Research on RC Frame Structure's Resistance to Continuous Collapse

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Abstract. A typical 8-story RC frame structure model with floor is established by using ABAQUS finite element software. The nonlinear static analysis method and the incremental dynamic analysis method are used to explore the influence of the floor slabs after the demolition on the continuous collapse resistance of the RC frame structure at the same time. Determine the most reasonable amount of reinforcement that meets the requirements for continuous collapse resistance of the frame beams of each layer, and the layer height that is most beneficial to the structure's continuous collapse resistance. It is concluded that the floor can greatly improve the continuous collapse resistance of the overall structure, and the nonlinear static analysis is conservative; the amount of longitudinal reinforcement in each frame beam should be increased by 1.9% ~ 2.9% to meet the most reasonable requirements for continuous collapse of the frame beam; the floor height is between 4.3 and 4.8 meters, which is the most ideal state for the structure to resist continuous collapse.

1.Introduction

The continuous collapse of a building refers to the local damage caused by a sudden disaster or external load within the service life of the building, and the continuous damage along the structural members leads to an overall disproportionate collapse [1]. Although the continuous collapse is a small-probability event, this damage may trigger a domino effect and bring huge disasters to humans and society. Therefore, the structure's anti-continuous collapse design is an essential and important link in preventing the continuous collapse of the structure.

From the gas explosion collapse of the apartment in Luoranjiao, UK in 1968 and the Datong gas explosion in Shanxi in 2007, to the collapse of the river in New Delhi, India, in 2010, researchers at home and abroad gradually paid attention to the continuous collapse of the structure. Continued revision of anti-continuous collapse specifications in accordance with the structural characteristics of various countries directly promoted the development of structural anti-continuous collapse systems. However, China's anti-continuous collapse research started later than foreign countries. The current structural design codes and standards [2] have few provisions on continuous collapse and do not give specific design methods and failure criteria. Wang Hao et al. [3] carried out a collapse test on a single-layer RC plane frame and analyzed the resistance mechanism of continuous horizontal collapse; Yi Weijian et al. [4] proposed a method for estimating the bearing capacity of catenary mechanism through RC plane frame test. Zhou Yun et al. [5] compared and analyzed the dynamic response of the remaining structure after the failure of the corner columns of the RC frame structure.
through the finite element model and field tests. These studies raise the awareness of resistance to progressive collapse of RC frame structure, but previous studies in order to simplify the problem and focuses on the impact beams, columns, structure, ignoring the role of the floor, making the results and are somewhat anti-progressive collapse conservative.

This paper discusses the anti-collapse performance of the remaining structure after dismantling the frame columns using the nonlinear static analysis method and nonlinear dynamic analysis under the consideration of the slab action in the RC frame structure, and draws relevant conclusions.

2. Resistance to continuous collapse failure
At present, there are many methods for structural anti-continuous collapse design, such as demolition component design and conceptual design. This paper adopts the method of removing components and sequentially removes the corresponding structural frame columns in accordance with the removal order in GSA2003 [6] and DOD2010 [7] codes for numerical simulation of continuous collapse of the entire structure. And in the process of removing the components, it is necessary to analyze only one frame column at each time and consider the impact of each removal separately.

The famous domestic expert Lu Xinzheng [8] believes that if the maximum vertical displacement of the removed point during the component removal process is less than 1/5 of the length of the shortest frame beam connected to the point, the structure will not collapse continuously. The usefulness of this failure criterion is fully confirmed in its tests, and beyond this limit, the structure will risk an irreversible collapse. Therefore, this article refers to this failure criterion to determine whether the structure has continuously collapsed.

3. Structural modeling
According to the "Specifications for the Design of Concrete Structures" [2], an 8-story typical RC frame structure analysis model with a seismic fortification intensity of 6 degrees, a seismic level of 2 and a site category of 3 was established using PKPM software. Among them, the main design information of the beam and column cross-section dimensions of the model is shown in Table 1. According to the requirements of "Building Structure Load Specification" (GB 50009-2012) [9], the standard value of the floor constant load is 26 kN/m, the standard value of the room live load is 22 kN/m, and the standard value of the corridor live load is 23.5 kN/m. The standard value of roof constant load is 27 kN/m, the roof live load is snow load 20.4 kN/m, and the standard value of partition wall and maintenance wall load is 8 kN/m.

| Table 1. Structure parameter table |
|-----------------------------------|
| Beam section size(mm) | Column section size(mm) | Longitudinal reinforcement grade | Stirrup grade | Concrete grade | Board thickness (mm) |
|------------------------|--------------------------|---------------------------------|---------------|---------------|---------------------|
| 300*600                | 450*450                  | HRB400                          | HRB335        | C30           | 150                 |

