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Progressive Collapse Analysis of Concrete-filled Steel Tubular Column to Steel Beam Connections Using Multi-scale Model

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ABSTRACT

The multi-scale model which combined the fiber beam element with the fine element was used to investigate the progressive collapse performance of steel beam to concrete-filled steel tubular (CFST) column connections. By using the nonlinear static analysis method and taking into account the influence of the adjacent framework of joints, the resistance of progressive collapse, the failure modes and the stress distribution revealed the resistance mechanism of these joints during the process of progressive collapse. And the vertical displacement time history curves of joints which displayed the progressive collapse resistance demands of these joints were obtained by using the nonlinear dynamic analysis method. The relationship between resistance capacity and resistance demand of these joints were obtained by analyzing the nonlinear static analysis results and the nonlinear dynamic analysis results. These analysis results showed that the frame structure with these joints which enabled to form the resistance mechanism and new alternate path of unbalanced loads can prevent the occurrence of progressive collapse after the failure of column connected to joints. And the adjacent framework can improve the ability of anti-progressive collapse of these joints.

1. Introduction

Since the 911 event, more and more researchers have focused on the investigation of the resist progressive collapse performance of structures [1–6]. It is important to predict the failure mechanism and the alternate load path of structures which occur progressive collapse under abnormal accidental events. Some researchers have found that the joint areas connected with the failure column can generate an unbalanced load when frame structures occur progressive collapse. Moreover the unbalanced load is able to disperse to the adjacent areas by the beam resistance mechanism and catenary resistance mechanism which provide by the beam-column joints [7,8]. Therefore the beam-column joints are key elements for frame structures to resist progressive collapse events.

Some experimental investigations have focused on the performance of steel beam-column joints [9–15] and reinforced concrete beam-column joints [16,17]. These study results suggest that the catenary resistance mechanism developed in the beams and connections plays a critical role in the resistance of structure progressive collapse. However, these experiments have only studied the joint parts and did not consider the effects of the other structural parts that are connected with these joints. Moreover, there are few researches focus on the study of progressive collapse of the steel beam to CFST column connections by now. Thus the performance of some steel beam to CFST column connections was investigated under a central-column-removal scenario in this paper. In order to improve the understanding of the behavior of these connections to resist progressive collapse, the multi-scale numerical model which could reflect the effect of the adjacent structures was used to investigate the performance of these joints. And these numerical models adopted the nonlinear static analysis method and the nonlinear dynamic analysis method to study the progressive collapse resistance capacity of the steel beam to CFST column connections.

2. Steel beam to CFST column connection model

2.1. Design model

In order to study the progressive collapse performance of the joints in steel beam to CFST tubular frames under a central-column-removal scenario, two 9-story and 4-span CFST columns with I-shape steel beams planar frames were designed. The circular and square section columns, respectively, were chosen as the frame columns. And the two frames have the same size in story height and span. The height of first story is 4.2 m, and the height of other stories is 3.6 m. The span is 6.6 m. The middle joints at the first story are the main objects to be investigated in this paper. Fig. 1 shows the four types of these joints which include steel beam to circular or square CFST column connections with outside stiffening ring plate or with penetrating ring plate. The steel

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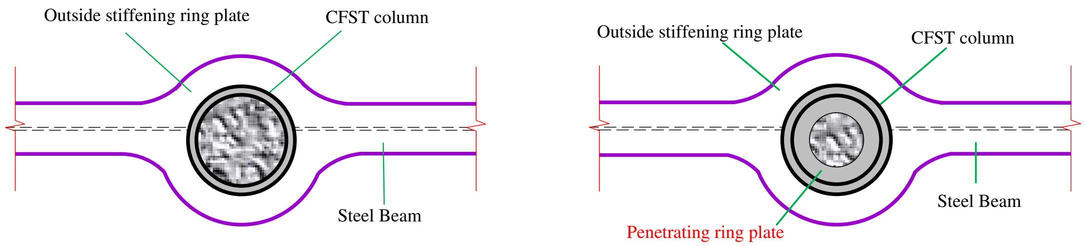
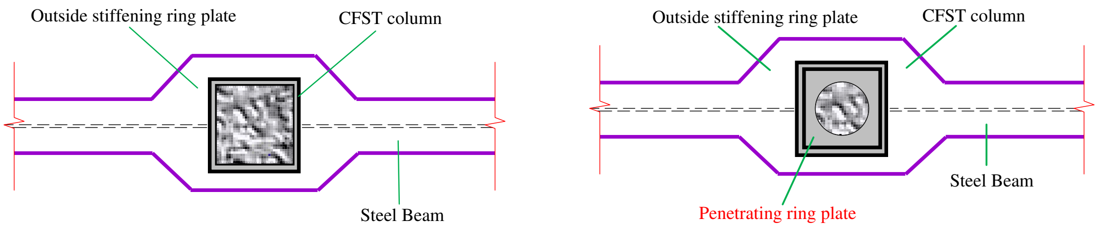


