Opinion Article

A Review of Structural Seismic Vulnerability Research Based on Seismic Time History Method

Abstract ：This paper reviews the application of seismic time-history analysis in the seismic design and assessment of structures, emphasizing its significance in seismic vulnerability analysis. Traditional seismic design methods such as static analysis and response spectrum analysis are widely used for preliminary assessments but have limitations for complex structures and unique forms. While time-history analysis is suitable for complex structures, its computational demands often result in low efficiency. In contrast, seismic time-history analysis synthesizes multiple seismic time histories to conduct nonlinear dynamic analysis of structures, providing a more accurate simulation of their response under earthquake loading. This method is particularly suitable for evaluating the seismic performance of complex structures and significantly improves efficiency compared to Incremental Dynamic Analysis (IDA), while ensuring accuracy and reliability. Additionally, this paper introduces the fundamental theory of seismic vulnerability analysis and its application in structural engineering, highlighting the important role and broad prospects of seismic time-history analysis in earthquake engineering. In summary, seismic time-history analysis, as an emerging method in structural dynamics analysis, not only enhances the precision and reliability of engineering design but also provides robust technical tools and methodologies for assessing the seismic performance of engineering structures.

Keywords: Seismic time-history analysis, Nonlinear dynamic analysis, Seismic vulnerability

1 Introduction

Current seismic design methods for building structures primarily employ force-based analysis methods, including equivalent static analysis and response spectrum analysis, which are typically used for preliminary assessments of structural seismic performance. To accurately verify the dynamic response of structures under seismic action, Incremental Dynamic Analysis (IDA) is required [1]. The traditional static Pushover method has limitations when dealing with complex structures such as bridges or buildings with unique forms. It fails to fully account for the randomness of earthquake ground motions and the dynamic characteristics of structures, hence it is not suitable for precise analysis in these complex scenarios. In contrast, IDA performs nonlinear calculations using multiple seismic time histories, allowing for a more comprehensive depiction of the true response of complex structures under different seismic events. However, IDA requires simultaneous handling of multiple seismic time histories, leading to high computational costs and inefficient analysis. In summary, while IDA provides crucial dynamic analysis tools for evaluating the seismic performance of complex structures, its high computational costs and time-consuming nature remain significant challenges in practical engineering applications.

2 Research Status and Development Trends

Estekanchi et al. [2] first proposed the Endurance Time Method (ETM) for seismic time-history analysis and applied it to study the seismic performance of steel frame structures of varying heights. Their research not only covered key indicators such as damage indices and peak displacements but also validated that the ETM analysis results can reasonably and accurately predict the average response of structures. The ETM method employs artificial seismic acceleration time-history curves where the amplitude gradually increases over time. Due to this characteristic, the ETM method can comprehensively simulate the entire process of structures from intact to collapse with a single time-history analysis. This study introduced a new dynamic analysis method to the field of structural engineering, particularly suitable for seismic performance analysis and evaluation of complex or special-shaped structures.Valamanesh et al. [3] studied the seismic performance of three-dimensional steel frames with different numbers of stories under bi-directional seismic inputs, demonstrating the applicability of the ETM to such structures for seismic analysis. The study showed that as the number of stories increases, predictions by traditional response spectrum methods and static methods deviate significantly from actual responses, whereas the ETM method can reasonably approximate the behavior of structures.Hariri-Ardebili et al. [4] investigated the application of the ETM in determining the engineering parameters of the coupled bending dam-reservoir-foundation system under seismic action. The results indicated that this method accurately predicts the failure modes of dams under seismic conditions. These studies provide substantial support for the application of the ETM in various types of structures and engineering systems, emphasizing its importance in providing accurate and reliable analyses under complex seismic environments.Bai J L [5] validated the effectiveness and feasibility of seismic time-history curves in predicting seismic response and failure modes of elastic-plastic SDOF systems and concrete frame structures. The study demonstrated that the seismic time-history method has significant advantages in evaluating the seismic performance of large-scale structures such as ultra-high-rise and long-span buildings.Shen Y [6] utilized the efficiency of the seismic time-history method in bridge collision analysis under seismic actions, validating its applicability. Based on this, a seismic design method for bridges considering collision effects was proposed.Xu S T [7] proposed a damage index analysis method based on the seismic time-history method and established an evaluation index, the area difference of response spectrum, which can macroscopically assess dam damage. This was verified through seismic time-history analysis and harmonic response analysis of the Koyna concrete dam, demonstrating the reliability of this index.Huang J D [8] evaluated the seismic performance of bridges under longitudinal seismic actions using seismic time-history analysis and compared the results with the Incremental Dynamic Analysis (IDA) under far-field and near-field seismic actions. The study showed that seismic time-history analysis method exhibits good effectiveness and reliability in evaluating the seismic performance of ultra-large-span corrugated steel web continuous rigid-frame bridges.Li H J [9] discussed the influence of wave effects on the seismic response of bridges using the seismic time-history method combined with displacement loading method. The study showed that as a new evaluation method, the seismic time-history method has significant advantages in analyzing the seismic response and failure process of large and complex bridge structures.Feng Z C [10] proposed a seismic performance evaluation method for rib arch culverts based on the seismic time-history method and established a corresponding vulnerability analysis system. This included vulnerability curves for culvert rib columns and arch ribs, and a system vulnerability curve was drawn using the limit estimation method, forming a comprehensive vulnerability analysis system for culverts.

