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Experimental study and numerical analysis of progressive collapse resistance of composite frames

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ABSTRACT

A partial damage caused by an abnormal load could trigger progressive collapse of high rise buildings which may lead to terrible casualties. However, in the process of column failure, "catenary action" plays an important role in redistributing the internal load and preventing progressive collapses of the structure. Rigid composite joints, thanks to their high strength and good ductility, exert great influence in catenary action. Therefore, an experiment related to a 1/3 scale progressive collapse resistance with the use of rigid composite joints was conducted, and the results of the experiment were analyzed. Based on the experiment results, a FE model was developed and analyzed. This paper describes the experiment, the results analyzed, and the FE model in detail. The experiment showed that the progressive collapse mechanism of composite frame consisted of 6 stages: elastic stage, elastic–plastic stage, arch stage, plastic stage, transient stage and catenary stage. In catenary stage, catenary action evidently enhanced the resistance to the progressive collapse of the frames. The steel–concrete composite frame with rigid connections designed in accordance to current design standards showed a good resistance to progressive collapse. It is also found that horizontal restraining stiffness of the frame exerted great influence on the resistance in catenary stage.

1. Introduction

Partial or full range progressive collapse of structures which is triggered by a local damage due to abnormal events such as gas explosion, bombing attack or vehicle collision may lead to terrible casualties and severe economic loss. It is mainly because that the loads on superstructures cannot be transferred downwards when a vertical load-carrying component fails. To prevent the progressive collapse of the structure, the internal force should be redistributed by Alternate Load Path, Tie Force [1–3], and especially the so called "catenary action". The resistance and ductility of the beam-to-column joints play important roles in the formation and performance of catenary action. The damage of joints may lead to the failure of forming catenary action, and then initiate the progressive collapse of the structures.

Compared with steel joints and reinforcement concrete (RC) joints, rigid composite joints consisting of steel beams and RC slabs exhibit a higher load-carrying capacity and better deformation ability [4–7]. Furthermore, the reinforcements in the RC slab are essential components contributing to "catenary action", especially when the steel joints do not satisfy the rotation demand of catenary action [8]. Therefore rigid composite joints are advantageous construction types of joints used in the system of preventing progressive collapses.

Since the collapse of Ronan Point of London in 1968, preventing progressive collapse of buildings has been recognized as an important design consideration. A series of design codes, standards and guidelines have been published, such as the British Standard and Regulation [1–3], Eurocode [9,10], NBCC [11], ASCE7-05 [12], ACI318 [13], GSA2003 [14], and DoD 2009 [8]. In these codes and standards, there are two main design methods known as "direct design" and "indirect design". Direct design focuses on quantitative performance of structures while indirect design tends to prevent progressive collapse in the perspective of qualitative performance.

In recent years, there have been many analytical and numerical studies on progressive collapse analysis. Kaewkulchai and Williamson proposed a beam–column element formulation and solution procedure which can be used in dynamic analysis [15]. Buscemi and Marjanishvili [16] proposed a concise methodology for evaluating the predisposition of a structure to progressive collapse, in which the pendulum analogy method was adopted in the paper. Their pendulum analogy method reduced the progressive collapse issue to a conventional dynamic problem. Khandelwal and EI-Tawil [17] used computational simulation to investigate catenary action in moment resisting steel frames accounting for hardening, softening and ductile fracture behavior of steel. Izzuddin et al. [18] developed a novel simplified framework and a new design-oriented methodology for progressive collapse assessment of multi-storey composite buildings. The methodology offers a practical means for assessing structural

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Nomenclature

E_s	Young's modulus of steel
F	Tie force
f_y	Yield stress of steel
f_u	Ultimate strength of steel
L	Length of beam
M_1	Sagging moment
M_{p1}	Plastic positive moment resistance
M_2	Hogging moment
M_{p2}	Plastic negative moment resistance
P	Vertical load
P_p	Plastic vertical resistance
Δ	Vertical displacement
θ	Rotation of joint

robustness at various levels of structural idealization. Lee et al. [19] proposed two nonlinear analysis methods to be used for a simplified but accurate evaluation of progressive collapse potential in welded steel moment frames. A collapse spectrum for a quick assessment of the maximum deformation demands in progressive collapse was established. Mohamed [20] investigated the implementation of UFC 4-023-23 to protect against progressive collapse of corner floor panels when their dimensions exceeded the damage limits. Fu [21] built a 3-D finite element model representing 20-storey composite building. The model displayed the overall behavior of the 20-storey building under a sudden loss of column and provided important information for the additional design guidance on progressive collapse. Li et al. [22] improved the current Tie Force (TF) method to take into account the important factors such as the load redistribution in three dimensions, dynamic effects and internal force correction. Iribarren et al. [23] investigated the influence of design and material parameters in the progressive collapse analysis of RC structures including reinforcement ratio and column removal time.

