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

Yao Li [a*]

[a] *School of Civil and Transportation, North China University of Water Resources and Electric Power, Zhengzhou, Henan 450045, China.*

Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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ABSTRACT

This paper reviews the application of endurance time method in seismic design and evaluation of structures and its importance in seismic vulnerability analysis. The traditional methods such as static elastoplastic method and response spectrum method have low accuracy in the face of complex structures and structural nonlinear effects, while the incremental dynamic time history method has high accuracy but low efficiency. In contrast, endurance time method synthesizes multiple endurance time curves for nonlinear dynamic analysis of structures, which can more accurately simulate the real response of structures under earthquake action, and is especially suitable for seismic performance evaluation of complex structures. This method can significantly improve work efficiency while ensuring the accuracy and reliability of the results. At the same time, this paper also introduces the application of endurance time method in structural seismic vulnerability analysis and broad prospects. In summary, endurance time method, as an emerging

**Corresponding author: E-mail: leeyao.ncwu@foxmail.com;*

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structural dynamic analysis method, not only improves the accuracy and reliability of structural design, but also provides powerful technical tools and methodological support for seismic performance assessment and seismic vulnerability analysis of engineering structures.

Keywords: Endurance time method; seismic performance; seismic fragility.

1. INTRODUCTION

At present, the research methods of seismic performance of building structures mainly include static elastoplastic analysis, response spectrum analysis and incremental dynamic time history analysis. The traditional static elastoplastic analysis method is relatively simple, easy to understand and implement, and can provide rough estimation of structural strength and displacement, but the accuracy is poor in the face of complex structures with special forms, and the influence of ground motion and the dynamic characteristics of structures cannot be considered. Compared with static elastoplastic analysis, response spectrum analysis is more accurate and can obtain the maximum response of complex multi-degree-of-freedom structures at different frequencies, but it is less accurate to analyze complex structures with strong seismic nonlinear effect. Static elastoplastic analysis can effectively deal with nonlinear effects and accurately simulate the real response of structures under different seismic actions, but it requires a lot of computing resources and time, and the calculation efficiency is low. In summary, although the application of the above three methods in the study of structural seismic performance has been very mature, how to ensure the accurate simulation and calculation efficiency of nonlinear effects of complex structures is still the main challenge in practical engineering [1].

2. ENDURANCE TIME METHOD RESEARCH STATUS

Estekanchi et al. [2] proposed the endurance time method for the first time and applied it to study the seismic performance of steel frame structures with different heights. The research not only covers the key indexes such as damage index and vertex displacement, but also verifies that the endurance time analysis results can reasonably and accurately predict the average response of the structure. The endurance time method adopts the time-history curve of human construction site vibration, as shown in Fig. 1. Its acceleration amplitude gradually increases with time. Due to this characteristic, the endurance time method can comprehensively simulate the whole process from intact structure to collapse through a time-history analysis. This research introduces a new dynamic analysis method in the field of structural engineering, which is especially suitable for the seismic performance analysis and evaluation of complex structures or special structures.

