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Research on seismic design methods for high-rise building structures

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Abstract. In recent years, with the increase of the number of high-rise buildings and the increase of the frequency of earthquakes, the requirement of seismic design of high-rise buildings is getting higher and higher. Therefore, this paper mainly studies the requirements of the existing seismic design code and the basis of designing the seismic performance of high-rise buildings. The results of this paper show that the performance-based seismic design method is the most popular and practical seismic design method at present. It also concluded that the seismic capacity of high-rise buildings can be improved by changing the calculation method of bearing capacity and adopting stable lightweight materials. In addition, this paper also introduces the new seismic methods such as preset yield mode, so as to improve the seismic ability of tall buildings as a whole. In the future, more new and innovative technologies will be applied to the seismic design of high-rise buildings to provide a stable and safe environment for people's production and life.

Keywords: High-Rise Building, Earthquakes Performance, Seismic Design Method.

1. Introduction

Earthquakes cause serious human casualties and property damage. For example, the 6.8 magnitude earthquake that struck Turkey in February 2023 killed more than 50,000 people. In 2008, the 8.0-magnitude earthquake in Wenchuan, China, killed nearly 300,000 people [1]. This shows that earthquakes cause great harm to human beings. At present, the first stage of the seismic design of buildings is to calculate the bearing capacity by taking the first level of ground vibration parameters to calculate the standard value of the elastic seismic effect of the structure and the corresponding seismic effect. On the basis of reliability analysis, the seismic checking of structural members' cross-section bearing capacity is carried out by adopting the expression of sub-coefficient design to meet the goal of "small quake is not bad". The second stage of design is elastic-plastic deformation checking, for irregular structures with weak layers or structures with special requirements. Through the elastic-plastic interlayer deformation checking and adopting corresponding structural measures, it can meet the defense objective of "not falling down in big earthquakes". The "repairable in moderate earthquakes" objective is realized through conceptual design and several seismic measures, which are mainly embodied in the first stage of design. The conceptual design includes structural sizing, limiting the height of the building, and minimizing the seismic shear force. Seismic measures include internal force adjustment and amplification, and structural requirements for different seismic levels.

With the development of economy, the demand for high-rise buildings is rising. The increase in the height of the buildings makes the traditional seismic design unable to meet some special requirements of high-rise or ultra-high-rise seismic design. The study of seismic resistance of high-rise buildings is to investigate the design that can best resist earthquakes and enhance the stability of high-rise buildings during earthquakes. Because this paper mainly studies the seismic design methods and related requirements of high-rise construction, so as to provide effective reference for engineering design.

2. Seismic design methods for high-rise buildings

2.1. Conventional seismic design methods

Since the 1980s, in the revision of the official seismic design code for industrial and civil buildings by the Chinese government and relevant departments of construction, the seismic design objective of "no damage in small earthquakes, repairable in medium earthquakes and no collapse in large earthquakes" has been put forward for the seismic design of building structures, and the "three-level, two-stage design" method has been adopted in the actual seismic design. In the two-stage design method, the main work of seismic design is to calculate the load carrying capacity of building structural members, i.e. to calculate the seismic load carrying capacity of building structural members in terms of internal force and deformation of seismic effects. The second is to calculate the elastic-plastic deformation of the building structure and take corresponding seismic structural measures. In 2016, a specification was also made for the seismic design of houses, and the Code for Seismic Design of Buildings was published [2]. With a modern perspective, the methods and steps of seismic code design have initially taken the shape of performance design, thus meeting the needs of the three levels.

2.2. Performance-based seismic design

Seismic design based on the performance of the building itself is the main seismic design method in recent years. Initially, this idea was proposed by American scholars in the early 1990s.It has received increasing attention from the engineering community. ATC40 (1996) and FEMA237 (1997) f the United States of America propose the use of multiple performance objectives in the evaluation and strengthening of existing buildings and provide design methods [3, 4]. The basic connotation is that under the specified seismic level, the designed structure needs to meet the performance level and the selection of target performance in seismic design. The performance level refers to the maximum level of damage that the building structure can withstand during an earthquake. Due to the unbalanced technical and economic development of each country, the performance level specified by each country is not consistent. The target performance is the coefficient of variation of the structure's response to different levels of earthquakes, which requires the consideration of many factors, such as the post-earthquake damage to the building, the destruction of some historical values, and other multifaceted efficiency issues. Thus, the goal is to achieve an optimal balance between the cost of the building and the losses due to earthquakes that meets the objectives of the original investors [5]. A comparison between conventional and performance-based design methods is shown in table 1.