Some experimental tests have also been conducted under column-removal scenarios. Yi et al. [24] conducted a 1/3 scaled progressive collapse test of a 3-storey reinforced concrete frame building with 4-bay, simulating the load transmission process. The experimental results showed that the RC frame with middle column failed would go through 4 stages including elastic stage, elastic–plastic stage, plastic stage and catenary stage. Demonceau et al. [25] conducted a test simulating the loss of a column in a 2-D composite frame with semi-rigid connections. Horizontal brace was used to provide lateral restraint for the composite frame. The development of the catenary action in the frame was observed and the results confirmed the development of membrane force in the beams. Yang and Tan [26] conducted seven experimental tests on the performance of common types of bolted steel beam–column joints subjected to catenary action. In the test, the extremity of joints was pinned which was a simplified boundary condition. This study provided the behavior and failure modes of different connections, including their abilities to deform in catenary action. Sadek et al. [27] conducted an experimental study of two steel joints and two reinforced concrete joints under monotonic vertical displacement of a center column. Portions of structural framing systems were designed as the boundary condition of the joints. The study provided insight into the behavior and failure modes of steel joints and concrete joints, including the development of catenary action. Oosterhof and Driver [28] conducted a series of experimental tests on common steel shear connections under a middle-column-removal scenario. Three types of shear connections were investigated in a test set-up capable of applying any independent combination of moment, shear and tension. The study examined the relative performance of three connection types, as well as the effects of connection geometry and loading states.

From above studies, it can be seen that, they were mainly focused on numerical and theoretical studies. Some experimental tests have been carried out to investigate the behavior of the steel joints and concrete joints under column-removal scenario recently. The joints in these tests were mostly installed into a simplified boundary condition, rather than in a frame level. In this way, only the behavior of the joint directly above the removal column was studied. In addition, few tests have been carried out to date on the progressive collapse behavior of composite joints. Composite joint possesses higher moment-resistance, which makes it widely used in steel and composite structures. To clearly investigate the behavior of rigid composite joints in frames during progressive collapse, in this paper, a pseudo-static experiment of a rigid beam-to-column connected composite frame under the loss of middle column was conducted. There is no extra lateral restraint for the frame which means that the joints could be tested in a more practical boundary condition. The behavior of the frame was studied in detail, including not only the behavior of the joint directly above removal column, but also the joints adjacent to the removal column. In addition, a finite element simulation was also carried out to further study the capacity of the composite frames in resisting the progressive collapse. Based on the model, parametric studies were also performed.

2. Experimental program

2.1. Specimen design and fabrication

Based on the loading capacity of actuator and experimental setup, a 1-storey composite frame with 4-bay was designed and fabricated in 1/3-scale. The height of storey was 1.2 m, and the span was 2 m. Steel beams were fully welded to the flanges of steel column to make rigid connections. This is a typical rigid connection type with high moment resistance, high initial stiffness and fast track for construction. The cross sections of steel beam and column were H200 × 100 × 5.5 × 8 and H200 × 200 × 8 × 12[H-overall depth (d) × flange width (b_f) × web thickness (t_w) × flange thickness (t_f)] respectively. The depth and width of RC slab were designed as 100 mm and 800 mm, respectively. The reinforcement mesh ratio for the RC slab was 0.85%. Longitudinal plane reinforcements with the diameter of 12 mm are placed in two layers with equal spacing along the width of the slab. Two layers of 8-mm-diameter plane bars are supplied as transverse reinforcement to prevent longitudinal splitting failure of the concrete slab. The design of the shear studs for the composite joints in the frame is based on the Chinese Code for Design of Steel Structures (GB 50017-2003) following full composite design assumption. The shear studs with diameter of 16 mm were welded to the steel beam with spacing of 100 mm. The strength of studs is 235 MPa. Detailed dimension of the specimen is shown in Fig. 1. The middle column was not supported which is to simulate the loss of a column. Fig. 2 shows the casting process of the connections.

To determine the steel material properties, three coupons were cut from each structural steel member and rebar respectively. The tensile strength was tested in accordance with the Chinese standard GBJ2975(1982). The material properties are listed in Table 1, where f_y, f_u, and E_s are steel yield stress, tensile strength and elastic modulus respectively. Concreting work was carried out in the laboratory of Harbin Institute of Technology. The non-absorbent plywood was used as bottom formwork and side shuttering. Casting of 150 × 150 mm cubes for strength test and 150 × 150 × 300 mm cylinder for Young's modulus was carried out at the same time. They were cured in similar conditions as the slab. The test of these concrete cubes was carried out in accordance with the Chinese standard GBJ81-85(1985). The average compressive strength of concrete cubes is 26.4 MPa. The Young's modulus of concrete is 2.65×10^4MPa.