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Development and Practice of Performance-Based Seismic Design of High-Rise Buildings in China

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Abstract Seismic performance-based design methods are widely used in the field of engineering. This paper introduces the current status of seismic performance-based design methods for high-rise buildings in China, and summarizes latest advancements in seismic performance-based design methods for high-rise buildings in China, with a focus on the design methods based on predetermined yield mode and the design methods based on member ductility requirements. Finally, the development direction of seismic performance-based design method for high-rise buildings is prospected.

Keywords High-rise buildings, Seismic resistance, Performance-based design, Predetermined yielding mode, Ductility

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1. Introduction

High-rise buildings in China began to develop gradually after 1955. A number of high-rise hotels, office buildings, apartments, and residential buildings were constructed in several large and medium-sized cities, such as the White Cloud Hotel in Guangzhou and the Front Three Gates high-rise architectural ensemble in Beijing. Since the 1990s, high-rise building construction in China has entered a rapid development phase, with building heights increasing and structural complexity growing. In the past decade, the development has accelerated even further, ranking among the top in the world. Some notable completed high-rise buildings include the Shanghai Tower (632 m), Shenzhen Ping An International Finance Center (600 m), Guangzhou East Tower (530 m), and the CITIC Tower (528 m). These iconic buildings have become symbols of cities and even the nation, showcasing the country's economic strength.

2. Seismic Design Methods for High-Rise Buildings

2.1. Traditional Seismic Design Methods for High-Rise Buildings

Currently, the seismic design of high-rise buildings in China follows the three-level design criteria of 'No damage under minor earthquakes, repairable under middle earthquakes, and no collapse under major earthquakes'. The main approach used to achieve these three levels of design criteria is the 'two-stage design' method. The first-stage design involves capacity verification, where the first-level seismic motion parameters are used to calculate standard values of elastic seismic action and corresponding seismic effects. The seismic resistance of structural members is then evaluated using subfactor design expressions based on reliability analysis, satisfying the 'No damage under minor earthquakes' objective. The second-stage design involves elasto-plastic deformation verification. For irregular structures with weak layers or specific requirements, the 'no collapse under major earthquakes' design criteria are addressed by conducting elasto-plastic interstory drift calculations and implementing corresponding structural measures. The design criteria of 'repairable under middle earthquakes' is primarily realized through conceptual design and several seismic measures, mainly reflected in the first-stage design. Conceptual design includes structural selection, height restrictions, minimum seismic shear, and other considerations. Seismic measures encompass internal force adjustment and amplification, as well as structural requirements for different seismic design levels.

2.2. Performance-based seismic design method

Currently, countries around the world are adopting performance-based seismic design theories and methods, gradually formulating and improving related design codes and standards. In 2010, the Pacific Earthquake Engineering Research Center in the United States released the 'Performance-Based Seismic Design Guidelines for Tall Buildings' (PEER-2010), formally introducing performance-based seismic design methods into the seismic design of

tall structures. China's 'Technical Code for Concrete Structures of Tall Buildings' (JGJ3-2010) and 'Code for Seismic Design of Buildings' (GB50011-2010) have both incorporated performance-based seismic design, providing performance objectives, performance levels, and corresponding evaluation criteria for performance-based design.

4. New Methods for Seismic Performance-Based Design of High-Rise Building Structures

4.1. Performance-based design method based on predetermined yield mode

4.1.1. Problems existing in seismic performance design at present

For the complex high-rise building structure in China, the current code mainly controls its irregularity, and then formulates corresponding performance targets for the specific exceed-code conditions. The performance objectives of the weak parts are improved to ensure that it can have better seismic performance under earthquake and avoid the destruction of weak layers of the structure. However, there are still some problems in performance-based seismic design:

1) The performance objectives of the members are independent.

2) Calculation and analysis cannot fully reflect the change of overall structure performance.

3) The actual yield mechanism of members is poor.

4.1.2. Design process

The basic process of seismic performance-based design method based on predetermined yield mode is shown in Figure 1. Considering that the 'three-level' fortification target is the most basic requirement of structural seismic design in China, the predetermined yield mode should also be based on the minimum standard of 'no damage under minor earthquakes, repairable under middle earthquakes, no collapsing under major earthquakes.'

1) Design stage of minor earthquake

All structural members should remain elastic and not damaged under minor earthquakes and elastic analysis method can be used in design. Different from the design method of code in China, there is no need to consider internal force adjustment for the elastic design of members under minor earthquakes. The seismic performance level under middle and major earthquakes is guaranteed by subsequent steps.

