Experimental study on anti-collapse performance of beam-column assembly considering surrounding constraints

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Abstract: Due to the uncertainty of the position of the failure column in the building structure, the surrounding constraints of the beam-column substructure are different after the local failure. Three-column and two-beam substructures with two different boundary conditions are taken as the research object (overall constrained and partially constrained), the failure mode, mechanical form and anti-collapse mechanism of the beam-column substructures are investigated by static loading tests. Tests show that the deformed forms of the two specimens are similar, the development process of the resistance mechanism follows the beam mechanism stage, the mixing stage of beam mechanism and catenary mechanism, and the catenary mechanism stage, however, boundary conditions have a significant influence on the development of catenary mechanism of beam-column substructure, the catenary mechanism of overall constraint specimens accounts for 30% of the total resistance, while the ultimate deformation capacity of partial constraint specimens is weak, and the catenary mechanism resistance only accounts for 15%.

1. Introduction
The continuous collapse of a building is a phenomenon in which a certain part of the structure is damaged by accident or severe local overload, and the overall damage is caused by transmission along the path, resulting in the loss of the bearing capacity of the main structure and then causing the overall collapse. This kind of collapse phenomenon, which is disproportionate to the initial destruction, seriously threatens the safety of human life, so it has aroused widespread concern in society and academia.

At present, the design methods for continuous collapse resistance proposed by countries all over the world include conceptual design method, bond-strength design method, dismantled component method, and key component method[1-2]. Among them, the dismantled component method is to remove one or several components, and then analyze the collapse resistance of the remaining structure, which makes the collapse resistance research of the structure mainly focus on the beam-column structure with clearer force. Compared with the double half-span substructure, the two-span three-column substructure can fully consider the change in the position of the beam's reverse bending point during the failure of the substructure, and can more truly reflect the internal force change and resistance mechanism of beam column structure during the process of continuous collapse resistance after the failure of the middle column[3].
Due to the limitations of the test conditions, the relevant regulations on frame structures at home and abroad are mainly based on experience or the results of finite element analysis. Alogla et al.[4] studied the influence of different reinforcement ratios on the collapse resistance of the structure through the collapse test of the beam-column structure considering the surrounding constraints. The static test results were converted into dynamic results through the energy conservation method. The analysis shows that the ductility and collapse resistance of reinforced concrete beam and column structures can be improved by using reasonable reinforcement ratio. Zhou Yun and Chen Taiping[5] analyzed the influence of side span constraints on the bearing capacity of the studied substructures against continuous collapse, and analyzed the bearing capacity of the structure during the removal of the bottom column of the frame. The research factors on the continuous collapse resistance of substructures at home and abroad mainly lie in the beam-column joint form, span ratio, reinforcement ratio, etc.[6-9] The influence of lateral constraints on the collapse resistance of beam and column structures is rarely considered, and the test of lateral constraints on the collapse resistance of steel frame structures is rarely reported.

Current research results show that the continuous collapse resistance process of the steel frame is divided into three parts: beam mechanism stage, beam mechanism and catenary mechanism mixing stage, and catenary mechanism stage. The catenary mechanism stage is the last line of defense against continuous collapse of the structure, and the play of catenary is closely related to the form of peripheral constraints. Therefore, it is necessary to study the influence of surrounding constraints on the collapse resistance of the substructure. In this paper, two kinds of beam-column substructures with different boundary conditions, namely the overall constraint structure with the failure member located in the middle of the structure and the partial constraint substructures with the failure of the secondary column, are selected to carry out quasi-static tests under the failure of the middle column. The impact of the beam-column structure's collapse resistance, the failure form, force mechanism and resistance mechanism of its collapse process are deeply analyzed.

2. Test

2.1. Specimen design
In this experiment, two beam-column structure specimens, which are overall constrained and partially constrained, were designed, and their numbers are WUFG and WUFG-S. The scale of the specimen model is 1:3. The beams and columns are all H-shaped cross-sections with dimensions of 150 mm× 100 mm× 6 mm× 9 mm, 150 mm× 150 mm× 8 mm× 10 mm, the left and right span beams are L=1500 mm, and the column length LC is 1100 mm. The geometric dimensions of the beam and column structure are shown in Figure 1. All of them adopt Q235B steel. The beam-to-column node at the center column of the substructure adopts a trapezoidal cover plate bolted connection (CPS) method. This node type has the characteristics of large rotation stiffness, strong deformation ability and superior collapse resistance, and the detailed diagram is shown in Figure 2.

