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Research Progress on Earthquake Collapse Resistance of Reinforced Concrete Frame Structures

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Abstract: With the development of modern society, people put forward higher requirements for building safety, which makes the construction project face new challenges. Reinforced concrete frame structure as a common engineering type, although the construction technology has been relatively mature, but its earthquake collapse ability still needs to be strengthened. This paper analyzes the specific factors that affect the seismic collapse ability of reinforced concrete frame structure, summarizes the previous research results, and puts forward innovative application of fiber-reinforced polymer (FRP) composite materials, play the role of smart materials, improve the isolation and energy dissipation devices, etc., to promote the continuous optimization of reinforced concrete frame structure design, and show better seismic performance.

Keywords: Reinforced concrete frame structure; Seismic performance; Collapse; Research status

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1. Introduction

At present, as a common form of building structure, the seismic collapse performance of reinforced concrete frame structure has attracted much attention. It is of great significance to improve the safety of buildings in earthquakes by deeply exploring the factors that affect the collapse resistance of the structure.

2. Factors affecting collapse resistance

2.1. Structural design parameters

2.1.1. Column-to-beam stiffness ratio analysis

Jizhi *et al.* put forward the design concept of "strong column and weak beam," thinking that the beam-column linear stiffness ratio is the key factor affecting the flexural stiffness of reinforced concrete frame structures with bending moment resistance, and put forward the limit setting values for different seismic grades. When the beam-column linear stiffness ratio is less than the limit setting value, the beam-hinge mechanism can be realized. In the experiment, ⅓ scale models of two 3-hole, 3-story reinforced concrete frame structures are constructed, and a series of nonlinear dynamic analyses are carried out for the numerical models that do not conform to or conform to the linear stiffness ratio limits of beam-columns by low reciprocating load tests. Based on the test results, it can be seen that the column area of the structure with large beam-column linear stiffness is more susceptible to earthquake damage, resulting in increased energy consumption of the structure. Therefore, the factor of beam-column linear stiffness ratio should be considered comprehensively when optimizing the seismic design of reinforced concrete frame structures [1]. By studying the isolation effect of a 15-story reinforced concrete building under the change of beam-column stiffness ratio,

Chun adjusted the vibration period between the superstructure and the isolation layer to adjust the beam-column stiffness ratio. When the isolation period was 2.5 times longer than the natural vibration period of the undisturbed structure, the beam-column stiffness ratio was relatively small, and the damage to the reinforced concrete building structure was reduced by about ⅓. This shows that reducing the stiffness ratio of the beam to column by increasing the safety of the superstructure is beneficial to strengthening the seismic resistance of reinforced concrete frame structures [2].

Chen *et al.* believed that in the seismic response analysis of reinforced concrete frame structures, due to the large stiffness of the beam-column joint area, a certain rigid region needs to be set in the construction process, and the rigid region will directly affect the seismic response ability of the structure. Moreover, different rigid region setting methods are compared based on the fiber finite element method of the flexibility method, to determine a more appropriate stiffness ratio of the beam-column. Effectively guarantee the earthquake resistance of reinforced concrete frame structure and reduce post-earthquake damage [3].

2.1.2. Different beam-column connection types and effects

By analyzing the influence on the seismic performance of reinforced concrete frame structures under the new flexible connection and energy-dissipating connection modes of beam-columns, Holley *et al.* used finite element software to conduct static push nappe analysis and elastoplastic time history analysis and compared the damage mechanism under horizontal earthquake action and seismic performance under dynamic load. Based on the test results, it can be seen that when the rigid beam-column connection is adopted, the bolts at the connection joints are damaged, and the frame beams are seriously damaged. When flexible connections and energy-consuming connections are used, the connection bolts are kept in good condition. In addition, compared with the flexible connection mode, the damage state of the main structure under horizontal earthquake is lighter, and the displacement response of the beam-column energy-dissipating connection mode is reduced by 24.8%, 32.9%, and 36.5% compared with the flexible connection mode [4].

Sun *et al.* used different beam-column connection methods to compare and analyze the whole process of deformation and failure of reinforced concrete frame structures under earthquake action, to analyze the influence of beam-column connection methods on the seismic performance of structures. According to the research results, the relative displacement between the wall panel and the beam-column will occur when the card connection method is given by the atlas, but the L-shaped card can play a certain restraint role. When the beam and column are connected by the existing installation process of the enterprise, the wall panel and the main frame have good integrity from the beginning of the loading, and the loading stage has a great contribution to the lateral stiffness and lateral bearing capacity of the structure, but the wall panel has an out-of-plane deflection in the later stage. This shows that the two kinds of beam-column connection have their advantages and disadvantages, and the beam-column connection should be optimized reasonably [5].