2) Design stage of middle earthquake

In the design stage of middle earthquake, the yield mode of middle earthquake should be predetermined first. This mode should take 'repairable under middle earthquakes' as the minimum standard, but it can be appropriately improved according to the requirements of owners or designers. For the members which are allowed to yield, the stiffness degradation degree should be determined firstly, and the stiffness reduction coefficient of these members which are allowed to yield should be obtained through an elasto-plastic analysis of the overall structure under middle earthquake. Then the design based on

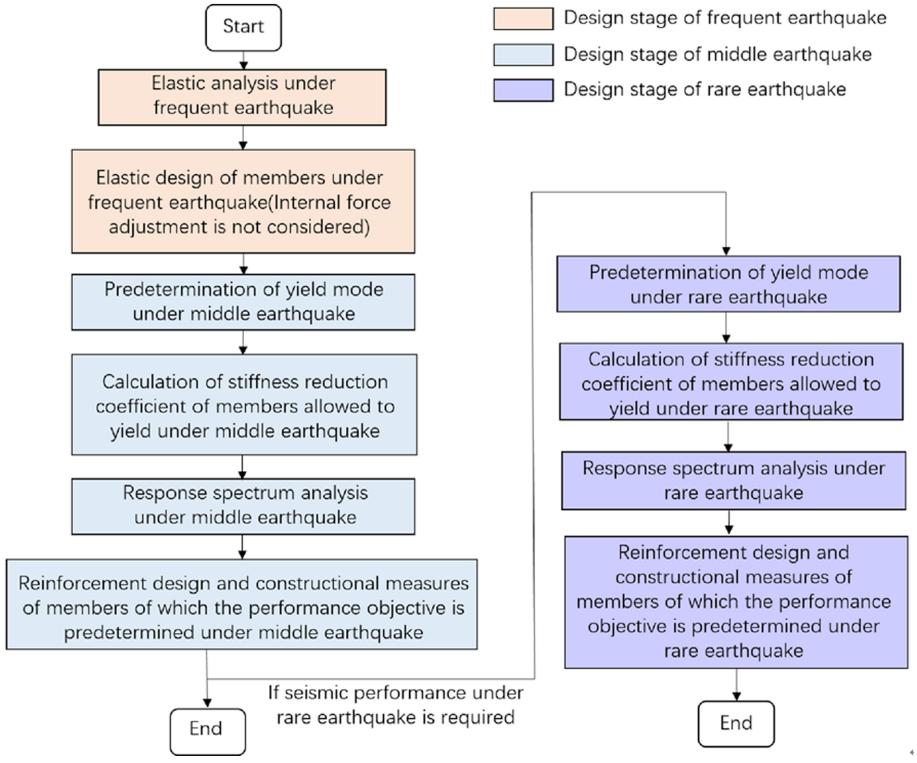


Figure 1. Seismic design method based on predetermined yield mode.

response spectrum method is carried out to directly determine the reinforcement of elastic members. Except for the elastic members and energy dissipation members, the stiffness reduction coefficient of some part of the members can be directly specified, that is, the damage of these members can be specified. This part of the members can be reinforced according to the internal force after the response spectrum analysis under middle earthquake. Different from the performance-based design method recommended by the codes, the elastic response spectrum analysis under middle earthquake in this method takes into account the reduction of stiffness and the increase of damping of some members after entering plasticity, which can better reflect the stress of the structure under middle earthquake.

3) Design stage of major earthquake

Similar to the design stage of middle earthquakes, the yield mode should also be predetermined in the design stage of major earthquakes. This mode should take 'no collapse under major earthquakes' as the minimum standard, but it can be appropriately improved. Similarly, the stiffness degradation degree of the members allowed to yield is determined first, so as to accurately determine whether the bearing capacity of the members which are not allowed to yield can meet the requirement.

4.1.3. Advantages of the method

The seismic performance-based design method based on predetermined yield mode has the following advantages:

1) Through the idea of predetermined yield mode, the failure sequence of the structure is gradually controlled. At the same time, the design process is simpler and more reasonable, and the complex internal force adjustment is avoided.

2) The stiffness reduction coefficient of structural members is obtained by dynamic elasto-plastic analysis method, which can reflect the real stress state of the structure and improve the calculation accuracy.

3) The response spectrum analysis of the overall structure is not only convenient for designers to understand and apply, but also can avoid the earthquake wave selection problem that must be faced in the dynamic elasto-plastic time history design.

