.

The failure probability of a structure can be directly expressed by the probability that $Z < 0$, i.e.:

$$P_f = P(Z < 0) = \int_{-\infty}^0 f(Z) dZ = \int_{-\infty}^0 \frac{1}{\beta_z \sqrt{2\pi}} \exp\left[-\frac{1}{2} \left(\frac{Z - \lambda_z}{\beta_z}\right)^2\right] dZ \quad (1-8)$$

For ease of tabulation, $N(\lambda_z, \beta_z)$ is reduced to the standard normal variable $N(0, 1)$. Let $Z = \lambda_z + t\beta_z < 0$, then $t < -\lambda_z/\beta_z$. The standard normalization transformation process is as follows:

$$P_f = P\left(t < -\frac{\lambda_z}{\beta_z}\right) = \int_{-\infty}^{-\lambda_z/\beta_z} \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{t^2}{2}\right] dZ = \Phi\left(-\frac{\lambda_z}{\beta_z}\right) = \Phi\left(-\frac{\lambda_c - \lambda_d}{\sqrt{\beta_c^2 + \beta_d^2}}\right) \quad (1-9)$$

The probability of failure at a given stage is derived:

$$P_f = \Phi\left(-\frac{\ln(\hat{C}/\hat{D})}{\sqrt{\beta_c^2 + \beta_d^2}}\right) = \Phi\left(\frac{\ln(\hat{D}/\hat{C})}{\sqrt{\beta_c^2 + \beta_d^2}}\right) \quad (1-10)$$

2 Structural seismic vulnerability analysis methods

At present, the main methods applied to the seismic vulnerability analysis of structures are: the historical seismic damage statistical method, combined empirical and theoretical method, fuzzy comparison method, structural calculation method and dynamic analysis method, etc[3].

2.1 Empirical statistical analysis method

The empirical statistical method is to analyze the main seismic damage states of the building structure based on the seismic design theory of the building structure according to the data of the past earthquake damage, and then summarize the commonalities and characteristics of each type of damage. Through the statistical regression of the weights and influencing parties of each influencing factor, the corresponding vulnerability research method is obtained [4]. This method mainly adopts mathematical and statistical methods to find out the main damage-causing factors and the corresponding influence weight coefficients from a large number of historical seismic data, so as to accurately judge and predict the weak links and damage probability of the structure under the action of earthquakes. Due to the seismic data of the structure and the empirical limitations of the engineering designer, the empirical and statistical analysis method has a large limitation [5].

2.2 Theoretical analysis method

The seismic vulnerability analysis of the structure needs to obtain the relationship between the seismic response of the structure and the ground shaking intensity of the region, and then

predict the degree of earthquake damage. This is usually done by two methods: one is a statistical analysis based on earthquake damage reports, and the other is a numerical simulation with finite elements. The theoretical analysis method requires the establishment of a reasonable mechanical model for the structural object under study, and the dynamic time course analysis of the numerical model based on the seismic design theory, so as to obtain the whole process of the response of the structure under the effect of earthquakes of different intensities [6].

3 Structural seismic susceptibility curve

The form of susceptibility curve to study the seismic susceptibility of structures originated in the early 1970s from the probabilistic seismic risk assessment of nuclear power plants, in the form of a probability distribution function to represent the seismic performance of mechanical and structural systems, assess the seismic reliability of the [system](#), and predict the probability of structural damage. The seismic vulnerability curve graphically represents the seismic hazard to predict the probability of damage to a certain type of building structure under earthquake-induced ground motion. The seismic susceptibility curve describes the continuity of the probability that the seismic response of a structure will exceed a certain limit state when subjected to different intensities of seismic excitation [7].

Three parameters are involved in obtaining the seismic susceptibility curve of a structure: the ground shaking demand parameter (EDP) of the structure, the ground shaking intensity parameter, and the ultimate state point of the structure. The damage state of the structure is closely related to the intensity of seismic action, and a reasonable selection of parameter indicators can take into account a series of stochastic factors such as the structure's own performance and ground shaking parameters, and predict the degree of damage by calculating the exceeding probability of the structure to reach a specific state [8].

The seismic susceptibility curves are mainly obtained by three methods, namely, the frequency statistics method of exceeding the damage state, the linear fitting method of the probabilistic demand model, and the curve fitting method of the [capacity-to-demand](#) ratio model. It is found that the frequency counting method beyond the damage state is prone to large systematic errors, while the linear fitting method of the direct regression probability demand model and the curve fitting method of the capacity-to-demand ratio model are more accurate in the calculation results. Since curve fitting can reduce the dispersion of regression, it is more reasonable to choose the curve fitting method of the capacity-to-demand ratio model to obtain the seismic vulnerability curves of structures [9].