Valamanesh et al. [3] studied the seismic performance of three-dimensional steel frames with different layers under two-way seismic input, and found that the endurance time method is suitable for seismic analysis of such structures. The results show that with the increase of the number of structural layers, the prediction of the traditional response spectrum method and the static method is quite different from the actual reaction, but the endurance time method can reasonably predict the behavior of the structure. Hariri-Ardebili et al. [4] studied the application of endurance time method in determining the engineering parameters of the coupling of flexural dam-reservoir-foundation system under earthquake action. The results show that this method can accurately predict the failure mode of the dam under the action of earthquake. These studies provide substantial support for the application of the endurance time method in different types of structures and engineering systems, and emphasize the importance of providing accurate and reliable analysis in complex ground motion environments. Bai Jiulin [5] verified the effectiveness and feasibility of endurance time curve in predicting structural seismic response and seismic failure mode through seismic response analysis of elastoplastic Single-Degree-Of-Freedom system and concrete frame structure. The results show that the endurance time method has a significant advantage in the seismic performance evaluation of major engineering structures such as super tall buildings and long spans. Shen Yu [6] made use of the high efficiency of the endurance time method and applied it to the collision analysis of Bridges under earthquake action to verify the applicability of the endurance time method. On this basis, he proposed an aseismic design method for Bridges considering the impact of collisions. Xu Shutong [7] proposed a damage index analysis method based on endurance time method, and established an evaluation index - response spectrum difference area, which can be used to assess the damage situation of dam body in a macroscopic way. The reliability of this index was verified by analyzing the endurance time and harmonious response of Koyna concrete dam. Huang Jiadong [8] evaluated the endurance performance of the bridge under longitudinal seismic action through endurance time analysis, and compared the results with the incremental dynamic time-history analysis method under far-field and near-field earthquakes. The results show that the endurance time method is effective and reliable in evaluating the seismic performance of ultra-long continuous rigid frame Bridges with corrugated steel webs. Li Hongjian [9] discussed the influence of traveling wave effect on seismic response of Bridges through endurance time method combined with displacement loading method. The results show that endurance time method, as a new evaluation method, has a significant advantage in the analysis of seismic response and failure process of large complex bridge structures.

In summary, endurance time method can effectively reflect the whole process of the structure from elasticity to plasticity to failure, and can measure the seismic capacity of the structure by the ground motion time that the structure can withstand, with good reliability and accuracy, and effectively avoid the problem of low calculation efficiency of incremental dynamic time-history analysis method. It is especially suitable for the engineering which needs to accurately predict the dynamic response of structure and consider the characteristics of complex structure. This method has an important position and wide application in earthquake engineering.

3. RESEARCH STATUS OF VULNERABILITY BASED ON ENDURANCE TIME METHOD

The seismic vulnerability analysis of a structure can represent the probability that the seismic response of a structure exceeds the specified limit state at a given level of ground motion intensity. It quantitatively describes the seismic performance of engineering structures from the perspective of probability, and reflects the relationship between the intensity of ground motion and the degree of structural damage. It provides the necessary basis for determining the weak links of structures, seismic reinforcement and risk assessment. The structural vulnerability analysis based on endurance time has high accuracy and efficiency, and a reliable vulnerability curve can be obtained with only a small amount of endurance time analysis results.

Feng Zhichao [10] proposed a seismic performance evaluation method of ribbed arch aqueduct based on endurance time method, and established a corresponding vulnerability analysis system according to the principle of vulnerability analysis. The vulnerability curves of ribbed column and arch rib of aqueduct were obtained through endurance time analysis. Combined with the limit estimation method, the vulnerability curve of the system is drawn, and a relatively comprehensive vulnerability analysis system of aqueduct is formed. Xu Qiang et al. [11] used the endurance time method to analyze the