4.2. Design Method for Transverse Reinforcement of Structural Members in Reinforced Concrete Structures Based on Ductility Requirements

The current Chinese design codes primarily rely on inclined section bearing capacity design and seismic structural measures to allocate transverse reinforcement, aiming to ensure the shear capacity and ductility of structural members. However, they may not fully consider the true ductility requirements of different members under seismic actions. If key members fail prematurely due to insufficient deformation capacity, it can hinder the full utilization of ductility in other members, leading to loss of structural bearing capacity or even overall collapse.

The design method for transverse reinforcement based on the ductility requirements of structural members essentially establishes a quantitative relationship among 'the bearing capacity', 'ductility requirements' and 'transverse reinforcement amount' of the members. The essence of ductility design lies in first ensuring that the overall structure has a reasonable deformation mode and yield mechanism, and then achieving the ductile deformation capacity of members through structural measures.

4.2.1. Design Process

For new buildings, the specific steps of the transverse reinforcement design process for reinforced concrete structures based on the ductility requirements of members, as shown in Figure 2, are as follows:

1) Perform minor seismic elastic analysis according to the code requirements to obtain the section and inclined section bearing capacity demands of the members. Design

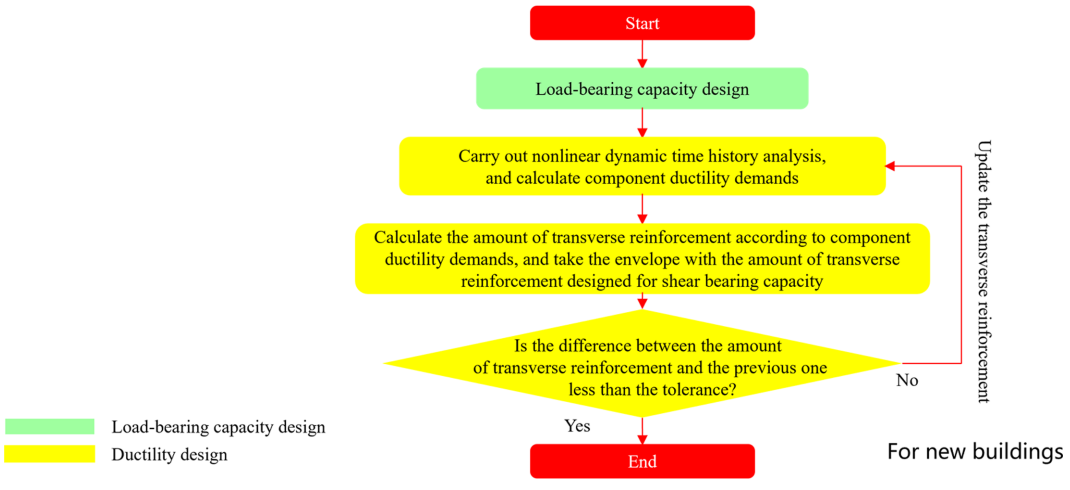


Figure 2. Design process for new buildings.

longitudinal reinforcement and transverse reinforcement. For members with medium and major seismic performance requirements, perform equivalent linearization analysis for medium and major earthquakes to obtain the section and inclined section bearing capacity demands of the members. Design longitudinal reinforcement and transverse reinforcement accordingly.

2) Based on the ductility design objective, use a concrete constitutive model that accurately considers the confinement effect of transverse reinforcement to perform nonlinear dynamic time history analysis under corresponding seismic intensities.

3) Calculate the member deformation based on the nonlinear dynamic time history analysis to determine the ductility requirements of the members. The amplification of ductility requirements based on the member performance objectives can be considered.

4) Calculate the amount of transverse reinforcement based on the ductility requirements. Take the envelope of the transverse reinforcement amount determined by the inclined section bearing capacity demand as the transverse reinforcement amount for the member.

5) Update the transverse reinforcement of the member and perform a new nonlinear dynamic time history analysis to calculate the ductility requirements. Determine the transverse reinforcement amount and check if the difference between the current and previous transverse reinforcement amounts is less than a tolerance. If it is less than the tolerance, the ductility design is completed. If it is greater than the tolerance, update the transverse reinforcement of the member and perform a new ductility design iteration until the difference between two consecutive transverse reinforcement amounts is less than the tolerance.