In summary, the seismic time-history method effectively reflects the entire process of structures from elastic to plastic until failure, and measures the seismic capacity of structures by the time they can withstand seismic activity. It has good reliability and accuracy, effectively avoiding the problem of low computational efficiency in Incremental Dynamic Analysis (IDA). This method is particularly suitable for engineering projects that require accurate prediction of dynamic structural responses and consideration of complex structural characteristics. It holds an important position and has extensive applications in earthquake engineering.

Structural seismic vulnerability analysis quantitatively describes the seismic performance of engineering structures at given levels of seismic intensity (IM), where the seismic response (EDP) of structures exceeds specified limit states (DM). It provides a probabilistic perspective to macroscopically reflect the relationship between seismic intensity and structural damage, thereby providing necessary basis for identifying structural weaknesses, seismic strengthening, risk assessment, and other research.

Xu Q et al. [11] conducted vulnerability analysis of Baihetan Arch Dam using the seismic time-history method, selecting maximum transverse crack width, damage volume ratio, and downstream relative displacement as indicators to probabilistically reveal the failure states of the arch dam-foundation system under different seismic intensities. Yuan B et al. [12] verified the effectiveness of reinforcing steel cage measures using the seismic time-history method, demonstrating that watchtowers need structural stiffening measures to enhance overall rigidity.Yu Q et al. [13] established a finite element model library for large-span overhead steel truss arch bridges using OpenSEES, conducting time-history analysis of bridge models using the seismic time-history method and incremental dynamic analysis method, obtaining vulnerability curves of typical components, and verifying the applicability and effectiveness of the seismic time-history method.Chen D H et al. [14] established the relationship between limit states and structural performance indicators based on the seismic time-history analysis method, selecting dam damage volume ratio, upstream and downstream relative displacements of the dam crest and abutment, and arch beam transverse crack width as structural performance indicators, and drew corresponding vulnerability curves.

3 Basic Theory of Seismic Time History Analysis

In seismic time history analysis, the collapse resistance of different structures under earthquake actions can be evaluated using seismic time history curves[15]. These curves depict the seismic capacity of structures under varying earthquake intensities, indicating the duration of seismic motion that a structure can withstand. The ETA method synthesizes seismic acceleration time histories by fitting target response spectra and utilizes them as earthquake inputs[16]. This approach takes advantage of the characteristic that earthquake response spectra approximate a linear relationship over different time intervals, thereby simulating the input conditions of the same earthquake after amplitude modulation [17].

