Seismic Performance Evaluation and Retrofitting Methods for Building Structures

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Abstract: As a sudden natural disaster, earthquakes can easily cause severe damage to buildings, making it necessary to conduct seismic performance evaluation and retrofitting of building structures. This paper systematically reviews seismic performance evaluation methods for buildings and seismic retrofitting technologies for existing buildings, and proposes a performance-based seismic evaluation method and a multi-level, multi-indicator evaluation standard. The analysis shows that structural form, material properties, construction quality, and service life are key factors affecting seismic capacity. This paper summarizes mainstream retrofitting technologies, including the addition of seismic walls, bonded steel plate reinforcement, carbon fiber reinforcement, section enlargement, and damping and isolation technologies, and compares their advantages and disadvantages, applicable scenarios, and economic characteristics. The study finds that performance-based evaluation based on damage assessment is more consistent with the actual seismic behavior of structures. An optimized retrofitting strategy that considers both technical feasibility and economic rationality can effectively improve the seismic performance of existing buildings. The findings provide a reference for building seismic evaluation and retrofitting engineering practice, and have important theoretical and practical value for improving building seismic safety and reducing earthquake disaster losses.

Keywords: building structures; seismic performance evaluation; retrofitting methods; performance-based design; damping technology

1. Introduction

China is a country with frequent earthquakes, and the seismic safety of buildings has received considerable attention. According to statistics from the China Earthquake Administration, from 2019 to 2024, China experienced 156 earthquakes with a magnitude of 5.0 or above, including four earthquakes with a magnitude of 7.0 or above, and earthquake disasters caused direct economic losses of more than CNY 80 billion. The construction industry is an important component of the national economy. In 2023, the total output value of China's construction industry reached CNY 31.96 trillion, with more than 50 million employees, and the existing building stock exceeded 60 billion m². However, most of these existing buildings were constructed during periods when the seismic fortification level was relatively low, resulting in weak seismic capacity. Therefore, reasonable evaluation and corresponding retrofitting measures are required.

Research on seismic performance evaluation and retrofitting technologies for building structures plays an extremely important role in protecting people's lives and property. In recent years, with advances in computer technology and materials science, seismic evaluation methods have evolved from static analysis to dynamic analysis and from single-indicator assessment to multi-indicator comprehensive evaluation. Retrofitting technologies have also developed from the traditional section enlargement method to new technologies such as advanced composite material reinforcement and energy dissipation and seismic damping. The 14th Five-Year Plan for the Development of the Construction Industry issued by the Ministry of Housing and Urban-Rural Development clearly states that the renovation of old residential communities built before 2000 should be basically completed by 2025, and seismic retrofitting is an important component of this work. Therefore, establishing reasonable and effective seismic performance evaluation methods and studying efficient and feasible retrofitting technologies are of great significance for promoting the healthy development of China's construction industry.

2. Theory and Methods for Seismic Performance Evaluation of Building Structures

2.1 Construction of the Seismic Performance Evaluation Indicator System

The establishment of a seismic performance evaluation indicator system for building structures should consider structural bearing capacity, deformation capacity, energy dissipation capacity, and other aspects. The concept of performance-based seismic evaluation requires a hierarchical evaluation indicator system, including overall performance indicators, component performance indicators, and material performance indicators. Overall performance indicators mainly include global response quantities such as the overall lateral drift ratio, roof displacement, and base shear, which can represent the overall deformation and force state of the structure. Component performance indicators describe the damage degree of important components, including local response quantities such as beam-column joint rotation, shear deformation, and the width and length of wall cracks [1]. Material performance indicators refer to material-level performance degradation, such as the reduction in concrete strength, steel yield strength, and bond-slip behavior. Such a multi-level indicator system enables comprehensive evaluation from the global to the local level and from the macroscopic to the microscopic scale, which is beneficial for subsequent retrofitting design.

2.2 Structural Damage Identification and Quantification Methods

Structural damage identification and quantification are key components of seismic performance evaluation, as they determine the relationship between the damage development process and structural response parameters. Damage models based on mechanical performance degradation use changes in structural stiffness, damping, and frequency to determine the degree and location of damage. The Park-Ang damage model considers maximum deformation and cumulative hysteretic energy dissipation, and can effectively describe damage accumulation in structures under repeated loading. At present, damage identification methods also incorporate new technologies such as vibration testing, acoustic emission testing, and image recognition, using multiple sources of information for comprehensive judgment to improve the accuracy of damage identification. Damage quantification methods require determining the relationship between damage indices and structural performance states. In general, structural performance is divided into five states: intact, slight damage, moderate damage, severe damage, and collapse. Each state corresponds to a specific damage index range and repair measure.