Compared to new buildings, retrofitting and strengthening of existing buildings face more complex problems and constraints. The design process for reinforcement of reinforced concrete structures based on ductility requirements, as shown in Figure 3, involves the following steps:

1) Perform minor seismic elastic analysis according to the code requirements to obtain the section and inclined section bearing capacity demands of the members. Design longitudinal reinforcement and transverse reinforcement accordingly. For members with medium and major seismic performance requirements, conduct equivalent linearization analysis for medium and major earthquakes to obtain the section and inclined section bearing capacity demands of the members. Design longitudinal reinforcement and transverse reinforcement accordingly.

2) Based on the ductility design objective, use a concrete constitutive model that accurately considers the confinement effect of transverse reinforcement. Conduct nonlinear dynamic time history analysis of the structure under the corresponding seismic intensity.

3) Based on the results of the nonlinear dynamic time history analysis, calculate the deformation of the members and determine the ductility requirements. Amplify the ductility requirements based on the performance objectives of the members, if necessary.

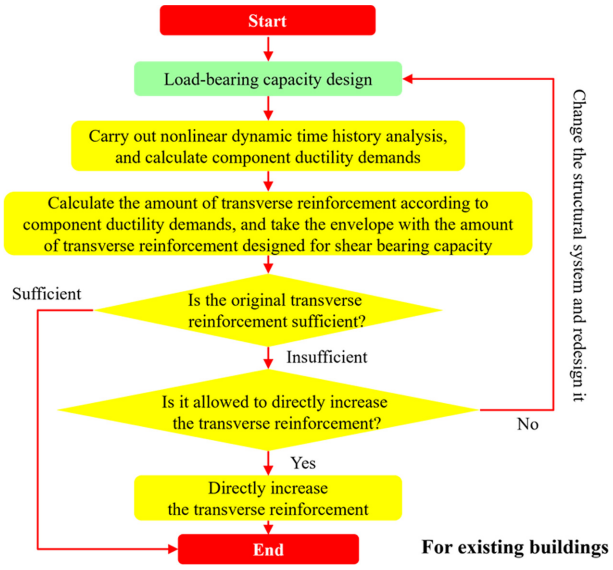


Figure 3. Design process for existing buildings.

4) Calculate the amount of transverse reinforcement based on the ductility requirements. Take the envelope of the transverse reinforcement amount determined by the inclined section bearing capacity demand as the transverse reinforcement amount for the member.

5) Check if the original transverse reinforcement of the member meets the requirements. If it meets the requirements, the ductility design process is completed. If it doesn't meet the requirements, proceed to step (6).

6) Determine if the functional use of the existing building allows for direct reinforcement of transverse reinforcement. If allowed, directly reinforce the transverse reinforcement (iterative design can be applied if necessary for members with insufficient transverse reinforcement, following the same iterative process as for new buildings). If not allowed, adjust the structural system and use methods such as base isolation or performance-based design to reduce the transverse reinforcement demand for members with insufficient transverse reinforcement, and proceed with the retrofit design.

4.2.2. Reasonable determination method of member ductility demand

To predict the transverse reinforcement of RC members, firstly, nonlinear structural dynamic analysis under specified earthquake ground motion is carried out to get the member deformation in the response history. Secondly, the member drift ratio demand is calculated based on member deformation. According to the current code in China, transverse reinforcement is mainly determined by shear bearing capacity design and seismic structural measures. There are three reasons for choosing drift ratio instead of curvature ductility as the input ductility

demand: (1) Drift ratio includes bending defor-mation and shear deformation, and is suitable for flexure critical, flexure-shear critical and shear critical columns; (2) Drift ratio does not depend on the definition of yield displacement or yield curvature; (3) Drift ratio is a routine record of all specimens, and can be directly related to drift limits specified in building codes.

4.2.3. Calculation Method of Transverse Reinforcement for RC Members Based on Machine Learning

The calculation method for transverse reinforcement is a key aspect of ductility design and plays a crucial role in providing deformability to the members. Existing methods for determining the amount of confinement reinforcement are mainly empirical or semi-theoretical/empirical models, which have poor accuracy and high variability. In this approach, the reinforcement amount is calculated based on the ductility requirements of the members using machine learning techniques.

Member drift ratio demands along with other member features are input into the trained ML model to predict the transverse reinforcement ratios required for individual member.