4 Seismic vulnerability analysis based on the incremental dynamic analysis (IDA) method

The incremental dynamic analysis (IDA) method, as an analytical method to evaluate the seismic capacity of the structure when it collapses as a whole, can examine the seismic demand capacity and the overall collapse resistance of the structure under the action of earthquakes of different intensity levels, and realize the analysis of the entire response course of the structure from linear elasticity to elasto-plasticity and then to the collapse of the structure as a whole, which can then comprehensively evaluate the seismic performance of the structure, and is therefore in the nonlinear analysis of the structure under the action of earthquakes. Therefore, it is widely used

in the nonlinear analysis of structures under earthquake[10].

The IDA method [11] is based on the input of one or more ground shaking records to the structural model, each of which is "amplified" to a different ground shaking intensity by a series of scaling coefficients, and then the structure is analyzed under the excitation of this set of "amplified" ground shaking records. Then the structure is analyzed under the excitation of this set of "amplified" ground shaking records. When a series of structural elastic-plastic seismic responses are obtained, one or more relationship curves between the damage index DM_i and the ground shaking intensity index IM_i are generated, i.e., IDA curves are generated. Finally, the overall seismic performance of the structure is evaluated by the disposition points on these IDA curves. The IDA method can select multiple seismic waves for analysis, which makes up for the single and discrete nature of the traditional dynamic time-course analysis. Meanwhile, the IDA method provides a data-base for the seismic vulnerability analysis of structures.

5 Flow of seismic vulnerability analysis based on IDA

(1) Select multiple ground shaking records according to relevant principles and determine the ground shaking intensity parameters. The number of ground shocks is generally between 10-20.

(2) Adjust each ground shock to peak ground acceleration (PGA).

(3) Apply the amplitude-tuned ground shaking to the silo finite element model for IDA analysis respectively, and obtain the seismic demand response of the structure.

(4) Select the appropriate damage index and classify the damage level, respectively, the ratio of seismic demand to each damage index, take the logarithm of these values with the corresponding seismic intensity, and then plot them in the coordinate system to obtain a series of scatter plots, and then fit the quadratic curve to these scatters to obtain the IDA curves of the capacity-demand ratio for each damage state [12].

(5) Use the quadratic polynomial regression of the least squares method to obtain the regression coefficients a, b, c, according to the following equations (5-1, 5-2) to obtain the mean λ and the standard deviation σ , and use the equation (5-3) to calculate the probability of exceeding the damage in the limit state.

$$\lambda = a(\ln(PGA))^2 + b\ln(PGA) + c \quad (5-1)$$

$$\sigma = \sqrt{\frac{S_r}{n-2}} \quad (5-2)$$

$$P_f = P\left[\frac{S_d}{S_c} \geq 1\right] = 1 - \phi\left[\frac{\ln(1) - \lambda}{\sigma}\right] = \phi\left[\frac{\lambda}{\sigma}\right] \quad (5-3)$$

Where, a, b, c are the coefficients obtained from the regression statistical analysis; S_r is the residual variance sum of each discrete point for the regression curve; S_d and S_c are the structural demand parameter and the capacity parameter, respectively; n is the number of discrete points.

(6) According to the above calculation results, the exceeding probability of exceeding a specific damage state under different seismic intensities is obtained, and the seismic susceptibility curve of the silo structure is plotted, and susceptibility analysis is carried out [11].

6 Conclusion

Over the past two decades, with the gradual deepening of the seismic vulnerability of building structures, China has also made certain achievements in the theory of seismic vulnerability, but from the current point of view, the seismic vulnerability of building structures in China is relatively independent of each other, and has not yet been able to systematically form the practical significance of the engineering and the value of a wide range of application of the results of the research [13].

On the basis of the existing seismic vulnerability analysis theories, it is necessary to consider multiple uncertainties in vulnerability analysis and the transfer linkage effect between them, to quantify the input parameters of ground shaking, the damage index of performance level, and the probability distribution model of vulnerability, and to establish a set of more effective seismic vulnerability analysis theories, which can be used to directly guide the seismic design of building structures based on the performance, and it requires the unremitting efforts of experts and scholars. The establishment of a more effective seismic vulnerability analysis theory to directly guide the performance-based seismic design of building structures requires the unremitting efforts of experts and scholars.

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