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A Review of Seismic Optimization Design of Building Structures with Uniform Response

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Abstract

Earthquakes threaten human survival with powerful destructive power, and the performance of buildings in earthquakes is crucial. The seismic design of traditional building structures has the limitations of non-uniform response to displacement and acceleration, which can easily lead to partial damage to the building, unreasonable structure and difficulty in post-earthquake repair, which seriously affects the comfort and safety of the building. It is emphasized that improving the seismic safety of buildings is not only an inevitable requirement to ensure the safety of people's lives, but also to meet people's needs for continuous improvement of building comfort. The review shows that it is of great practical significance to study the seismic optimization design method of building structures with uniform response, which provides an important reference direction for the future design of building structures.

Keywords

Comfort; Security; Optimize the design.

1. Introduction:

In the long history of the earth, the powerful destructive power of earthquakes has impacted the living space of human beings from time to time. As an important symbol of human civilization and the core carrier of life, under the test of earthquakes, the performance of architecture is related to the safety of many lives and the stability of society[1]. The traditional seismic design of building structures has certain limitations in many aspects, and the displacement and acceleration responses under earthquake often show non-uniform responses[2].

When a strong earthquake strikes, if the building structure cannot achieve a uniform response, it will cause non-uniform damage. On the one hand, local excessive stress and deformation will cause damage to some key parts, or even damage[3], which will cause the irrationality of the entire structure, such as the reduction of bearing capacity, local instability, and the change of force transmission path [4], which will also accelerate the aging of the structure and affect the durability of the structure. On the other hand, the uneven response can make it difficult for the structure to be repaired after an earthquake. The degree of damage varies greatly in different parts, requiring different repair methods, consuming a lot of manpower and material resources, and may also make the building unrepairable[5,6].

The magnitude of the displacement angle and acceleration is an important criterion for construction. Acceleration is an important criterion for building comfort[2,7], and acceleration directly affects people's feelings in the building, and large acceleration can cause people discomfort, even panic, dizziness, etc.[8]. If the acceleration is not evenly distributed, it will cause some people in the building to feel strong vibrations, which will seriously affect the comfort of the building. The magnitude of acceleration also reflects the intensity of the seismic forces on the structure. The displacement angle is an important criterion for the safety of the

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building. The displacement angle is related to the degree of deformation of the structure[9], which will cause the beams, columns, walls and other components to bear excessive stress, and are prone to cracks, fractures and other damage. Especially at the joints, damage may occur due to uncoordinated deformation. It will also lead to the deformation of doors and windows, the difficulty of opening and closing, and the reduction of sealing performance, which will affect the indoor thermal insulation, heat insulation, and sound insulation effects. It will also distort and break the water supply and drainage pipes, resulting in water leakage and other problems, affecting the normal life and production water. Living or working in a building with an excessive displacement angle can cause people to feel uneasy, worry about the safety of the building, and affect people's psychological state. The goal of the uniform response is to distribute the acceleration and displacement angles as evenly as possible in the building structure, thereby improving the comfort and safety of the building.

In recent years, with the continuous progress of engineering technology and the deepening of seismic research, the seismic optimization design concept of uniform response of building structures has emerged. At the same time, the development of software technology has also brought new opportunities in this field. OpenSees software plays an important role in the seismic analysis and design of building structures, which can carry out more accurate structural modeling and seismic response analysis, simulate the response of building structures under various seismic conditions, and help designers better understand the performance of structures and optimize design schemes. MATLAB software also has a unique value in the seismic optimization design of building structures. MATLAB's powerful numerical computing and data analysis capabilities can deeply process and optimize the response data of building structures to earthquakes. Complex algorithms are implemented through programming, and scientific basis is provided for the adjustment of design parameters. Combined with OpenSees, MATLAB can further expand the depth and breadth of analysis to validate and optimize designs from different perspectives.

It is of great practical significance to deeply explore the seismic optimization design method of building structures with uniform response. It is not only an important supplement and improvement to the traditional seismic design, but also to adapt to the higher requirements of modern society for building safety. In today's world, people's needs for buildings are not limited to basic functions, but also pay more attention to their reliability in the face of extreme disasters. Optimizing the design to achieve a uniform response of the building structure, combined with advanced software such as OpenSees and MATLAB for analysis and validation, can provide a safer and more secure environment for people to live and work.