This article refers to the anti-continuous collapse failure criterion proposed by the famous domestic expert Lu Xinzheng [7] to determine whether the structure has suffered continuous collapse. Lu Xinzheng [7] believed that if the maximum vertical displacement of the removed point during the component removal process is less than 1/5 of the length of the shortest frame beam connected to the point, the structure will not collapse continuously. The usefulness of this damage criterion was fully confirmed in its tests. Import the model into ABAQUS finite element software. The perspective view of the model and the positions of the frame columns to be removed are shown in Figures 1 and 2.
4. Analysis of structural layer height on continuous collapse resistance

Due to space limitations, this article only describes the case of removing the bottom pillar. Based on the order of the method of removing components, the height of the first layer of the structure is adjusted before each time the column is removed, starting from a height of 2.8m and increasing at 0.3m intervals. The relationship between the maximum vertical displacement of the failure point of the model and the height of the floor under the action of the slab is considered by ABAQUS software analysis (Figure 3). In Figure 3, the vertical displacement that occurs after the corner column fails is the largest, followed by the long side middle column, the short side middle column, and the inner column. When the floor height is 2.8 ~ 4.3m, the influence of the angular column on the vertical displacement of the overall structure becomes a downward trend. When the floor height is 4.3m, the vertical displacement is the smallest. When the floor height exceeds 4.3m, the vertical displacement increases with the floor height. The displacement-floor height curves of the long-, short-side middle and internal columns after failure have generally tended to coincide, and the vertical displacements generated were much smaller than those caused by the failure of the corner columns. Therefore, it is known that the corner pillar plays an important role in the process of resisting continuous collapse. Strengthening the structure of the corner pillar is the key to the design of continuous collapse resistance. It is recommended to design the floor height to be 4.3 ~ 4.8m, which can minimize the vertical collapse displacement of the structure.

5. Influence of reinforcement amount of frame beam on continuous collapse resistance of structure

After the failure of the corner column, the frame beam easily loses its vertical support and quickly fails. When designing the continuous collapse resistance, the frame beam must be required to meet the minimum reinforcement ratio of continuous collapse resistance. The original reinforcement ratio of the structural frame beam is designed based on the multi-layer reinforced concrete frame structure commonly used in China, and is obtained by the PKPM software.

The floor unit is removed to obtain a plane frame model without floor, and the influence of the
amount of reinforcement of the frame beam on the collapse resistance of the structure is compared and analyzed. The non-linear dynamic demolition component method can be used to find the reasonable reinforcement amount of the longitudinal reinforcement of the frame beam, which meets the lower limit requirements of the structural collapse resistance design, as shown in Table 2. As can be seen from Table 2, the original longitudinal tendons of the frame beams in each layer of the two models are approximately the same. The minimum reinforcement for the collapse resistance of each floor frame beam that satisfies the floorless model is 2.99% to 4.08% higher than the original longitudinal reinforcement; that is, the total longitudinal reinforcement increases by 3.51%; The longitudinal reinforcement of frame beams on each floor need only increase by 1.87% to 2.87% (the total longitudinal reinforcement only needs to be increased by 2.112%) to meet the lower limit requirement of floor models with continuous collapse resistance. This result indicates that the floor slab improves the rigidity of the overall structure, can effectively enhance the lateral support of the overall structure, and greatly contributes to the continuous collapse resistance of the structure. In view of the fact that the two models are based on the design information of China's universal multi-layer RC frame structure, which indicates that there is a certain deficiency in the continuous collapse resistance of the current reinforced concrete frame structure in China, it is recommended that the amount of longitudinal reinforcement of the frame beam should each layer is increased by 1.9% ~ 2.9% to meet the requirements of frame beams against continuous collapse.

