Comparison of Progressive Collapse Performance between Center Column Removal and Side Column Removal Scenarios

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Abstract. Center column removal and side column removal scenarios are the two typical research conditions in the investigation of progressive collapse of RC frame structures. The study provides insight into the comparison of progressive collapse performance between center column removal and side column removal scenarios based on experimental results, numerical investigation and theoretical analysis. Based on the difference of progressive collapse failure modes of two frame models, their collapse resistance mechanisms are analyzed, and the different collapse resistance models are proposed. And the comparison between two frame models on the experimental collapse resistances is presented, which is in good agreement with the proposed collapse resistance models. The research results can establish a foundation for progressive collapse analysis and assessment of RC frame structures.

1. Introduction

Progressive collapse was first recognized and concerned as the collapse of Ronan Point apartment in 1968, caused by a gas explosion. It can be defined as “the spread of an initial local failure from element to element, which eventually results in the collapse of an entire structure or disproportionately large part of it” [1]. The events of 11 September 2001 have rekindled the interest to understand the causes of progressive collapse in building structures and improve the structural robustness under extreme accidental events. In recent years, some researches on progressive collapse of building structures based on the experiments, numerical simulations or theoretical analyses, have been carried out [2-4]. Moreover, several design codes, specifications and guidelines [1, 5-6] of progressive collapse prevention have been published, which based on the existing research results.

Column loss scenarios often be used to experimentally or and numerically investigate the progressive collapse process and resistance of reinforced concrete (RC) buildings [7]. In a corner column removal scenario, where the free boundaries exist at the ends of RC frame beams and slabs near the removal column. Therefore, the frame beams and slabs with little or no catenary action and tensile membrane action contribute to progressive collapse resistance, respectively. Thus, the interior column removal (that is the center column removal, when the layout of structures is two-span and two-bay) and side column removal scenarios are the two typical research conditions in the investigation of progressive collapse of RC frame structures.
In this paper, based on experimental results, numerical investigation and theoretical analysis, the collapse failure modes, resistance mechanism and magnitude, are compared between side column removal and center column removal scenarios, where other parameters are exactly the same except for the different removal columns. The research results can establish a foundation for progressive collapse analysis and assessment of RC frame structures under different column removal conditions.

2. Progressive collapse failure modes and resistance mechanism

A four-span, eight-story and four-bay RC frame structure was designed considering the concrete design code and seismic design code of China [8-9]. For the purpose of the collapse experiment, two third-scale models of a segment of the original frame ground story were constructed for the collapse experiment, in which a side column or a center column was removed in advance, respectively. The design and parameters of RC frame models and the process of progressive collapse tests refer to the literatures [10] and [11].

The collapse failure modes of frame model under center and side column removal conditions are illustrated in Figure 1 and Figure 2. Based on the experimental failure phenomenon, it can be found that the negative moment yield lines are formed near the boundaries of the upper surfaces of the frame slabs in the vicinity of the removed columns. However, due to negative moment reinforcement along the edges of slabs and corner effects, the negative moment yield lines are approximately elliptic for the center column removal scenario, or semielliptic for the side column removal scenario, and there is a certain distance between their spindle ends and the boundaries of slabs. The positive moment yield lines are formed in the diagonal regions of the lower surface of the frame slabs, which pass through the removal columns and lie in the centers of the frame slabs, as shown in Figure 1 and Figure 2.

For the RC frame beams, it can be observed that the plastic hinges appear at both ends of the four frame beams adjacent to the removed center column, as illustrated in Figure 1. In the side column
removal scenario, the plastic hinges are formed at both ends of the two peripheral frame beams adjacent to the removed side column, but the plastic hinge only appears at the end of the interior frame beam (Beam 3 in Figure 2) away from the removed side column. This is because the free boundary exists at the end of Beam 3 (Figure 2), and Beam 3 is approximately a cantilever beam.

Based on the experimental failure phenomenon and the structural performance of the frame slabs during the progressive collapse, it can be noted that the tensile membrane action can be generated in Slabs 1 and 3 along the transverse direction, and in Slabs 2 and 4 along the longitudinal direction under the center column removal condition, which are surrounded by the positive and negative moment yield lines (Figure 1). For the frame beams adjacent to the removed center column, in large deformation state, the catenary action can contribute to progressive collapse resistance in Beams 1 and 3 along the transverse direction, and in Beams 2 and 4 along the longitudinal direction. Figure 3 illustrates the longitudinal reinforcement stresses at frame beam ends near the removed center column, which results from numerical simulation. It can be seen that the top and bottom longitudinal reinforcements in Beams 1, 2, 3 and 4 (Figure 3) are fully in tension and the values of the stress are larger in large deformation state. The above analysis validates the formation of the catenary mechanism in the four frame beams, and the analysis of the tensile membrane mechanism of the frame slabs is similar.

For the side column removal scenario, the tensile membrane action can only contribute to progressive collapse resistance in Slabs 1 and 2 (Figure 2) along the longitudinal direction. However, due to the free boundary of Slab 3 along the transverse direction, the contribution of the tensile membrane action of Slab 3 to progressive collapse resistance cannot be considered, which is verified by the phenomenon of the void of Slab 3 along the negative moment yield line, as shown in Figure 2. In the frame beams adjacent to the removed side column, the catenary action can only generated in
Beams 1 and 2 (Figure 2) along the longitudinal direction, and the contribution of the catenary action of Beam 3 cannot be considered, which can be confirmed by the longitudinal reinforcement stress at beam ends near removed side column (as shown in Figure 4) and the buckling of the longitudinal reinforcements (Figure 2).

3. Progressive collapse resistances

Figure 5 presents the comparison between the center column removal scenario and the side column removal scenario on the vertical load versus the vertical displacement of the removed columns, which derive from the experimental results. As illustrated in Figure 5, it can be observed that the frame model under the center column loss achieves a maximum vertical load of 135.7 kN with a vertical displacement of 256 mm. However, for the frame model under the side column loss, the structure attains a maximum vertical load of 60.7 kN at a vertical displacement of 345 mm. The comparison of progressive collapse resistance of two frame models shows that the progressive collapse resistance of the former is 2.24 times that of the latter. Moreover, the resistance results also verify the aforementioned analysis of the progressive collapse resistance mechanism.

4. Conclusions

In this study, based on experimental results, numerical investigation and theoretical analysis, the collapse failure modes, resistance mechanism and magnitude of RC frame structures under center and side column removal scenarios, are systematically investigated. It can be found that the negative moment yield lines on the upper surfaces of the frame slabs are approximately elliptic for the center column removal scenario, or semielliptic for the side column removal scenario, and there is a certain
distance between their spindle ends and the boundaries of slabs. For the RC frame beams, the plastic hinges appear at both ends of the four frame beams adjacent to the removed center column and the two peripheral frame beams adjacent to the removed side column, but the plastic hinge only appears at the end of the interior frame beam away from the removed side column.

The tensile membrane action and the catenary action can be generated in four frame slabs and four frame beams adjacent to the removed center column, respectively. However, for the side column removal scenario, the tensile membrane action and the catenary action can only contribute to progressive collapse resistance in two frame slabs and two frame beams along the longitudinal direction, respectively. And, it can be noted that the progressive collapse resistance of the center column removal frame is 2.24 times that of the side column removal frame.

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