Figure 1. Geometry dimensions of the specimens (mm)
2.2. Loading device and system
The test loading device is shown in Figure 3. The top of the failed column of the substructure is connected with a 100 T hydraulic servo actuator, and the vertical load is applied by static loading to simulate the load effect from the upper part when the structure collapses continuously. The loading process adopts displacement loading, each level applies at 5 mm, and the loading rate will not exceed 5 mm/min. After each level of loading is completed, holding the load for 3-5 min, and after the deformation of the substructure is stable, we proceed to the next level of loading until the specimen is damaged.

3. Analysis of test results

3.1. Test phenomena and failure modes
The load-displacement curves of WUFG and WUFG-S specimens obtained by the hydraulic servo actuator are shown in Figure 4, and there are two peak points correspondingly. The destruction phenomenon of each specimen is shown in Figure 5 and Figure 6.

(1) When the loading displacement of the WUFG specimen reaches 195 mm, cracks appear in the base material near the weld between the lower flange of the west steel beam and the cover plate. When the load-displacement curve reaches point A1, the tensile flange at the weld of the cover plate of the west steel beam breaks, and the load drops suddenly, and the test phenomenon is shown in Figure 5. Internal force redistribution occurs in the beams on both sides, and the load appears to rise, and then reaches point A2, and the specific phenomenon is shown in Figure 5.

(2) When the loading displacement of the WUFG-S specimen is increased to 209 mm (corresponding to point B1 in the curve in Figure 5), the load is instantaneously reduced after the fracture of the lower flange of the steel beam on the west side near the failed column and the base material near the weld of the trapezoidal cover plate. When the load drops instantaneously from 255 kN to 238 kN, the phenomenon is shown in Figure 6. As the loading displacement at the center column gradually increases, the fracture of the lower flange is intensified, and the internal force redistributes in the beam until the load reaches a new peak again, when the loading displacement reaches 320 mm (corresponding to curve B2 in Figure 4), The test phenomenon is shown in Figure 6.
The test results show that the fully constrained specimen first produced cracks at the lower flange of the steel beam on the west side of the failed column, and then the cracks developed to the web plate, and finally the web was completely broken. Due to the unbounded beam end column constraint of some constraint specimens, the base material of the lower flange close to the end of the cover plate near the failed column fractures first, and the cracks develop upwards. The test was ended with a complete fracture in the middle of the web plate. From the test results, the influence of peripheral constraints on the flexural bearing capacity of the beam-column structure is not obvious, but it has a significant effect on the transformation process of the structure's force mechanism, which greatly improves the ultimate bearing capacity of the substructure during the tension stage. The column displacement of the overall constrained substructure is larger than that of the partially constrained substructure. The ultimate deformation capacity of the partially constrained substructure is weaker.

3.2. Deformation analysis of substructure

The deformation development process of the two specimens is shown in Figure 7. It can be seen from the figure that the deformation trends of the two specimens are similar. At the initial stage of loading, the beam-column structure deforms due to bending (approximately a quadratic curve). As the loading displacement increases during the loading process, the beam-column structure shows large deformation characteristics. From the perspective of deformation, the chord rotation angle and node rotation capacity of the fully constrained substructure are both greater than that of the partially constrained substructure, which finally shows that the different lateral constraint stiffness caused by the boundary conditions will affect the rotation capacity of the substructure nodes.
4. Analysis of anti-collapse mechanism of beam and column structure

The development curve of the resistance mechanism of the two specimens with loading displacement is shown in Figure 8. It can be seen from the curve that at the initial stage of loading, the two specimens use the beam's flexural action to resist external loads, and the total resistance is mainly provided by the beam's flexural mechanism. As the loading displacement increases, the beam bending mechanism is almost stable. When the lower flange of the specimen is broken under tension, the resistance of the beam against bending gradually decreases. In this case, the resistance generated by the catenary mechanism suddenly increases. This process is the transition process from the beam's bending resistance mechanism to the beam catenary mechanism, that is, the transition stage. As the loading displacement increases, the catenary mechanism becomes more obvious, and eventually becomes the main resistance mechanism of the substructure.