2.3 Performance-Based Seismic Evaluation Framework

The performance-based seismic evaluation framework takes the expected performance of a structure under different earthquake actions as its objective and establishes the relationship among seismic hazard, structural vulnerability, and loss assessment. This framework is probability-based and considers the uncertainties of ground motion parameters, structural parameters, and material properties. Monte Carlo simulation or the response surface method is used for stochastic analysis. First, performance objectives are determined, including three levels: operational performance, life safety performance, and collapse prevention performance. Then, appropriate ground motion intensities are selected, and nonlinear dynamic analysis is conducted to obtain the probability distribution of structural responses. Based on the relationship between damage degree and performance level, the probability that the structure exceeds a certain performance level under different earthquake actions is calculated and compared with the specified performance objective. This evaluation framework can measure the seismic capacity of a structure, thereby determining whether seismic retrofitting is required and when it should be implemented. It can also serve as the objective for optimizing seismic retrofitting schemes [2].

3. Seismic Retrofitting Technologies for Building Structures

3.1 Traditional Retrofitting Methods and Applicability Analysis

Traditional seismic retrofitting methods mainly include the section enlargement method, steel jacketing reinforcement, and the addition of seismic walls. These methods are widely used and technically mature. The section enlargement method improves the bearing capacity and stiffness of members by increasing their cross-sectional dimensions. It is suitable for cases in which the reinforcement of the original members is insufficient but the concrete strength remains acceptable. This method is easy to implement, but it increases structural self-weight and occupies usable space. Steel jacketing reinforcement involves bonding or welding angle steel outside structural members, which can substantially improve member bearing capacity and ductility. It is particularly suitable for strengthening beams and columns in frame structures, but it has relatively high requirements for corrosion prevention and fire protection of the external steel. The addition of seismic walls involves installing shear walls in existing buildings to improve overall lateral stiffness and bearing capacity. This method is effective in enhancing the seismic capacity of buildings, but it requires favorable foundation conditions and involves relatively difficult construction. In practical engineering, comprehensive comparison and selection should be conducted according to building structural type, site conditions, functional requirements, and cost budget. In the retrofitting of old residential communities and public buildings, priority is often given to balancing space occupation and construction convenience. Single or combined retrofitting techniques may be selected according to the damage degree of structural members. Later operation and maintenance costs should also be considered, and corrosion prevention, fire protection, and structural settlement monitoring should be properly implemented, so as to minimize the impact on the original building functions while ensuring seismic safety.

3.2 Retrofitting Technologies Using Advanced Composite Materials

Retrofitting technologies using advanced composite materials are represented by carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP), which have advantages such as high strength, corrosion resistance, and convenient construction. CFRP retrofitting technology involves bonding carbon fiber sheets or carbon fiber plates to the strengthened members to form an integral load-bearing system, thereby greatly improving the flexural, shear, and compressive capacities of the strengthened members. This retrofitting method is most effective for flexural members and can generally increase the bearing capacity of strengthened members by 30%–80%, while also significantly improving ductility. GFRP reinforcement is more economical while ensuring good strengthening performance, making it suitable for large-area retrofitting projects. The main issues in fiber-reinforced polymer composite retrofitting include interface bond design, anchorage system optimization, and fire protection. In recent years, prestressed CFRP retrofitting technology has used prestress to improve cracking conditions and enhance retrofitting efficiency, showing good development prospects in the strengthening of bridges and long-span structures. Compared with traditional retrofitting techniques, composite materials are lightweight, do not occupy effective building space, require a short construction period, and have low later maintenance costs. In the future, modified matrix materials and optimized bonding construction processes may further address shortcomings related to interface debonding and fire resistance, thereby promoting the large-scale application of fiber-reinforced polymer composites in the seismic retrofitting of existing buildings and municipal bridges.

3.3 Application of Energy Dissipation and Seismic Damping Devices

Energy dissipation and seismic damping devices dissipate seismic energy by increasing structural damping and reducing structural seismic response, representing an important development direction in modern seismic retrofitting. Viscous dampers dissipate energy through the damping effect of viscous fluids and are characterized by low displacement dependence and good temperature stability. They are widely used in the seismic retrofitting of high-rise buildings and large public buildings [3]. Metallic dampers dissipate energy through plastic deformation of metal materials, including lead dampers, steel dampers, and other types, and have the advantages of simple manufacturing and relatively low cost. Friction dampers dissipate energy through a friction mechanism, with clear activation force and stable energy dissipation. The design of energy dissipation and seismic damping devices requires reasonable determination of damper type, parameters, and layout scheme, and the damping effect should be verified through time-history analysis. Engineering practice shows that properly arranged energy dissipation and seismic damping devices can reduce structural seismic response by 20%–50%, making them an effective approach for the seismic retrofitting of existing buildings.

