Contribution of RC slabs to progressive collapse resistance of RC frame structures

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Abstract. The present study investigated the contribution of RC (reinforced concrete) slabs to progressive collapse resistance of RC frame structures based on experiment and numerical calculation. During the progressive collapse of a RC frame structure under a center column removal, the damage of floor slabs was obviously observed. This indicates that the RC slabs have a significant effect to the progressive collapse performances of the frame structures. Based on the failure phenomenon of RC slabs and its resistance mechanism of progressive collapse, a simplified calculation model of progressive collapse resistance of RC slabs was proposed. The contribution to collapse resistance and the proposed model of RC slab were verified using experimental and numerical calculation results with and without slabs.

1. Introduction
Since the collapse of the World Trade Centre in 2001 due to the terrorist plane crash, the progressive collapse of building structures has received enough attention from scholars and engineering fields. As is known to all, the progressive collapse may cause serious casualties and property loss. Therefore, in recent years, scholars from all over the world have completed a series of research work on the progressive collapse of building structures [1-4]. In order to avoid or prevent progressive collapse accidents of building structures, many countries and regions have formulated the design codes and guidelines of structural collapse resistance [5-7]. However, because of the complexity of progressive collapse, there is still no perfect and accurate calculation theory for the progressive collapse resistance of building structures in the design codes of various countries and regions. At present, the experiments, numerical simulations and theoretical analyses about the progressive collapse performances of RC beams are relatively sufficient, and several typical models of progressive collapse resistance of RC beams have been presented. But for RC slabs, further research is needed to better understand the progressive collapse performances, and establish the rational models of the progressive collapse resistance.

In this study, the progressive collapse performances of RC slabs and its contribution to progressive collapse resistance of a RC frame structure, were investigated by experiment and numerical calculation. A simplified calculation model of progressive collapse resistance of RC slabs was proposed based on the principle of force equivalence. The contribution of RC slabs to progressive collapse resistance and the proposed model were also examined against the experiment and the numerical calculation with and without slabs.
2. Damage of RC slabs during progressive collapse

A third-scale model frame structure (Fig.1, single floor, two spans and two bays) was constructed for the progressive collapse experiment, and the details of the model frame structure could be see the reference [8]. The centre column of the model was removed in advance, when the model structure was built in the laboratory. During the progressive collapse test, the quasi-static vertical displacement was applied to the removal centre column head using a MTS servo actuator.

Based on the analysis of the experimental process and the progressive collapse mechanism of RC slabs, it can be seen that in the stage of small deformation, the RC slabs resisted the collapse load mainly by bending mechanism. With the increase of loading displacement, the collapse resistance mechanism of RC slabs was gradually transformed into compression membrane mechanism. In the stage of large deformation, the RC slabs resisted the collapse load mainly by tensile membrane mechanism.

Fig.2 shows the failure of the top and bottom surfaces of the RC slabs during the progressive collapse. The yield lines of negative moment were formed on the periphery of the top surfaces of RC slabs. And the yield lines of negative moment were approximately elliptical. However, on the bottom surfaces of RC slabs, the yield lines of positive bending moment were formed at the diagonal. And the yield lines of positive moment only appeared in the central regions of the RC slabs, and the length of its projection on each side was approximately half the side length of RC slabs. In the limit state of collapse, it can be found that the concrete near the yield lines of positive and negative bending moment was almost out of service. And some steel bars intersecting with the yield lines in the RC slabs were broken.

According to the principle of conservation of energy during the progressive collapse of the model frame structure, it can be found that the RC slabs contribute significantly the progressive collapse resistance of the whole RC frame structure.

A computational study was also carried out, in which the structural model (Fig.3a) is exactly the same as the experiment. The numerical analysis was done using the explicit nonlinear finite element software LS-DYNA [9]. And the concrete properties were modelled with a continuous-surface-cap model, the material parameters were obtained from the material test results. A piecewise-linear plasticity model was adopted for the steel bar material, and the stress-strain curves were obtained from
the tensile test data. The bond between concrete and steel bar adopted the one-dimensional contact interface model. The plastic strain distribution of the floor slabs is depicted in Fig.3b, which is consistent with the experimental result. And the failure of the RC slabs (including the failure of steel bars and concrete) also agree with the experimental progress and results.

3. Progressive collapse resistance of RC slabs

According to the failure pattern of RC floor slabs in the limit state of collapse, a simplified calculation model of tensile membrane action was developed to calculate its progressive collapse resistance, as shown in Fig. 4. For RC slab GHK, on the basis of the vertical force balance, its progressive collapse resistance can be expressed as

$$ R^{m}_{GHK} = \left( F_{y1}l_{x1} + F_{y2}l_{x2} \right) \frac{v}{\sqrt{v^2 + l_{y1}^2}} $$

where $v$ is the vertical loading displacement of the removal column head (namely Point K), which can be obtained from the reference [10] based on the deformation compatibility condition of RC beams and slabs. $F_{y1}$ and $F_{y2}$ are the yield capacities of steel bars in the unit width of RC slabs ① and ②, respectively. $l_{x1}$, $l_{x2}$, $l_{y1}$ and $l_{y2}$ are the corresponding projection lengths of the yield lines of positive moment on each side, respectively.

The calculation of other RC slabs is completely similar to the slab GHK. Based on Equation (1) and the superposition principle, the total progressive collapse resistance of all RC slabs can be derived. According to the above method, the total collapse resistance of all RC slabs in the model frame is 69.1 KN.

Fig. 3 Finite element quarter-model of model frame with or without slabs

Fig. 4 Diagram of collapse resistance of frame slabs
For the whole frame structure with RC slabs, according to the experiment and the numerical calculation, the progressive collapse resistances are 135.7 KN and 133.9 KN, respectively. A numerical frame model without slabs was established, as indicated in Fig. 3c, which is to discuss the contribution of collapse resistance of the RC slabs. According to the progressive collapse performances of the numerical model without slabs, its progressive collapse resistance is 60.4 KN. Ignoring the coupling effect of frame beams and slabs, on the basis of comparison between the progressive collapse resistances of frame models with and without slabs, the collapse resistance of the RC slabs can be calculated as 73.5 KN.

Comparing the calculation value of simplified model with the numerical result, it can be seen that the former is 6% smaller than the latter.

4. Conclusions
In this study, the contribution of RC floor slabs to the progressive collapse behaviour of RC frame structures was investigated by experiment and numerical calculation. On the basis of the experiment and numerical calculation, it can be observed that the upper and lower surfaces of the RC slabs were obviously damaged. The elliptical yield lines of negative moment appear on the periphery of top surfaces, and the diagonal yield lines of positive moment appear on the bottom surfaces. According to the tensile membrane mechanism and the vertical force balance, a calculated model of progressive collapse resistance of RC slabs was established. And its reliability was examined against the experimental and numerical results of model frames with and without slabs.

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