2. Background and Implications

2.1. Background

In the traditional seismic design of building structures, it usually relies on experience and existing design schemes, and adopts methods such as increasing structural stiffness and improving component strength to resist seismic action. However, such an approach does not take into account the integrity and coordination[10], and cannot guarantee the optimal design scheme, and may even be counterproductive. With the continuous development of structural mechanics, materials science and other disciplines[11], people have a deeper understanding of the mechanical properties and failure mechanisms of building structures. Through the study of the dynamic characteristics and seismic response of the structure, it provides a theoretical basis for the seismic design method of uniform response. With the acceleration of urbanization, complex building structures such as high-rise buildings and large-scale commercial complexes are emerging. The safety of these building structures in an earthquake is even more prominent,

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and in the event of an earthquake, it can have serious consequences. Therefore, it is necessary to study more effective seismic design methods to improve the safety of building structures.

In this context, many studies use the equivalent dynamic load of static load, which can usually only consider the static response of the structure, and it is difficult to accurately capture the dynamic characteristics of the structure under dynamic load, such as vibration frequency and damping effect. This may result in inaccurate designs in the face of actual dynamic loads, which do not adequately guarantee the safety, comfort, and durability of the structure [2,12]. Dynamic loads allow for a more accurate assessment of the response of a structure to dynamic action, such as displacement, acceleration, and stress. This helps to identify the weak points of the structure and provides a basis for the design of the reinforcement structure. Dynamic response analysis can also take into account the nonlinear behavior of the structure, such as the plastic deformation of the material and the large deformation of the structure.

In modern society, people's attention to life safety has reached an unprecedented height. As the main place where people work, live and live, the safety of buildings in natural disasters such as earthquakes is of paramount importance. The collapse of any building structure in a disaster can lead to a large number of casualties, causing great suffering and loss to families and society. Therefore, improving the seismic safety of building structures is an inevitable requirement to ensure the safety of people's lives [13]. In order to ensure safety, with the continuous improvement of people's living standards, the requirements for building comfort are getting higher and higher. The proposed values for the displacement angle began to be relaxed, which was accompanied by an emphasis on relative acceleration[14]. The violent shaking of the building structure can bring great fear and discomfort to people, and seriously affect people's quality of life. Therefore, improving the comfort of building structures during earthquakes[15] and reducing the impact of shaking on people have become important needs to improve the quality of life[16]. Therefore, the building structure has begun the process of multi-objective optimization, which often involves safety, comfort, economy, etc., and it is difficult to find the best balance between multiple objectives with traditional design methods, while multi-objective optimization methods can be used to weigh and optimize between multiple objectives through mathematical models and optimization algorithms[17,18] to obtain the optimal design scheme. Combined with OpenSees and Matlab, a series of work such as modeling, analysis, and optimization of building structures can be realized[19].

2.2. Research implications

The seismic design with uniform response can make more rational use of building materials and avoid material waste caused by local reinforcement or over-design on the premise of ensuring structural safety. By optimizing the size of structural components, the self-weight of the building can be reduced, the cost of foundation engineering can be reduced, and the conservation and sustainable use of resources can be realized. With the rapid development of cities, land resources are becoming increasingly tight, building structures are becoming more and more complex, and the requirements for the seismic performance of buildings are getting higher and higher. The seismic optimization design method with uniform response can provide effective seismic solutions for high-rise buildings, long-span structures, and complex structures in the city, meet the needs of urban development, and provide guarantee for the sustainable development of the city. In some irregular buildings, the seismic forces can be better distributed through a uniform response design, so that all locations of the structure can withstand reasonable loads.

Uniformly responsive structures reduce violent shaking and shaking amplitude in the event of an earthquake. This means that the discomfort that people feel during an earthquake will be greatly reduced. In contrast, buildings that do not respond evenly may experience strong local shaking, causing panic and physical discomfort such as dizziness, nausea, etc., to people living

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in positions of violent shaking. Buildings that have been optimized to achieve uniform response have a relatively stable and gentle shaking and can provide a relatively comfortable living environment for people.