For the specimen WUFG, the beam mechanism resistance contribution ratio is about 70% during the entire loading process, and the catenary mechanism resistance force contribution ratio is about 30%. For the test piece WUFG-S, there is no side column tie at one end, and the remaining structure does not provide sufficient lateral restraint in the case of large deformation, and the axial deformation of the beam is released, resulting in the insufficient development of the catenary mechanism of the beam. Its catenary mechanism resistance contribution ratio is only 15%.

5. Conclusion

(1) The WUFG specimen fractured first at the lower flange of the west beam. The WUFG-S specimen first fractured at the lower flange of the tie-side steel beam without side column, subsequently, the
flexural bearing capacity of the two specimen beams dropped suddenly, the beams on both sides developed coordinately, and the load reached a new peak after the internal force was redistributed. Therefore, in the beam mechanism stage, the strengthening of boundary conditions does not significantly increase the bearing capacity of the substructure. However, in the catenary mechanism stage, the bearing capacity of WUFG specimens has increased significantly, far exceeding that of WUFG-S specimens. The strengthening of the substructure boundary conditions can significantly improve the structural bearing capacity.

(2) The deformation shapes of the two specimens are similar, but the difference in the boundary conditions of the substructures can significantly affect their ultimate deformation capacity. With the enhancement of peripheral constraints, its deformability and node rotation ability are correspondingly improved.

(3) The resistance development process of the two-span three-column substructure of the composite beam has experienced three processes: the beam bending mechanism stage, the beam mechanism and the catenary mechanism mixing stage, and the catenary mechanism. However, the development of catenary effect is significantly influenced by different peripheral constraints of substructures. Among them, the catenary mechanism resistance contribution ratio of the test piece WUFG is about 30%. As for the test piece WUFG-S, the catenary effect has not been fully developed due to the lack of ties at one end and insufficient peripheral constraints, and the catenary mechanism resistance contribution ratio is only 15%.

References
[1] GSA 2013. Alternate path analysis & design guidelines for Progressive collapse resistance [S]. Washington,D.C., USA: United States General Services Administration, 2013.
[2] CECS 392: 2014, Code for anti-collapse design of building structures [S]. Beijing: China Planning Press, 2014. (in Chinese)
[3] Zhong Weihui, Meng Bao, Hao Jiping. Study on anti-collapse performance of double web angles connection under different span ratios [J]. Advanced Engineering Sciences, 2017, 49(4): 86-96. (in Chinese)
[4] Alogla K, Weekes L, Augusthus-Nelson L. A new mitigation scheme to resist progressive collapse of RC structures [J]. Construction and Building Materials, 2016, 125(30): 533-545.
[5] Zhou Yun, Chen Taiping, Hu Xiang, et al. Progressive collapse resistance of RC frame structures considering surrounding structural constraints [J]. Engineering mechanics, 2009, 36(1): 216-226. (in Chinese)
[6] Wang Wei, Li Ling, Chen Yiyi. Experimental investigation on progressive collapse behavior of WUF-B connections between SHS column and H beam [J]. Journal of Building Structure, 2014, 35(4): 92-99. (in Chinese)
[7] Chen Junling, Shu Wenya, Li Jinwei. Performance of various steel moment connections under progressive collapse scenario [J]. Journal of Tongji University (Natural Science Edition), 2016, 44(1): 53-58. (in Chinese)
[8] Meng Bao, Zhong Weihui, Hao Jiping. Experimental study on anti-collapse performance for beam-column assemblies with bolt and weld rigid connection based on different span ratio [J]. Engineering mechanics, 35(1): 79-85. (in Chinese)
[9] Hai S L, Bao Y, Sadek F, et al. An experimental and computational study of reinforced concrete assemblies under a column removal scenario [J]. Technical Note-1720, 2011: 11-58.