(a) Steel beam to circular CFST column connections with outside stiffening ring plate (CJ-O).

(b) Steel beam to circular CFST column connections with penetrating ring plate (CJ-P).



(c) Steel beam to square CFST column connections with outside stiffening ring plate (SJ-O).

(d) Steel beam to square CFST column connections with penetrating ring plate (SJ-P).

Fig. 1. Typical steel beam to CFST column connections.

beams and ring plates are welded to the steel tube to keep the connections firm. Table 1 shows the geometry and material information of steel beam to CFST column connections in the frame structures. The outer or inner plate size stands for its width outside or inside the column.

2.2. Finite element model

The finite element models for steel beam to CFST column connections were built in the finite elements software ABAQUS. And the multi-scale model was used for the finite element analysis. The multi-scale model is a kind of simulate method that combine different finite element types in one numerical model [18]. This model feature is illustrated in Fig. 2. The fine element is usually used for substructures or members simulation and has a high computational accuracy. In contrast, since the fiber beam element has a high computational efficiency, it is generally adopted by the global structural numerical calculation. Therefore the multi-scale model can take into account the high computational accuracy and the advantages of high computational efficiency at same time. But the interaction between these two elements is a key factor to consider when the multi-scale model is employed. The interface of these two elements need satisfy deformation compatibility condition, at the same time this interaction should keep the degree of freedom of fiber beam elements constant and do not increase additional constraints for fine elements. The coupling interaction in ABAQUS is employed for the fine element and fiber beam element in this paper.

Considering the advantage of the multi-scale model, it can be used in the finite element models for the analysis of the steel beam to CFST column connections. The joint parts which should be studied more thoroughly can use the fine element and other parts like beams and columns adopt the fiber model. This numerical model considers the tension behavior that is provided by the frame structures on the joints and reflects the deformation and failure mode of joint areas in detail.

Since the inflection point of the beam is located at the midpoint of the beam, only one-half span of the steel beam of the fine model is adopted. Fig. 3 shows the multi-scale model. For the fine joint parts, the four nodes shell element S4 was used for steel beam and tube and the concrete in columns employed the 8 nodes solid element C3D8. The fiber beam model iFiberLUT [19] which was developed in ABAQUS was employed by other parts in the frame structures. The detail information of concrete and steel material constitutive model could be found in the reference [20]. Fig. 4 shows the finite element models of these four designed joint parts.

The progressive collapse analysis of these joint models adopted the nonlinear static analysis method and the nonlinear dynamic analysis method. By using the nonlinear static analysis method, the progressive collapse mechanism, the failure modes and the stress distribution revealed the progressive collapse resistance capacity of these joints. And the vertical displacement time history curves of typical joints which displayed the progressive collapse resistance demand of these joints were obtained by using the nonlinear dynamic analysis method.

3. Numerical verification

Some experiments were chose to establish the numerical model in order to verify the validity of the finite element model. These experiments included CFST columns and steel joint models.

Table 1
The information of connections in the frame structure.

Joint Types		Column section/mm	Steel beam section/mm	Outer plate size/mm	Inner plate size/mm	Concrete cubic compression strength/MPa	Steel yield strength/MPa
Circular	CJ-O	Φ 500 × 12	I 450 × 250 × 12 × 16	125	0	40	345
	CJ-P	Φ 500 × 12		50	75		
Square	SJ-O	□ 500 × 12	I 500 × 300 × 12 × 16	150	0		
	SJ-P	□ 500 × 12		60	90		

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