Table 1. Comparison of Conventional and Performance Design Methods [6].

Project	Conventional seismic design	Performance-based seismic design
Defence Objectives	Small earthquakes cause small damage, medium earthquakes can be repaired, and large earthquakes do not collapse. There are clear performance indexes for small earthquakes, displacement indexes for large earthquakes, and the rest are macroscopic performance requirements.	Multiple desired performance objectives, including structural, non-structural, and facility-specific performance indicators, according to the type of use function and the degree of seismic exposure; the owner chooses the desired objectives for a specific project.

Table 1. (continued).

Implementation method	Design according to the provisions of directive and prescription forms; through the conceptual design of structural arrangement, elastic design for small earthquakes, empirical adjustment of internal forces, amplification and construction, as well as deformation calculation for large earthquakes of part of the structure, that is, it is considered to be able to realise the expected macroscopic fortification target.	In addition to meeting the basic requirements, a demonstration of compliance with the expected performance requirements, including the structural system, detailed analyses, seismic measures and the necessary tests, is required and confirmed by specialised evaluations.
Engineering application	Currently widely used, designers are already familiar with. There are clear restrictions on the applicable height and regularity, etc., with limitations, sometimes unable to adapt to the development of new technology, pre-materials and new structural system.	Currently less used, designers are not easy to grasp, the risk borne by the larger for the realization of the “super-limit” structure design provides a feasible method, is conducive to technological progress and innovation. There are still some technical problems to be studied and improved.

In order to meet the performance-based design objectives in high-rise buildings, the first step in the design process is to clarify the purpose of the building design and the needs of the users. Taking investment-benefit as the guideline, to meet individual needs while ensuring that the national building “small quake does not damage, medium quake can be repaired, large quake does not collapse” basic requirements. Based on the above performance objectives, the structural design is carried out using appropriate design methods. The designed structure is then evaluated for performance. If the performance requirements are met, the actual performance level of the designed structure is clearly given. In terms of design methods, they mainly include bearing capacity design methods, displacement-based design methods and energy design methods [7].

Firstly, it is based on the calculation of load bearing capacity, which realizes that when designing the load bearing capacity of a high-rise building, it is necessary to accurately calculate the overall components of the building structure and the force of each node. Secondly, the design method based on displacement, this design method is to predict the inter-story displacement of the building in the earthquake to predict the damage strength of the earthquake, so as to carry out the seismic structural design [8]. 1975 Freeman et al. in the U.S. Navy engineering projects to simplify the evaluation of the proposed capacity spectrum method. The method is to find the “performance point” of a building by establishing capacity and demand curves. The displacement of the original multi-degree-of-freedom system is used to determine whether the structure meets the seismic demands. The energy-based design method predicts the extent of damage to a building’s internal facilities by assuming the amount of energy consumed by the building’s internal structures in order to meet the design criteria.

In improving the original method can be done by changing the way of calculation, such as through the electrical calculation method can calculate the internal force of the oblique lateral force-resisting construction, so as to reduce the neglect of the oblique earthquake. And the real range analysis method can also be used in high-rise buildings by calculating the seismic acceleration wavelength. Thus reducing the impact of vertical earthquakes on the high-rise building conversion beams, long hanging wall construction and connecting structure of the connecting body itself. Some high-rise buildings have complex structural systems, it is difficult to accurately reflect the force state of each component, need to use at least two different mechanical models to calculate and be compared to analyze. Sometimes it is also necessary to determine the credibility of the calculation through the corresponding model test [5].