The seismic optimization design method of uniformly responsive building structures is of great significance to the development of related disciplines, involving knowledge in many disciplines such as structural mechanics, earthquake engineering, and computer science and technology. It promotes the transformation of seismic design from traditional empirical design to optimized design based on advanced theories and technologies, and promotes the development and innovation of architectural engineering disciplines.

3. Research Status of Seismic Optimization Design of Building Structures at Home and Abroad

In the past half century, many advances have been made in the seismic optimization of building structures, but the theoretical literature on the seismic optimization of building structures is limited. Considering the randomness and uncertainty of earthquakes, the reliability and risk of building structures under earthquake action are evaluated through probability analysis methods, and the performance of building structures under different seismic intensities is designed, so that the performance of building structures under earthquake action is more clear and predictable. This method can more comprehensively reflect the impact of earthquakes on the structure, provide a more scientific basis for the design, and help to reasonably balance the safety and economy of the structure in the design. With the continuous development of computer technology, the application of numerical simulation methods such as finite element analysis and time history analysis in the seismic design of building structures has become more and more extensive and in-depth. Today's numerical simulation software can more accurately simulate complex problems such as the nonlinear behavior, damage evolution, and internal interaction of structures under earthquakes, providing designers with more detailed structural responses and achieving more optimal design schemes. By numerically simulating the seismic response of the building, the shape and component size of the structure can be optimized, and the seismic performance of the structure can be improved. The rise of multi-objective optimization design no longer only focuses on the seismic performance of the structure, but comprehensively considers the economy, comfort and other objectives of the structure for optimal design. By using optimization algorithms, such as genetic algorithm, particle swarm optimization and optimization criterion method, the optimal solution can be found in many design schemes to achieve the best balance between structural performance and economic benefits.

3.1. Current status of research abroad

Sandgren E and Cameron T M. [20] have been using optimization algorithms to solve these problems as early as 2002. They used a combination of Monte Carlo and a genetic optimization algorithm to achieve the optimal solution of the structural design through this hybrid genetic algorithm, taking into account changes such as loads, which can cope with the changes in parameters in reality and make the design more practical, and it has been proved through multiple examples that this method is excellent in reducing the sensitivity of the design to changes and can improve the reliability of the design in practical applications.

IN 2006, KIM H S AND ROSCHKE P N. [21] COMBINED WITH MULTI-OBJECTIVE OPTIMIZATION, DEVELOPED A FLC SUITABLE FOR INTELLIGENT BASIC ISOLATION SYSTEMS, WHICH CAN REDUCE DISPLACEMENT WHILE AVOIDING ACCELERATION INCREASE. It pioneered the application of genetic algorithm to the design of fuzzy control system, providing a more efficient and unexpected control scheme. The FPS system and MR damper are used, and a multi-

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objective genetic algorithm named NSGA-II is used to solve the problem of multi-objective weighting in the traditional method, and make up for the lack of research in the field of structural vibration control of intelligent controllers.

Cherkaev E and Cherkaev A.[22] in 2008 discussed the problem of robust optimization design of elastic structures under uncertain loads, solved the problem of structural design under uncertain loads, optimized the performance of the structure under extreme loads, and ensured that the design could be safe under the worst conditions. The multiple optimal solutions in the design are demonstrated, which fills the design gap of the structure under incompletely known loads.

Kwok KCS, Hitchcock P A, and Burton M D[23](2009) elaborated on the study of people's acceleration perception and tolerance thresholds in buildings, highlighted the differences in comfort standards in existing studies, and proposed the need to develop internationally applicable operational standards, which promoted the study of building acceleration.

In 2011, Al-Ansari and Senouci[24] proposed a structural model for calculating displacement design in order to solve the displacement optimization problem under seismic loads. The model calculates the lateral displacement and interstory drift of the building, which enables more efficient structural design optimization. Al-Ansari and Senouci introduced an optimization algorithm to optimize the weight, top layer displacement and inter-layer displacement using MathCad software to solve the problem of optimal size selection of structural components.