Seismic time history analysis requires that within a seismic motion time history, the magnitude of the target acceleration response spectrum is linearly related to the duration ttt of that time history.

$$S_{aT}(T,t) = \frac{t}{t_{Target}} S_{aC}(T) \quad （1）$$

In the equation: t_{Target} represents the target time point, $S_{aC}(T)$ is the pre-defined response spectrum (typically a code spectrum or spectrum generated by earthquakes), T is the structural natural period, t is any time point, $S_{aT}(T,t)$ is the target acceleration response spectrum at time t.According to the above formula, under the given conditions of t_{Target} and $S_{aC}(T)$, the acceleration spectrum corresponding to any time point from zero time to an arbitrary time point linearly corresponds to the acceleration spectrum corresponding to the total time.

There exists a certain conversion relationship between displacement response spectrum and acceleration response spectrum. The target displacement response spectrum can be expressed as:

$$S_{uT}(T,t) = \frac{t}{t_{Target}} S_{aC}(T) \times \frac{T^2}{4\pi^2} \quad （2）$$

In the equation, $S_{uT}(T,t)$ represents the target displacement response spectrum.

Clearly, achieving the requirements of the seismic time history curve at every time point with a certain precision is difficult. Therefore, the problem needs to be transformed into an unconstrained variable optimization problem, namely:

$$minF(\ddot{u}_g) = \int_0^{T_{max}} \int_0^{t_{max}} \{[S_a(T,t) - S_{aT}(T,t)]^2 + \alpha[S_u(T,t) - S_{uT}(T,t)]^2\} dtdT \quad （3）$$

In the equation, $\ddot{u}_g$ represents the synthesized seismic time history curve to be generated, α is the weighting coefficient of the displacement spectrum, and $S_a(T,t)$ and $S_u(T,t)$ respectively denote the acceleration response spectrum and displacement response spectrum of $\ddot{u}_g$ at time t.

4 Seismic Vulnerability Analysis Theory

The term "vulnerability" was initially used to describe the susceptibility of military aircraft or ship hulls to physical collisions in the military domain. It later found extensive application in the field of architecture and became a pivotal area of vulnerability research[18]. Currently, the Performance-Based Earthquake Engineering (PBEE) framework proposed by the Pacific Earthquake Engineering Research Center

(PEER) in the United States is one of the most commonly used seismic design methods[19].

The PBEE framework divides the assessment of seismic performance of structures into four parts: probabilistic seismic hazard analysis, probabilistic seismic demand analysis, probabilistic seismic capacity analysis, and probabilistic seismic loss analysis. Structural seismic vulnerability analysis, which evaluates the probability that the seismic response (EDP) of a structure exceeds predefined limit states (DM) at a given seismic intensity level (IM), is a crucial component of this framework[20].

Vulnerability analysis quantifies the seismic performance of engineering structures from a probabilistic perspective, macroscopically reflecting the relationship between seismic intensity and the degree of structural damage, thereby providing important foundations for identifying vulnerable aspects of structures, conducting seismic retrofitting, and performing risk assessment[21].

The key to structural seismic vulnerability research lies in the formation of seismic vulnerability curves. Based on the source of data, structural seismic vulnerability analysis can be intuitively classified into two categories:

Empirical Vulnerability Studies:These studies typically rely on historical earthquake damage data and structural damage records obtained through observations over time. They select the primary influencing factors of damage and establish damage probability matrices or vulnerability curves within a specific region through statistical analysis.

Theoretical Vulnerability Studies:These studies derive vulnerability curves through computational analysis of structural seismic responses, effectively addressing the limitations of empirical vulnerability analysis [22].

5 Seismic Vulnerability Analysis Based on Seismic Time History Method

The seismic vulnerability of a structure describes the probability that under specific seismic intensity, the seismic demand on the structure reaches or exceeds a certain damage limit state, indicating the probability of the structure undergoing a specific form of damage. Therefore, the seismic vulnerability function can be expressed in the form of conditional failure probability.

$$P_f = P(D \geq C \mid IM = x) \tag{4}$$

In the equation:P_f represents the failure probability.D denotes the seismic demand on the structure.C represents the seismic capacity of the structure.IM stands for the seismic intensity indicator.