The seismic performance of high-rise buildings can also be improved by optimizing building materials in the design method. With regard to the analysis of the current existing buildings in China, the general building structure is composed of reinforced concrete structure. For general height of civil buildings, reinforced concrete structure is easy to meet the seismic performance. However, for the current high-rise buildings, when the building is higher than 150 meters, the reinforced concrete structure does not meet the general seismic performance. Therefore, high-rise buildings in the design of the general selection of three-layer supported steel structure to replace the concrete structure, with higher stability and defense against earthquakes.

3. Improvements in seismic design of high-rise buildings

3.1. Seismic method improvement

The pre-determined yield mode is a method of obtaining realistic stiffness reduction factors for structural elements by means of dynamic elastic-plastic analysis of the overall structure of the building. This method can improve the accuracy of the analysis of rare earthquakes, so as to reduce the harm of rare earthquakes on the building. And by analyzing the elastic-plasticity of high-rise buildings and thus controlling the damage mode of earthquakes at the same time, it is simpler, more reasonable, and avoids the more cumbersome design process of adjusting the internal forces of complex structures by the code.

The specific implementation steps of this methodology are as follows: first, a structural analysis of the building, including static and dynamic analyses, is performed to understand the loads, seismic actions, and structural response of the building. Determine the performance objectives in the design, which include the maximum displacements, deformations, and load carrying capacity of the building. Based on the performance objectives, the design engineer develops a structural design program that includes material selection, structural forms, and connections. To achieve the preset yield modes, controllers need to be designed and installed. These controllers usually include dampers, braces, swing arms, etc. Installation and commissioning of the controllers to ensure that they work properly and are integrated with the building structure. Installation of a structural monitoring system for real-time monitoring of the building’s performance, including displacements, stresses, vibrations, etc. After construction is complete, seismic simulations and testing are performed to verify that the building is performing as designed.

At the same time, the design process should take into account the design requirements of the “three levels”. Therefore, it is also necessary to design the yield mode to meet the minimum standard of “no damage in small earthquakes, repairable in medium earthquakes, and no collapse in large earthquakes”. The design of components based on the elasticity of small earthquakes does not need to consider the adjustment of internal forces. At the minor earthquake design stage, an elastic analysis method can be used to keep the structure elastic and undamaged. At the mid-seismic design stage, the design requirements are appropriately increased and reaction spectrum analysis methods are used to realistically respond to the forces on the structure under mid-seismic conditions. The standard is also raised from the mid-seismic method for large earthquake design. The seismic design process for the preset yield mode is shown in figure 1.