Miguel L F F and Lopez R H.[25] (2015) used the Bayesian method and non-probabilistic fuzzy method to calibrate the stiffness parameters of the finite element model based on the data obtained from the experiment to identify, quantify, and locate the structural damage. It provides an easier and more accurate way to update the finite element model, improving the consistency of predictions with experimental results.

In 2017, WEI Zitian, LIU Ji-ke, and Lu Zhong-rong[26] proposed an improved particle swarm optimization algorithm based on particle swarm optimization algorithm, which helps particles jump out of local optimization by introducing perturbations to avoid premature convergence, and enhances the global optimization ability of the algorithm, which fills the gap in the lack of algorithm efficiency and robustness in existing research, and improves the accuracy and stability of damage recognition.

Xu J, SPENCER B F, Lu X , et al.[7], in 2017, proposed a performance optimization method for nonlinear structures under stochastic excitation, and calculated the Pareto optimal frontier for low, medium, and high intensity earthquakes, considering the structural safety and serviceability, respectively, to demonstrate the trade-offs. The optimization goal is defined as the variance of the response of the stationary structure, and the results show that this method effectively balances the competing goals between the safety of the structure and the serviceability.

In 2021, Do B and Ohsaki M[27] proposed an adaptive optimization method to solve the optimization problem, which is used to solve the discrete robust design optimization problem of steel frames. The algorithm only needs to carry out several experiments to find the exact optimal solution or a good approximate solution, which fills the research gap that is difficult to be applied by the existing methods in the design of steel structures.

In 2024, OKASHA N M, ALZO'UBI A K, and MUGHlEDA O[28] proposed an efficient cross-section standardization method by combining the improved version of the multi-objective particle swarm optimization method with the proposed cross-section standardization algorithm to solve the reliability design optimization problem of multi-objective systems.

Remarkable progress has been made in the study of seismic optimization design methods for uniformly responsive building structures. Researchers and scholars in many countries are committed to developing more advanced design concepts and technologies, proposing

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innovative design methods, and developing advanced technologies such as seismic isolation, energy dissipation and shock absorption to achieve uniform structural response. to improve the comfort and safety of building structures under the action of earthquakes.

3.2. Current status of domestic research

In 2012, Sun Aifu, Hou Shuang, and Ou Jinping[29] proposed a method to improve the overall seismic resistance of high-rise steel structures, and analyzed the damage law of high-rise steel structures under horizontal earthquake according to the nonlinear calculation model of the structure and the limit state discrimination criterion. The design method to eliminate the weak layer is proposed to improve the overall seismic capacity through uniform damage design, and its effectiveness is verified by push-over analysis, and the feasibility of the method is verified by the limit time history and push-over analysis of two 20-storey steel frame structures.

In 2015, Bai Jiulin, Yang Le, and Ou Jinping [30] discussed the optimization of seismic performance of steel frame structures based on the concept of equal damage, but the current seismic design cannot ensure that the structure forms the expected failure mode in a strong earthquake, resulting in the material properties being underutilized. By using the OpenSees platform and using the optimization criterion method, a seismic design method with equal damage is proposed. The severely damaged parts are strengthened, the less damaged parts are weakened, and the component cross-section is adjusted while keeping the material cost constant. The results show that the design strategy of equal damage can effectively improve the seismic performance of the structure, which has important engineering application value.

In 2018, Haoxiang He, Wentao Wang, and Shaoyong Fan[31] discussed the optimal stiffness distribution of bending-shear structures under different load distributions. The deformation and damage of the building structure under the action of external forces such as earthquake and wind load are more uniform, so that the structure can achieve the best stiffness distribution, and the correctness of the analytical solution is verified by numerical simulation and finite element analysis, which provides theoretical support and practical guidance for structural optimization.

In 2020, Haoxiang He, Wentao Wang, and Shan Wu[19] discussed the seismic optimization design of frame structures under earthquakes, and proposed a hybrid intelligent algorithm based on Differential Evolution Algorithm (DE) and Particle Swarm Optimization Optimization (PSO), which takes the relative displacement equality between layers as the optimization goal to optimize the stiffness of each floor, and the existing structural optimization algorithm has low calculation efficiency, and proposes an optimization process and empirical formula, which provides an important reference for the structural optimization design.