Assuming that the seismic demand D and seismic capacity C of the structure both follow lognormal distributions, the seismic vulnerability function is expressed as:

$$P_f = P(D \geq C \mid IM = x) = P\left(\frac{S_d}{S_c} \geq 1\right) = 1 - \Phi\left[\frac{ln(1) - \lambda}{\sigma}\right] = 1 - \Phi\left[\frac{\lambda}{\sigma}\right] \tag{5}$$

In the equation: S_d represents the seismic demand on the structure. S_c denotes the seismic capacity of the structure. λ is the regression mean. σ stands for the standard deviation.

Under different seismic actions S_a, a series of seismic response data is collected. The average seismic response for each S_a is computed, and these averages are logarithmically transformed relative to a certain damage index. The logarithmically transformed data is plotted against the logarithm of seismic intensity S_a on the same coordinate system. By fitting a curve to these data points, the logarithmic curve of the seismic capacity ratio for the structure is obtained.

$$\lambda = a[ln(S_a)]^2 + b\,ln(S_a) + c \quad （6）$$

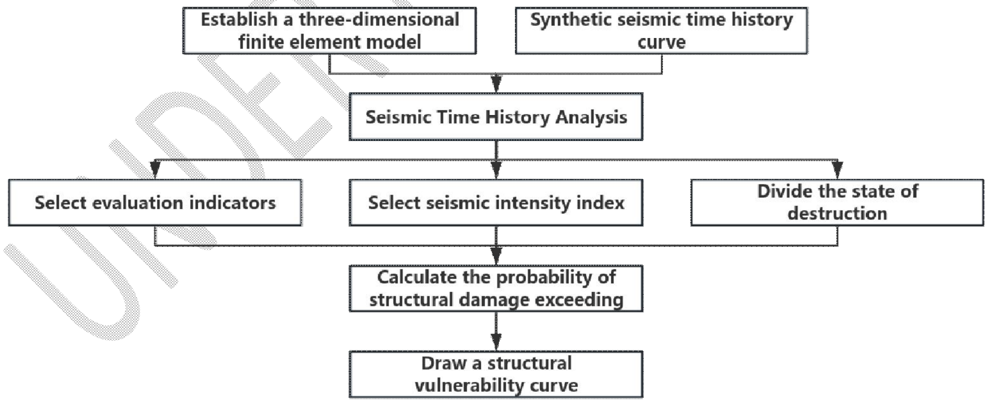
$$\sigma = \sqrt{\frac{S_r}{(n-2)}} \quad （7）$$

In the equation: a、b、c is the regression coefficient. S_r represents the sum of squares of residuals relative to the fitted regression curve. The standard deviation σ can be calculated using this sum of squares of residuals.

When conducting seismic fragility analysis using the seismic time-history method, it is necessary to convert the seismic duration t into spectral acceleration S_a.

$$S_a(T) = S_1 \times S_{aS}(T) = \frac{t}{t_{Target}} S_{aC}(T) \quad （8）$$

Based on the above discussion, this paper proposes a seismic fragility analysis process based on the seismic time-history method:



6 Conclusion

The core idea of the seismic time-history method is to synthesize a series of acceleration time-history curves that increase in intensity with duration based on predefined target response spectra. Nonlinear dynamic time-history analysis is then conducted on structures using these curves. This method effectively captures the entire process of a structure's response from elastic to plastic behavior and ultimately to failure. It also allows for comparison of the seismic resistance capabilities of different structures, reflecting the duration of seismic motion that a structure can withstand.

The seismic time-history method requires only one seismic acceleration time-history input to accurately predict the maximum dynamic response of a structure, overcoming the efficiency issues associated with Incremental Dynamic Analysis (IDA). In summary, the seismic time-history method enables rapid prediction of seismic response and damage, effectively assesses the seismic performance of structures, and offers high computational efficiency. Therefore, it represents a novel and effective approach for seismic analysis of structures, characterized by its accuracy and reliability.

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