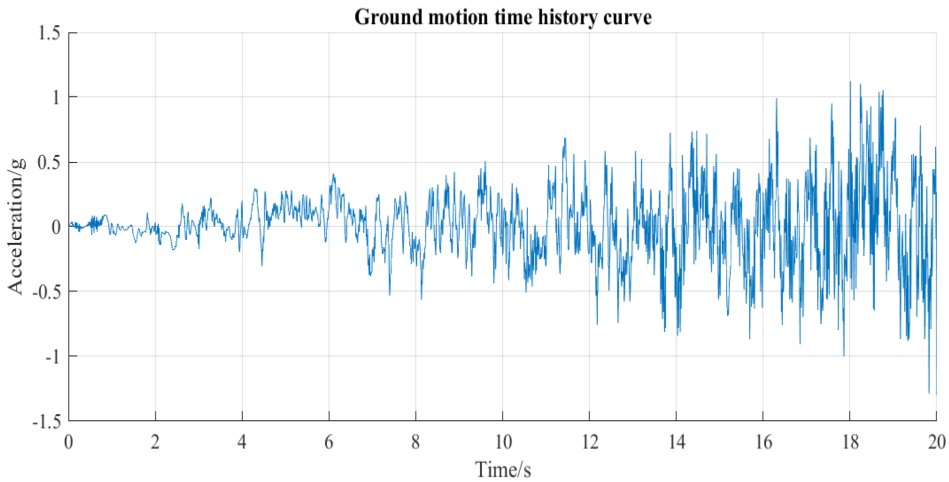

Fig. 1. Seismic time-history acceleration curve

vulnerability of Baihetan arch dam, and selected the maximum transverse crack opening, damage volume ratio and relative displacement along the river as indicators to reveal the failure state of the arch dam-foundation system under different ground motion intensity from a probability perspective. Yuan Bo et al. [12] verified the effectiveness of reinforcement measures with steel cage by using endurance time method, and the research results showed that the Diaolou needed reinforcement measures to improve the overall stiffness of the structure. Yu Qi et al. [13] used OpenSEES to establish a finite element model sample library of long-span upbearing steel truss-arch Bridges. The endurance time method and incremental dynamic analysis method were used to conduct time-history analysis on the bridge models, and the vulnerability curves of typical components were obtained, which verified the applicability and effectiveness of the seismic time-history method. Based on the endurance time method, Chen Hongdeng et al. [14] selected the damage volume ratio of the dam body, the relative displacement of the dam top and dam heel along the river and the transverse joint opening of the arch girder as the structural performance indexes, established the relationship between the limit state and the structural performance indexes, and drew the corresponding vulnerability curve.

4. ENDURANCE TIME METHOD BASIC THEORY

In endurance time analysis, the collapse resistance of different structures under earthquake action can be evaluated by the endurance time curve [15]. This curve reflects the endurance of the structure under different earthquake intensities, that is, the time that the structure can withstand the ground motion. The endurance time method synthesizes the endurance time by fitting the target response spectrum and takes it as the seismic input [16]. This method uses the characteristic that the response spectrum of ground motion in different time periods is approximately linear to simulate the input condition of the same ground motion after amplitude modulation [17]. endurance time method requires that in a certain period of ground motion, the target acceleration response spectrum is linearly related to the duration t of the period:

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

In the equation: t_{Target} represents the target time point, $S_{aC}(T)$ is the pre-defined response spectrum, 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, given the premise of t_{Target} and $S_{aC}(T)$, the acceleration spectrum corresponding to the endurance time curve from zero time to any time has a linear relationship with that corresponding to the total time history.

The displacement response spectrum has a certain conversion relationship with the acceleration response spectrum, and the target displacement response spectrum can be expressed as:

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

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

Obviously, it is difficult to meet the requirement of endurance time curve at every time point with a certain precision, so this problem should be transformed into an optimization problem with unconstrained variables, namely:

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

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.

5. VULNERABILITY ANALYSIS THEORY BASED ON ENDURANCE TIME METHOD

The term "vulnerability" was originally used to describe the vulnerability of an aircraft or hull to a physical collision in the military field, and has since been widely extended to the construction field and has become an important direction of vulnerability research [18]. At present, Performance-Based Earthquake Engineering proposed by Pacific Earthquake Engineering Research Center is one of the most commonly used seismic design methods [19].

The performance-based Earthquake Engineering framework divides the seismic Performance evaluation of structures into four parts: probabilistic seismic risk analysis, probabilistic seismic demand analysis, probabilistic seismic capability analysis and probabilistic earthquake loss analysis. Seismic Fragility Analysis is an important part of this work, which evaluates the probability that the seismic response (EDP) of the structure exceeds the specified limit state (DM) at a given level of ground motion intensity (IM) [20].