The model establishing steps of transverse reinforcement ratio prediction model, as shown in Figure 4, are as follows: (1) Collect sufficient experimental data covering a wide range of parameters; (2) Carry out feature engineering to select the right features for ML models; (3) Split the data set into training set (80%) and testing set (20%) randomly; (4) Select appropriate ML methods and train the models on the training set; (5) Adopt grid search and 10-fold cross validation method to optimize the hyper-parameters; (6) Train ML models using the optimal hyper-parameters on training set and evaluate the performance on testing set through four typical quantitative metrics; (7) Interpret the established model results through SHAP method and partial dependence plot (PDP) to verify the reliability of the trained ML model; (8) Choose the best ML model as the final model to predict the transverse reinforcement ratio of RC columns.

4.2.4. Advantages of the Method

1) Provides a rational method for determining the ductility requirements of members, addressing the issue of transverse reinforcement design for reinforced concrete members.

2) Pioneering the application of machine learning techniques to structural transverse reinforcement design, establishing a predictive model for the transverse reinforcement ratio of reinforced concrete members, achieving precise and quantifiable reinforcement design.

3) This method quantifies the relationship between the transverse reinforcement ratio of members and deformation requirements, axial compression ratio, etc., providing an effective approach to addressing the challenges of reinforcing existing structures with inadequate transverse reinforcement.

5. Conclusions and prospects

5.1. Conclusions

1) The seismic performance-based design method has overcome the limitations of traditional seismic design methods with a single performance objective. Engineers can now select appropriate performance objectives based on the actual situation of the structure.

2) The seismic performance-based design method based on the predetermined yield mode is proposed, and the basic design process is provided. This method enables the seismic design of complex high-rise buildings, moving from the control of irregularities according to existing codes to the control of failure modes. It effectively avoids the risk of premature loss of bearing capacity in complex high-rise structures due to the failure of weak members during intense earthquakes, thereby improving structural safety margins.

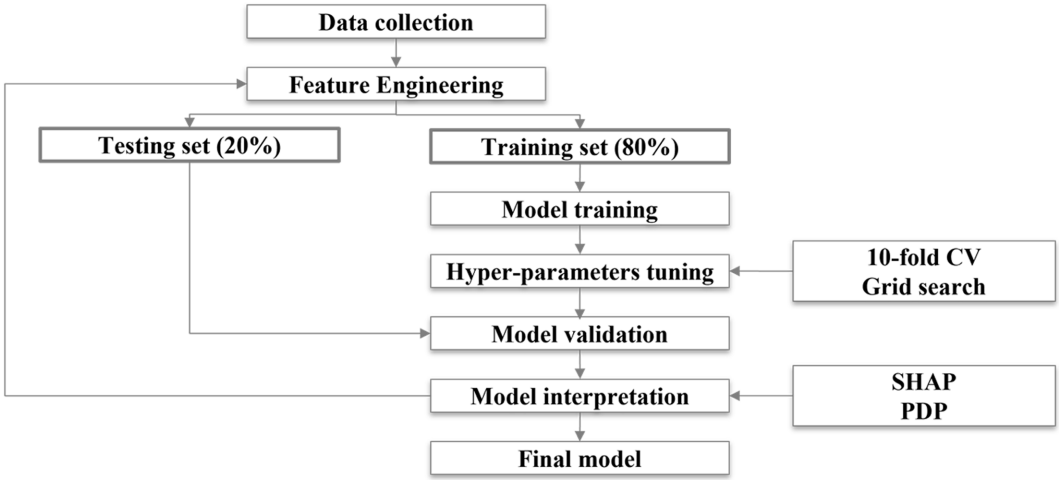


Figure 4. Modeling process of transverse reinforcement ratio prediction model.

3) A method for the design of transverse reinforcement in reinforced concrete structures based on the ductility requirements of structural members is proposed. This method breaks through the limitations of current codes, which mainly rely on empirical reinforcement provisions based on seismic design measures. It aims to achieve targeted and quantified transverse reinforcement allocation in reinforced concrete structures.

5.2. Prospects

1) The seismic performance-based design method based on the predetermined yield mode can overcome the limitations of existing codes regarding regularity, new structural systems, and the application of new materials. It can more directly control the failure modes of structures.

2) The seismic performance-based design method based on the predetermined yield mode and the transverse reinforcement design method based on the ductility requirements of members can be closely integrated with sophisticated seismic performance evaluation to achieve quantified and precise seismic performance design.

3) The integration of the seismic performance-based design method based on the predetermined yield mode, the transverse reinforcement design method based on the ductility requirements of members, and intelligent methods such as big data and machine learning can advance the development of intelligent design in high-rise building structures.

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