Cheng *et al.* believed that the connection of beam-column joints of prefabricated reinforced concrete structures is very important. By innovatively constructing prefabricated partial steel-reinforced concrete frame structures and setting steel bones in the connection area of components and the core area of beams and columns, the bearing capacity of the frame structures is enhanced, which is three times that of traditional reinforced concrete specimens. Moreover, the degradation of bearing capacity and stiffness is slower, and the seismic performance is superior. It inspires the optimization of beam-column connection mode of reinforced concrete frame structures [6].

2.1.3. Floor system design considerations for seismic resistance

Nguyen believed that in reinforced concrete frame structures, the variation of floor parameters would affect the stiffness of beam-column joints, and thus affect the seismic collapse performance of the frame structures. When the floor stiffness is increased, it is beneficial to increase the restraint ability of the beam, and reduce the deflection of the beam, to avoid the excessive deflection of the beam after the earthquake, resulting in the deformation and damage of the frame structure.

Therefore, in the reinforced concrete frame structure, to improve its seismic resistance, it is necessary to strengthen the rigidity of the floor system, thereby enhancing the bearing capacity and rigidity of the beam, rationally planning the size and scale of the floor, and then ensuring the safety and reliability of the frame structure [7]. Xu found that the buildings with reinforced concrete frame structures were seriously damaged by earthquake damage statistics. After analyzing the failure mechanism, he proposed to further improve the seismic design of the floor system, strengthen the seismic performance of the frame structure through diversified measures and methods, make the building have stronger deformation resistance and stability, and strengthen the building quality of reinforced concrete frame structure [8].

2.2. Material properties

2.2.1. Concrete strength, ductility, and high-performance varieties

Wang *et al.* believed that compared with ordinary concrete, reactive powder concrete has higher toughness, strength, and significant application value. By studying the long-term performance and durability of reactive powder concrete, such as impact resistance, fatigue resistance, chloride ion resistance, and other indicators, the latest research results are reviewed and proposed in the design of reinforced concrete frame structures. Reactive powder concrete should be used to replace traditional concrete, thereby strengthening the seismic performance of the structure, resisting the damage caused by earthquakes with high-quality concrete, and promoting the continuous optimization of reinforced concrete frame structures [9].

In addition to reactive powder concrete, the selection of concrete materials with higher performance should consider the section height and steel ratio. The section height and steel ratio have the greatest impact on the damage to steel-reinforced high-strength concrete (SRHSC) beams, and the section size and axial compression ratio have the greatest impact on the damage to SRHSC columns, which lays a foundation for the application of concrete materials in the seismic design of frame structures. Moreover, some studies have shown that based on the concept of "strong column and weak beam," it should be combined with the strength and ductility of concrete to select a more appropriate strength grade of concrete, thus ensuring the seismic performance of the frame structure.

2.2.2. Steel reinforcement characteristics and bond behavior

Zheng *et al.* proposed that steel bar corrosion is formed by the chemical reaction of iron elements on its surface with oxygen and water. Proper corrosion can enhance the surface roughness of steel bars, and then strengthen the mechanical occlusion between concrete and steel bars to form higher bonding properties. However, excessive corrosion will lead to loose corrosion products on the surface of steel bars, resulting in a decline in the bonding strength between steel bars and concrete. In this paper, the bond strength and bond stress-slip constitutive relation of the corroded steel bars are analyzed by analyzing the change of bond property of the corroded steel bar. It is suggested that the research on the bonding properties under the splitting failure mode should be strengthened, and the prediction model of bonding force should be built based on the width of the rust expansion crack, to better control the corrosion strength of steel bars. The bond between reinforcement and concrete can be guaranteed, and the seismic resistance of reinforced concrete frame structures can be improved [10].

Zhou researched the bonding properties of corroded reinforced concrete members and found that the volume of steel bars will increase after corrosion, resulting in splitting effect stress in concrete. This results in a significant decrease in the bond property of steel bars. Therefore, the finite element method was used to conduct simulation calculation, analyze the degradation mechanism of the bond properties of corroded reinforced concrete members, find out the specific influencing factors, and provide inspiration for the design optimization of reinforced concrete frame structures, to strengthen its seismic performance [11].