IM is an index that describes the intensity of ground motion. Common indexes include earthquake acceleration, velocity, displacement, etc. EDP describes the engineering demand or response characteristics of a structure under the action of an earthquake. It is a quantification of the structural response. Common indicators include structural displacement, deformation, internal force, acceleration, etc. DM is used to quantify the damage degree of structures or buildings under the action of earthquakes. Common indicators include the failure grade of structures, crack width, displacement, loss of bearing capacity, etc [21].

Vulnerability analysis quantifies the seismic performance of engineering structures from the perspective of probability, and reflects the relationship between ground motion intensity and structural damage degree in a macroscopic way, providing an important basis for determining the vulnerable links of structures, seismic reinforcement and risk assessment [22].

This paper proposes the vulnerability analysis process based on endurance time method as shown in Fig. 2.

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: $\mathrm{P_f}$ 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.

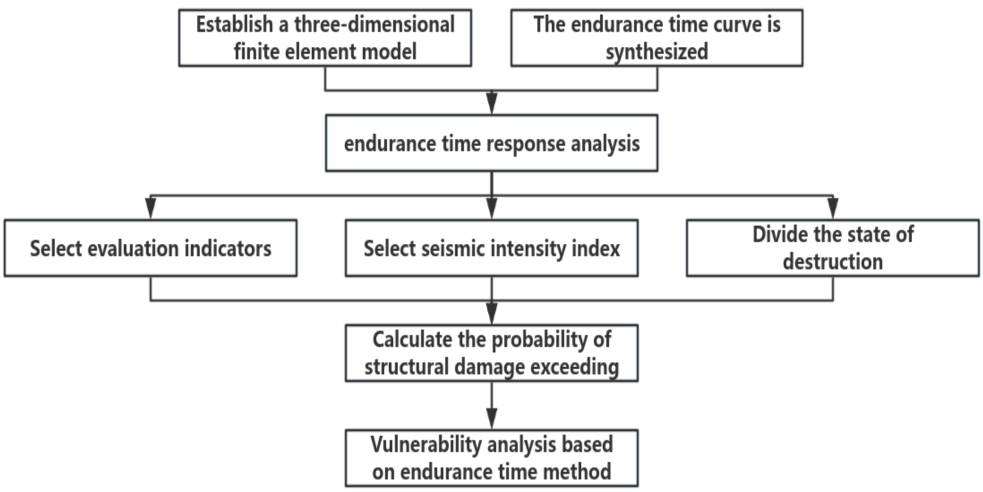

Fig. 2. Flowchart of vulnerability analysis based on endurance time method

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 the endurance time method is used to analyze the seismic vulnerability of the structure, the endurance time t needs to be converted into spectral acceleration S_a:

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

6. CONCLUSION

In this paper, the important development of endurance time method in the study of structural seismic performance and vulnerability analysis in recent years is summarized. The core idea of endurance time method is to synthesize a series of acceleration time-history curves with increasing duration and intensity of ground motion according to the pre-defined target response spectrum. These time-history curves are used as seismic wave input to the structure and nonlinear dynamic time-history analysis is carried out. Finally, the whole process of the structure from elasticity to plasticity to failure can be obtained, and the seismic capacity of different structures can be compared, that is, the time of ground motion that the structure can withstand.

By citing a lot of literature, this paper demonstrates that the endurance time method has important practical application value in seismic performance research and vulnerability, and gives the structural vulnerability analysis flow method based on the endurance time method. In summary, endurance time method can effectively make up for the limitations of existing methods, and is a research method for structural seismic performance with high computational efficiency, good accuracy and good reliability.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