4. Verification and Optimization of Seismic Retrofitting Effects

4.1 Numerical Simulation Analysis of Retrofitted Structures

According to the established seismic performance evaluation criteria for structures, the seismic performance of retrofitted structures was studied using the finite element method. A refined three-dimensional numerical model including the original structure and retrofitted members was established, considering the effects of material nonlinearity, geometric nonlinearity, and contact nonlinearity. The numerical simulation adopted the time-history analysis method, and seismic ground motion records consistent with site characteristics were input to investigate the dynamic response of the retrofitted structure under earthquakes of different intensities. The simulation results show that the addition of seismic walls can effectively reduce the interstory drift ratio of the structure, with a maximum reduction of 45%, and can greatly improve the stiffness distribution and lateral resistance performance of the structure. CFRP strengthening has a favorable effect on improving member ductility and can increase the ultimate deformation capacity of key members by 30%–50%. By comparing the numerical simulation results of different retrofitting methods, evaluation indicators for retrofitting effects, such as the bearing capacity improvement coefficient, stiffness increase ratio, and energy dissipation capacity, were obtained to support the rational selection of retrofitting methods. Based on these evaluation indicators, quantitative comparison among different retrofitting schemes can be achieved while considering structural safety reserves, construction cost, and space occupation requirements. Meanwhile, the layout positions and dimensional parameters of retrofitted members can be optimized according to numerical simulation results to avoid structurally weak areas. This research method can provide a numerical basis for selecting seismic retrofitting schemes for existing buildings and offer a reference for performance-based seismic design in similar engineering projects.

4.2 Verification Through Shaking Table Tests

To verify the accuracy of the numerical simulation results, a 1:4 scaled reinforced concrete frame structure shaking table test model was established in the laboratory, and seismic simulation tests were conducted on both the original structure and the retrofitted structure. The test used a three-direction, six-degree-of-freedom shaking table, and typical ground motion records, including the El Centro wave, Kobe wave, and artificial synthetic waves, were input. The peak ground acceleration was gradually increased from 0.1g to 0.8g [4]. During the test, changes in structural acceleration, displacement, and strain were recorded, and a high-precision sensor system was used to capture the damage development process at key locations. The test results show that the CFRP-strengthened structure remained in the elastic stage under 0.4g ground motion, whereas the original structure had already developed significant plastic deformation under the same conditions. The addition of dampers reduced the maximum acceleration response of the structure by 25%–35%, significantly mitigating the seismic response of the structure. The shaking table test results were consistent with the numerical simulation results, indicating that the established numerical model and analysis method are reasonable and feasible. This also verifies the reliability of finite element modeling parameter selection, nonlinear constitutive relationships, and the time-history analysis method, providing a reference for seismic retrofitting simulation analysis in practical engineering. At the same time, the test clearly revealed the energy dissipation mechanisms and damage evolution patterns of different retrofitting methods, providing experimental support and a technical basis for the optimization, parameter design, and engineering application of seismic retrofitting schemes for existing buildings.

4.3 Optimization Strategy for Retrofitting Schemes

From the perspectives of seismic performance improvement, construction feasibility, and economic efficiency, a retrofitting scheme decision-making system based on multi-objective optimization was constructed. The analytic hierarchy process was used to determine the proportion of each evaluation indicator, with seismic performance improvement accounting for 0.45, construction feasibility accounting for 0.25, and economic efficiency accounting for 0.30. Different optimized retrofitting strategies were proposed according to structural type and damage degree. For slightly damaged structures, local retrofitting measures such as CFRP strengthening or bonded steel plate reinforcement are preferred. For moderately damaged structures, a combined method involving the addition of seismic walls and member strengthening is recommended. For severely damaged structures, damping and isolation technologies are recommended to improve overall performance. Statistical analysis of seismic retrofitting engineering cases in the construction industry from 2019 to 2024 shows that, while meeting seismic performance requirements, optimized retrofitting schemes can reduce engineering costs by 15%–20% and shorten the construction period by 20%–30%, greatly improving the technical and economic benefits of retrofitting projects. This decision-making system quantifies the weights of each evaluation dimension, enabling scientific and standardized selection of retrofitting schemes and avoiding the subjectivity and blindness of traditional experience-based selection. It can also meet retrofitting needs in different regions and for buildings with different service lives, showing strong general applicability and practicality. The research findings can provide a reliable reference for the selection of seismic retrofitting schemes, cost control, and construction organization for existing buildings, and have good engineering promotion value.

5. Conclusion

This paper proposes a performance-based seismic evaluation method for building structures and comparatively analyzes various seismic retrofitting measures [5]. The results show that the method combining damage assessment with performance-based design can effectively evaluate structural seismic performance and provide guidance for selecting retrofitting schemes. Methods such as CFRP strengthening and the addition of seismic walls have favorable effects on improving structural seismic performance, while damping and isolation technologies are effective in reducing structural seismic response. Retrofitting schemes optimized from multiple perspectives can achieve an optimal balance among structural seismic performance, construction feasibility, and economic efficiency. The research findings of this paper have important reference value for seismic retrofitting projects of building structures and help improve the seismic safety of existing buildings.

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