| Layer | Original longitudinal tendon amount (t) | Meet the minimum amount of reinforcement for continuous collapse (t) | Increased from the original structure | Original longitudinal tendon amount (t) | Meet the minimum amount of reinforcement for continuous collapse (t) | Increased from the original structure |
|-------|----------------------------------------|---------------------------------------------------------------|--------------------------------------|----------------------------------------|---------------------------------------------------------------|--------------------------------------|
| 1     | 2.121                                  | 2.203                                                         | 3.87%                                | 2.071                                  | 2.130                                                         | 2.87%                                |
| 2     | 2.377                                  | 2.463                                                         | 3.62%                                | 2.487                                  | 2.547                                                         | 2.24%                                |
| 3     | 2.377                                  | 2.463                                                         | 3.62%                                | 2.487                                  | 2.547                                                         | 2.24%                                |
| 4     | 2.377                                  | 2.463                                                         | 3.62%                                | 2.997                                  | 3.057                                                         | 2.01%                                |
| 5     | 2.894                                  | 2.981                                                         | 2.99%                                | 3.102                                  | 3.160                                                         | 1.87%                                |
| 6     | 3.065                                  | 3.163                                                         | 3.21%                                | 3.102                                  | 3.160                                                         | 1.87%                                |
| 7     | 3.065                                  | 3.163                                                         | 3.21%                                | 3.120                                  | 3.180                                                         | 1.92%                                |
| 8     | 3.121                                  | 3.248                                                         | 4.08%                                | 3.120                                  | 3.180                                                         | 1.92%                                |
| total | 21.397                                 | 22.147                                                        | 3.51%                                | 22.486                                 | 22.961                                                        | 2.112%                               |

6. Impact of floor slab on continuous collapse resistance of structure
In order to determine the anti-continuous collapse resistance of the remaining structure after the corner column is removed, static and dynamic nonlinear methods are used to compare and analyze the anti-continuous collapse performance of the floor structure with and without a more accurate conclusion. The floor unit is removed to obtain a plane frame model without a floor.

Due to space limitations, this article only analyzes the situation of removing the first corner column. Take the load as: $\lambda(DL + 0.55LL)$ When using static nonlinear analysis, $\lambda = 2.0$. When the dynamic non-linear analysis method is used, the first value is 1, and the incremental dynamic analysis method is used to increase at intervals of 0.1 and then increase at intervals of 0.01 until the program calculates divergence, indicating that the remaining structure reaches the limit resistance to continuous collapse. Figures 4 and 5 show the nonlinear static analysis curve and nonlinear dynamic analysis curve obtained by the program.
With reference to Figures 4 and 5, it can be seen that the vertical displacement analysis curve of structures considering the action of cast-in-place floor slabs is always located above the structure curve that does not consider the action of cast-in-place floor slabs, whether static static method or dynamic nonlinear method is adopted. This result indicates that the unbalanced internal forces of the remaining structure are redistributed through the floor ties. The floor slab increases the stiffness and horizontal support of the structure and greatly reduces the vertical displacement of the remaining structure, which greatly contributes to the continuous collapse resistance of the structure. What’s more, the load-vertical displacement curve obtained by the incremental dynamic analysis method is always located above the nonlinear static curve, that is, under the same vertical displacement, the nonlinear static analysis method always needs to apply a larger load, which indicates that the nonlinearity The static analysis method is conservative. In order to show the comparison of static nonlinearity and dynamic nonlinearity more intuitively, Table 3 lists the maximum values of the analysis results of the two. This result also reminds everyone to use the method of removing components to simulate the continuous collapse of the RC frame structure. Do not ignore the floor action to make the analysis result more accurate.

### Table 3. Comparison of static and dynamic nonlinear analysis

| Analytical method        | No floor effect | When floor is acting |
|--------------------------|-----------------|----------------------|
|                          | Maximum         |                     |
|                          | displacement    | λ                    |
| Static nonlinear analysis| 291.29mm        | 2.63                 |
|                          | 252.83mm        | 2.97                 |
| Dynamic nonlinear analysis| 234.32mm       | 2.21                 |
|                          | 213.49mm        | 2.54                 |

7. Conclusion

Based on the ABAQUS software and the method of removing components, an analysis of the continuous collapse resistance of an 8-storey typical RC frame structure building was made, and the following conclusions were concluded:

1. Compared with the long and short side columns and internal columns, the corner column has the greatest influence on the continuous collapse of the structure. Strengthening the corner column structure is the key to the design of continuous collapse resistance. A layer height between 4.3 and 4.8 meters is most beneficial to the continuous collapse resistance of the structure.

2. The research shows that there is a certain shortcoming in the continuous collapse resistance of the existing reinforced concrete frame structure in China. It is proposed that the reinforcement of the longitudinal reinforcement of the frame beam should be increased by 1.9% to 2.9% to meet the most reasonable requirement for continuous collapse of the frame beam.

3. The analysis results obtained based on the nonlinear static analysis and incremental dynamic analysis both show that the structural rigidity of the floor can be greatly improved, and the continuous collapse resistance of the structure can be greatly improved; under the same vertical displacement of the failure point, the nonlinear static analysis The method always needs to apply a larger load, which indicates that the nonlinear static analysis method is conservative.
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