1. GB50011-2010, Code for Seismic Design of Buildings [S]. Beijing, China Architecture & Building Press; 2010.
2. Estekanchi HE, Vafai A, Sadeghazar M. Endurance time method for seismic analysis and design of structures [J]. Scientia Iranica. 2004;11(4):361-370.
3. Valamanesh V, Estekanchi HE. Compatibility of the endurance time method with codified seismic analysis approaches on three-dimensional analysis of steel frames [J]. The Structural Design of Tall and Special Buildings. 2013;22(2).
4. Hariri-Ardebili MA, Furgani L, Meghella M. A new class of seismic damage and performance indices for arch dams via ETA method [J]. Engineering Structures. 2016; 110.
5. Bai Jiulin. Analysis and optimization of main seismic failure modes of reinforced concrete frame structures [D]. Harbin Institute of Technology; 2015.
6. Shen Yu. Seismic collision analysis of beam bridges based on endurance time method [D]. Harbin Institute of Technology; 2017.
7. Xu Shutong. Vulnerability analysis of concrete dams based on endurance time method [D]. Dalian University of Technology; 2019.
8. Huang Jiadong. Seismic performance study of super large-span corrugated steel web continuous rigid-frame bridges [D]. Guangzhou University; 2022.
9. Li Hongjian. Seismic vulnerability analysis of high-pier large-span continuous rigid-frame bridges considering wave effects

based on ETM [D]. Chongqing Jiaotong University; 2023.
10. Feng Zhichao. Study on damage evolution mechanism and seismic vulnerability using endurance time method for rib arch culverts under strong earthquake action [D]. North China University of Water Resources and Electric Power; 2023.
11. Xu Qiang, Yao Wenbin, Chen Jianyun. Vulnerability analysis of arch dam-foundation system based on endurance time method [J]. Journal of China Three Gorges University (Natural Sciences). 2023;45(05):59-65.
12. Yuan Bo, Wu Guanzhong, Liu Yang, et al. Vulnerability analysis of Qiang nationality watchtowers based on endurance time method [J]. Science Technology and Engineering. 2023;23(25):10902-10909.
13. Yu Qi, Zheng Shixiong, Ding Zihao, et al. Vulnerability analysis of large-span steel truss arch bridges based on endurance time method [J]. Railway Standard Design. 2024;68(06):106-113.
14. Chen Denghong, Wang Ruinan, Lin Tiancheng, et al. Seismic vulnerability analysis of high arch dams based on endurance time method [J]. Journal of Hydroelectric Engineering. 2024;43(03): 108-119.
15. Nozari A, Estekanchi HE. Optimization of endurance time acceleration functions for seismic assessment of structures[J]. Iran University of Science & Technology. 2011;1(2):257–277.
16. Mohammadreza Mashayekhi,Homayoon E. Estekanchi,Hassan Vafai. Simulation of Endurance Time Excitations via Wavelet Transform[J]. Iranian Journal of Science and Technology, Transactions of Civil Engineering. 2019;43(3).
17. Estekanchi HE, Arjomandi K, Vafai A. Estimating structural damage of steel moment frames by endurance time method [J]. Journal of Constructional Steel Research. 2008;64(2):145-155.
18. Deierlein G, Krawinkler H, Cornell C. A framework for performance-based earthquake engineering [C]. Proceedings of the 2003 Pacific Conference on Earthquake Engineering, Christchurch, New Zealand, Elsevier. 2003;1-8.
19. Salek Faramarzi Mohammadreza,Taghikhany Touraj. Direct performance-based seismic design of strongback steel braced systems[J]. Structures. 2020;28.
20. Kechidi Smail, Colaço Aires, Alves Costa Pedro, et al, Marques Mário. Modelling of soil-structure interaction in OpenSees: A practical approach for performance-based seismic design[J]. Structures. 2021;30.
21. Edmond V. Muho,Jiang Qian,Dimitri E. Beskos. Modal behavior factors for the performance-based seismic design of R/C wall-frame dual systems and infilled-MRFs[J]. Soil Dynamics and Earthquake Engineering. 2020;129.
22. Jia Hanxi, Lin Junqi, Liu Jinlong. A review of research on seismic vulnerability analysis of building structures [J]. Disaster Prevention and Mitigation Technology. 2019;(01).

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