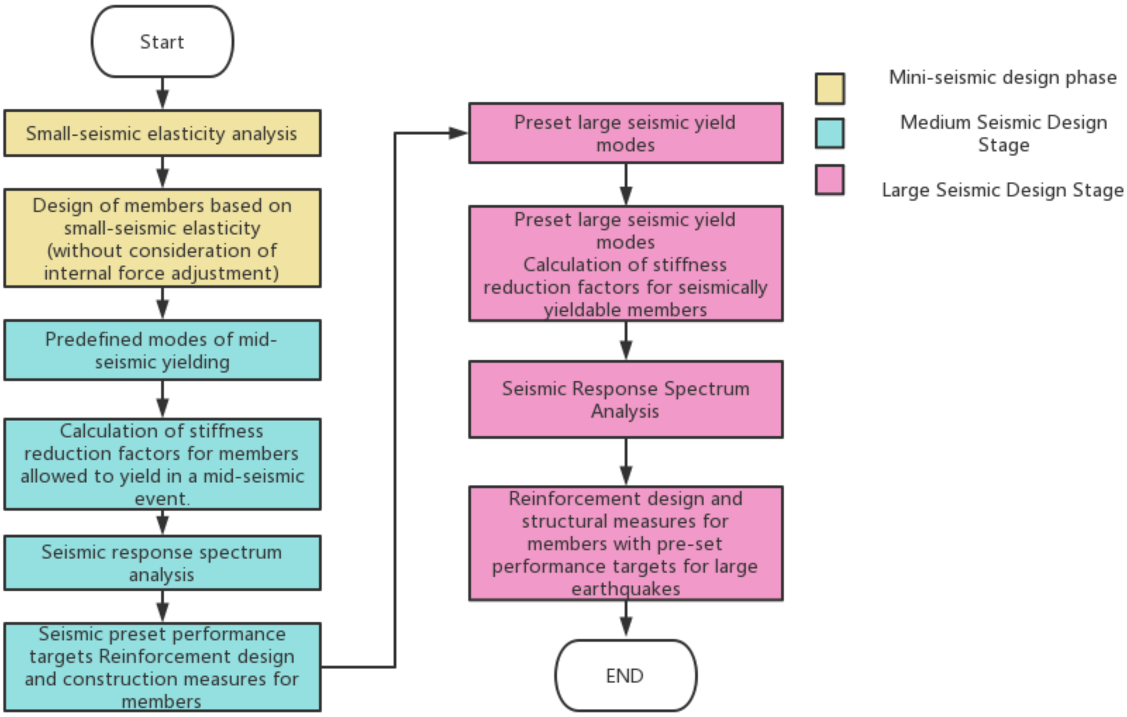

Figure 1. Performance-based seismic design method of predetermined yield mode [9].

Among them, the response spectrum analysis method is an engineering method commonly used to measure the seismic performance of a building or structure during an earthquake. This method is based on the specific seismic spectrum of ground shaking and assesses the seismic performance by numerically analyzing the structure and estimating the response spectrum of the structure. It collects data about the seismic activity, such as the location, depth, and magnitude of the earthquake. to create a numerical model of the building or structure, including the geometry, material properties, mass distribution, etc. of the structure. Usually, finite element analysis or equivalent static method is used to create the model. to perform time-course analysis, in which the displacements, velocities, and accelerations of a structure are obtained over time, and then these data are used to calculate the response spectrum of the structure. The response spectrum is the acceleration of the structure as a function of frequency. Accordingly, the seismic rating is preset to enhance the seismic performance of the building. The preset yield design mode helps to enhance the toughness of the structure so that it can maintain some of its functionality during earthquakes, which improves the safety of life [10].

3.2. *Future developments and applications*

There are many potential trends and opportunities for future development and application of performance-based seismic design and improvement methods. The first will be more accurate performance assessments. Future developments will focus on improving the accuracy of performance prediction and the use of more advanced numerical simulation and data analysis techniques that can more accurately predict the response of structures in earthquakes. On this basis, the intelligent monitoring and control is studied, and the intelligent system that can monitor the structural performance in real time and adjust it according to the actual situation is developed to minimize the earthquake loss. Secondly, new materials such as high-performance concrete and fiber reinforced materials can also be researched and developed, as well as innovative structural design methods to improve the seismic performance of structures. Improving the seismic performance of tall buildings also requires integrating multidisciplinary approaches such as seismic engineering, civil engineering, mechanical engineering

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and artificial intelligence into performance-based seismic design to gain a more comprehensive understanding and optimize solutions.

4. Conclusion

This paper summarizes three approaches to seismic design of high-rise buildings, namely, conventional building design criteria, performance-based building design approach and preset yield mode seismic design. The basic process of design and the conditions that can be met are given accordingly. Then the three design methods are analyzed from various aspects, and it can be seen that the conventional seismic methods can hardly meet the seismic demands of high-rise buildings. The performance-based seismic design method is the most widely used seismic design method, which can ensure that the building meets the predicted performance criteria. The preset yield mode design method is an improvement on the performance-based approach. The deformation of the structure is controlled to ensure that the structure achieves a specific level of performance during an earthquake. To a certain extent, the two methods may be used in combination in practical engineering to improve the overall seismic performance of the structure.

The seismic design of high-rise buildings has higher needs. Therefore, while improving structural stability, the seismic capacity of high-rise buildings can also be enhanced through the selection of lightweight and high-strength building materials. At the same time, seismic design methods with the development of science and technology and the emergence of more intelligent systems will also be applied to the field of seismic design, high-rise buildings can withstand the intensity of the earthquake will continue to increase.

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