2.2.3. Long-term material degradation factors and impacts

To investigate the influence of construction joints on the seismic resistance of reinforced concrete frame structures, Wu conducted a nonlinear time-history analysis with the new model. According to the research results, with the extension of the use time of the building, the construction material will degrade, resulting in the continuous expansion of the construction joint, and the construction joint will increase the displacement of the top of the frame structure, resulting in the change of the displacement distribution between the layers, and further aggravate the local response of key components, resulting in the decline of the seismic performance of reinforced concrete frame structures. Therefore, it is necessary to optimize construction materials and processes, minimize the width of construction joints, and reduce the adverse impact on the seismic resistance of reinforced concrete frame structures [12].

According to the linear damage theory, Zhang *et al.* built the damage index calculation model of concrete and reinforced concrete materials, combined with the weighted coefficient, and calculated the damage index of materials, reinforced concrete components, floors, and frame structures more accurately and efficiently, providing an effective basis for targeted optimization of materials and better resistance to earthquake damage. Ensure the high-quality development of reinforced concrete frame structures [13].

3. Strengthening and retrofit strategies

3.1. Fiber-reinforced polymer (FRP) composites in retrofit

To strengthen the seismic collapse ability of reinforced concrete frame structure, fiber-reinforced polymer (FRP) composite materials should be flexibly used to further strengthen the beam and column joints, strengthen the axial bearing capacity of the frame structure, and better resist earthquake damage.

Firstly, because FRP has good strength and stiffness, it can effectively restrain the lateral deformation of reinforced concrete columns and significantly improve the axial bearing capacity of columns. For example, in the seismic reinforcement project of old teaching buildings, the use of carbon fiber reinforced polymer (CFRP) to strengthen the columns can effectively improve the ultimate bearing capacity of concrete columns and enhance the stability of the overall structure under earthquake action.

Secondly, under the repeated action of earthquakes, FRP-confined concrete columns can produce more plastic hinges, increase the energy dissipation capacity of the structure, avoid brittle failure of the column, and the structure has better deformation and energy dissipation capacity under strong earthquakes.

Thirdly, compared with the traditional strengthening method, FRP material is light in weight, simple in construction, does not require large construction equipment and wet operations, can greatly shorten the construction period, reduce the impact on the use of building functions, strengthen the earthquake collapse capacity of the frame structure at the same time, and increase the economic benefits of the building [14]. Fourthly, the construction personnel should paste FRP strips or adopt FRP stirrup on the side of the beam, to significantly improve the shear-bearing capacity of the beam. For example, in the reinforcement of bridge structure, the stirrup made of aramid fiber reinforced polymer (AFRP) is used to replace part of the traditional steel stirrup, further improve the shear strength of the beam, and effectively improve the failure mode of the beam under the strong shear force caused by the earthquake, to avoid the sudden collapse of the structure due to shear failure.

3.2. Smart materials and their potential use in strengthening

In the seismic collapse optimization of reinforced concrete frame structure, the positive role of smart materials should be played to further strengthen the intelligent level of frame structure, and real-time monitoring of structural health status, to ensure the structural performance, improve its seismic resistance, and avoid continuous collapse.

Firstly, the construction personnel should introduce the shape memory alloy (SMA) material, which has a strong self-resetting ability, and apply it to the reinforced concrete frame structure node, which can strengthen the self-resetting ability of the frame structure, so that the connector can restore the initial state after the earthquake, reduce the residual deformation of the structure, and then ensure the recovery of the frame structure after the earthquake.

Secondly, the construction personnel should introduce advanced piezoelectric materials and combine them with intelligent control elements to form an efficient intelligent damper, which automatically adjusts the damping size based on the vibration of the structure to further strengthen the safety of the building.

Then, in the design of reinforced concrete frame structure, the application of magnetorheological fluid (MRF) should be strengthened, the MRF device should be applied in the supporting members, and the stiffness of the support can be automatically adjusted according to the intensity of ground vibration and the response of the structure so that the structure can maintain good seismic performance and improve the collapse resistance of the structure.

3.3. Base isolation and energy dissipation devices for existing structures

Designers should improve the internal components of the reinforced concrete frame structure, improve the isolation and energy dissipation devices, further strengthen the seismic ability of the structure, and effectively prevent collapse.