In 2021, He Haoxiang, Huang Lei, Wu Shan et al.[32] studied the design concept of uniform damage of bridges, and found that high-pier bridges are prone to serious damage in earthquakes, especially at the plastic hinges of bridge piers, resulting in the failure of the overall function of the bridge. It fills the weak point problem caused by the difference of stiffness of each pier in the traditional design, and has important theoretical and engineering application value.

In 2023, Shi Yundong, Shen Hongyi, Tan Hanming et al. [5] proposed an identification criterion based on the characteristic parameters of ground motion, combined with viscous dampers, to achieve uniform damage control of structures. Based on the nonlinear dynamic time history analysis and the interstory displacement angle index, an effective damping control strategy is proposed, which provides a new theoretical support for the seismic design of high-rise steel frame structures and has important engineering application value.

In 2024, Wu Shan, He Haoxiang, and Lan Bingji[33] proposed a uniform damage design method for RC frame structures, with the goal of equal or similar damage index on each floor, and the reinforcement rate of each layer frame column as the optimization variable, and the DE

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algorithm was used to optimize the reinforcement ratio of each layer of columns, and the iterative optimization was carried out until the convergence condition was satisfied. This paper proposes a universal optimization method, which is convenient for practical engineering application.

The domestic performance-based seismic design theory continues to developUnder the action of earthquakes of different intensities, building structures should meet different performance objectives, from simply ensuring that the structure does not collapse under the earthquake, to considering the degree of damage of the structure, the recoverability of the use function and other aspects of performance. It emphasizes the overall scheme of the building structure from a macro perspective, including the selection, layout, and stiffness distribution of the structure. Domestic designers are increasingly aware of the importance of conceptual design in seismic design, and through reasonable conceptual design, the structure can achieve uniform response under seismic action. With the development of computer technology, optimization algorithms have been widely used in the seismic design of building structures. By establishing the mathematical model of the structure, the seismic design problem is transformed into an optimization problem, and the optimization algorithm is used to find the optimal design scheme. In practical engineering, some new seismic technologies and products have been more and more widely used.

3.3. Problems and analysis in the field

To sum up, experts at home and abroad have achieved a lot of research results in steel structure structure and reinforced concrete structure through simulation analysis and theoretical calculation. In recent years, the use of various intelligent algorithms has gradually become a universal optimization method. Further research is needed on the applicability and optimization efficiency of the algorithm, and how to better solve the unpredictability of earthquakes

Earthquakes are a complex natural phenomenon, and there is still a great deal of uncertainty in the prediction of ground motion. The intensity, spectral characteristics, duration and other parameters of ground motion are affected by a variety of factors, such as the source mechanism, propagation path, site conditions, etc. Deterministic seismic waves are usually used for analysis in terms of ground motion inputs, but actual ground motions are highly random, and different seismic waves may cause significant differences in structural responses. Seismic action is not only random, but also multidimensional and coupled.

The stochastic ground motion model is introduced to consider the randomness and uncertainty of ground motion. By generating a large number of random ground motion samples, the random vibration analysis of the structure is carried out to obtain the statistical characteristics of the structural response. The probabilistic seismic demand analysis method is used to evaluate the failure probability of the structure under different seismic intensities, so as to provide a more scientific basis for the seismic design of the structure. At the same time, the influence of spatial correlation and nonstationarity of ground motion on the structural response is studied, so as to improve the reliability of the seismic design of the structure.

Improve the convergence and efficiency of optimization algorithms, develop more efficient optimization algorithms, and improve the convergence and computational efficiency of algorithms. Advanced optimization algorithms, such as genetic algorithm, simulated annealing algorithm, particle swarm optimization algorithm, etc., are used to optimize the structure design in combination with structural analysis software. The parameter setting and optimization strategy of the optimization algorithm are studied to improve the performance and applicability of the algorithm. At the same time, the integration of optimization algorithm and structural analysis software is carried out to realize the automatic optimization design of the structure. Methods that can effectively deal with multi-objective optimization problems,

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such as multi-objective genetic algorithm, multi-objective simulated annealing algorithm, etc. A mathematical model of multi-objective optimization is established, and the optimal design scheme is found by considering multiple objectives such as strength, stiffness, deformation, and economy of the structure.

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