Firstly, in the design of the frame structure, the application of rubber isolation bearings should be improved, the material and process of the isolation bearings should be optimized, the mechanical properties should be maintained, the isolation effect of the structure should be sustained, and reliable, the seismic energy should be consumed and isolated through its deformation, and the direct effect of seismic forces on the superstructure should be reduced [15].

Secondly, the designer should optimize the metal yield energy dissipation device, adopt mild steel dampers, quickly enter the yield state, consume a lot of seismic input energy, and significantly reduce the seismic response of the main structure. Designers should also connect the energy-consuming device with the frame structure, not change the original structure form, and better strengthen the seismic performance of the structure, thereby improving the safety of the building.

4. Summary

To sum up, factors such as beam-column stiffness ratio, beam-column connection mode, seismic design of floor system, concrete performance, reinforcement bonding force, and material aging will significantly affect the seismic resistance of reinforced concrete frame structures. Therefore, it is necessary to study these influencing factors in detail, and actively introduce new technologies, new processes, and new materials to promote the continuous optimization of reinforced concrete frame structure.

Disclosure statement

The author declares no conflict of interest.

References

[1] Su J, Liu B, Xing G, et al. Influence of Beam-to-Column Linear Stiffness Ratio on Failure Mechanism of Reinforced Concrete Moment-Resisting Frame Structures[J]. Advances in Civil Engineering, 2020, 2020(1): 9216798.

[2] Chun Y, Hur M, 2015, Effects of Isolation Period Difference and Beam-Column Stiffness Ratio on the Dynamic Response of Reinforced Concrete Buildings. International Journal of Concrete Structures and Materials, 9(4): 439–451.

[3] Chen L, Feng Y, 2012, Influence of Stiffness Zone on Seismic Performance of Reinforced Concrete Frame Structures. Industrial Building, 42(09): 75–78.

[4] He L, Chong X, Sha H, et al., 2024, Research on Seismic Performance of Reinforced Concrete Frame Structure of External UHPC Curtain Wall with Different Connection Modes. Earthquake Research, 47(01): 94–104.

[5] Sun J, Li B, Meng C, et al., 2019, Siding with Beam-Column Connection Mode Between the Structure Seismic Performance Influence [J]. Journal of Building Structures, 49(08): 16–21.

[6] Cheng W, Song Y, Wang J, 2015, Experimental Study on Seismic Performance of Joints in Beams and Columns of Prefabricated Partial Steel-Reinforced Concrete Frames. Journal of Dalian University of Technology, 55(02): 171–178.

[7] Nguyen SH, Tran QV, Nguyen HQ, 2019, Influence of Parameters Reinforced Concrete Floor to Stiffness of Beam—Columns Connector in Composite Structures. International Journal of Innovative Technology and Exploring Engineering (IJITEE), 8(10): 3071–3075.

[8] Xu Kaiming, 2012, Seismic Damage Analysis and Research on Seismic Measures of Reinforced Concrete Frame Structure Houses. Science and Technology Vision, 2012(17): 191–193.

[9] Wang K, Lin J, Yang W, et al., 2017, Research Progress on Long-Term Properties and Durability of Reactive Powder Concrete. Concrete, 2017(11): 27–30 + 34.

[10] Zheng S, Yang J, Zheng Y, et al., 2020, Review on Bond Slip Performance of Corroded Reinforced Concrete. Materials Reports, 34(S2): 1221–1226.

[11] Zhou J, 2016, Study on the Degradation of Bonding Properties of Corroded Reinforced Concrete Members. Housing and Real Estate, 2016(36): 290–291.

[12] Yu J, Liu X, Liang X. The influence of construction joint on the seismic behavior of reinforced concrete frame structure[J]. Advances in Structural Engineering, 2017, 20(7): 112 5-1138.

[13] Zhang Y, Chen J, Du X, et al., 2015, Research on Material-Based Damage Model of Multi-Storey Reinforced Concrete Frame Structures. Building Structures, 45(06): 7–13.

[14] Del Rey Castillo E, Griffith M, Ingham J. Seismic behavior of RC columns flexurally strengthened with FRP sheets and FRP anchors[J]. Composite Structures, 2018, 203: 382-395.

[15] Orfeo A, Tubaldi E, Muhr A H, et al. Mechanical behaviour of rubber bearings with low shape factor[J]. Engineering Structures, 2022, 266: 114532.