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Application of Fiber Model for Progressive Collapse Analysis of Reinforced Concrete Frames*

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Abstract: The progressive collapse of the building structures due to accidents has become a hot research topic of civil engineering all around the world. The researches and designs on progressive collapse are based on accurately simulation for the failure process of whole structural systems. However, due to the complicated material and geometric nonlinearity and large computational workload in collapse simulation for a real reinforced concrete (RC) structure, normal finite element (FE) analysis with solid elements are not feasible in collapse researches. Hence, a fiber beam model is proposed in this work to simulate the collapse of RC frame. The fiber beam model is firstly verified with a collapse test of a planar RC frame. And then following the design process proposed in DoD 2005, the collapse processes of two typical Chinese 8-story RC frames with and without slabs respectively are simulated and compared. The influence of slabs on the progressive collapse behavior of structures is studied and the result proofs that the slabs can greatly improve the progressive collapse resistance of structures.

Keywords: fiber model; progressive collapse; simulation; reinforced concrete frame; slabs

1 Introduction

The progressive collapse of a building is initiated by an event that causes local damages which the structural system cannot absorb or contain, and that subsequently propagates throughout the structural system, or a major portion of it, leading to a final damage state that is disproportionate to the local damage that initiated it[1]. Although some advanced regulations[2] to resist progressive collapse were presented, the progressive collapse design is still lack in China. One of major difficulties is that normal finite element (FE) analysis with solid elements lead to large computational cost in collapse simulation of whole RC structures. On the contrary, fiber beam model is a kind of high efficiency computing element which associates the nodal force/deformation of beams or columns with the nonlinearity of material. So it has bright application future in collapse researches and designs. In this study, a fiber beam model for RC structures (referred as THUFIBER) is developed, which is based on the general-purpose finite element package of MSC.MARC that has significant capacity of solving nonlinear problems. Dynamic time-history analysis for a RC planar frame experiment is carried out to proof the capacity of the proposed fiber beam model, and a farther research on the influence of slabs on the progressive collapse behavior of structures is also presented.

2 THUFIBER Program

2.1 Discretization in section and longitudinal direction

In the THUFIBER program, each section of the RC member is divided into 36 concrete and 4 reinforcement

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fibers as shown in Figure 1. Users can define the position, area and constitutive model of each fiber. The program calculates the strain of each fiber by assuming plane remains plane and can insure that the stresses on the section are in equilibrium by iteration [3-4]. Users can also define the quantity and position of sections (integration points) in a beam element, as shown in Figure 2.

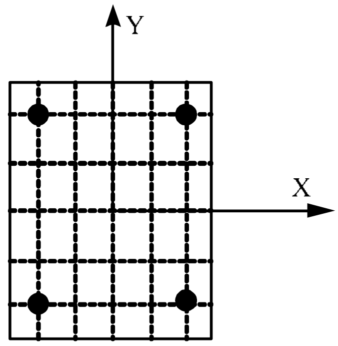


Fig. 1 Section discretization

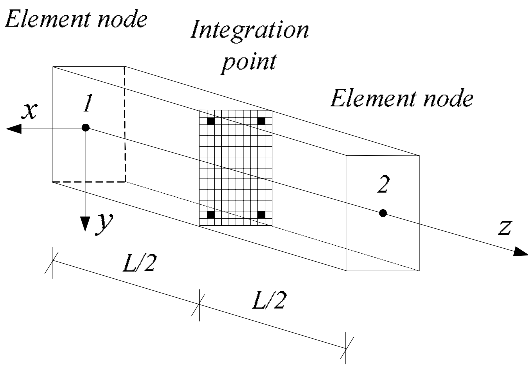


Fig. 2 A fiber beam with one integration point

2.2 Constitutive relation of fibers

In THUFIBER program, the constitutive relation used for concrete fiber is shown as Figure 3. Users input 6 parameters to define the uni-axial stress-strain relation: the initial Young's Modulus of the concrete, the peak compressive strength f_c and the corresponding strain ε_o, the ultimate compressive strength σ_u and the corresponding strain ε_u, and the ultimate tensile strength f_t. The compressive constitutive model of concrete has a envelop curve containing two parts. The ascending part of the envelop curve is expressed by Equation 1, and the descending part is a straight line. The program can simulate confined and unconfined concrete behavior as well. The constitutive relation of rebar fiber is based on the Légeron model and Bauschinger effect is also considered[5], as shown in Figure 4.

$$\sigma = f_c[2(\frac{\varepsilon}{\varepsilon_c}) - (\frac{\varepsilon}{\varepsilon_c})^2] \tag{1}$$

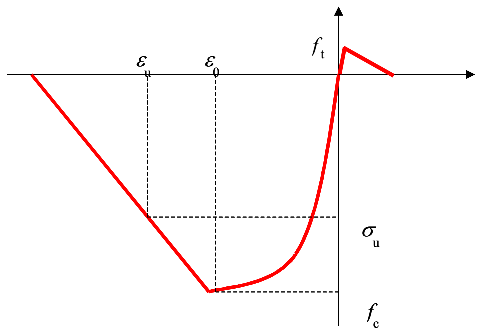


Fig. 3 Constitutive relation of concrete fiber

2.3 Test verification

THUFIBER program with the above mentioned constitutive models for the concrete and the rebar fiber agrees well in the dynamic simulation for the collapse experiment of RC planar frame [6], as shown in Figure 5. Figure 6 shows the relation between the axial force and displacement of the removed column. Obviously, the program has enough accuracy in collapse simulation. Besides, only 156 fiber beams with one integration point are used in dynamic time-history analysis which accomplishes within 1 minute on a general personal computer. That indicates great efficiency of fiber model.

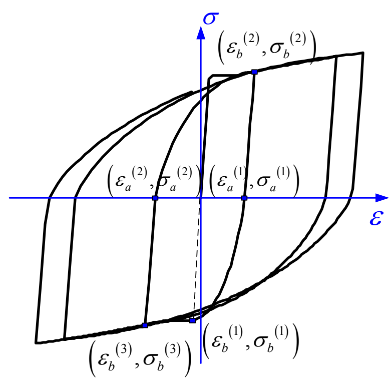


Fig. 4 Cycle tension-compression stress-strain curves of steel fibers

Fig. 5 Collapse test of plane frame

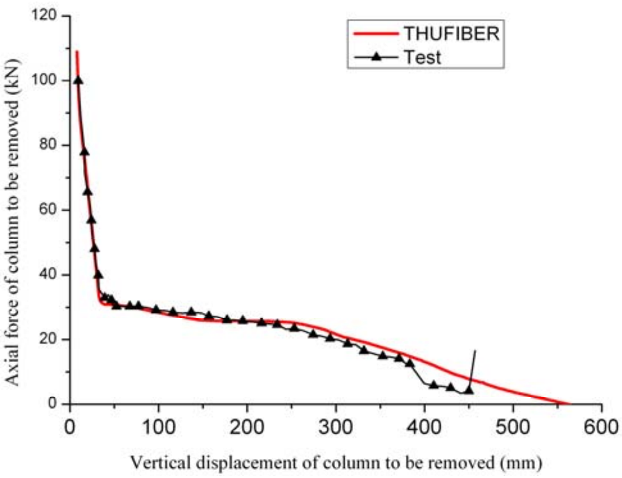


Fig. 6 Comparison for the axial force and displacement of removed column: simulation vs. test

3 Computational Models for Progressive Collapse

3.1 Geometric model

According to Chinese concrete code [7], an 8-stories RC frame is designed without special collapse design to check the collapse resistance of typical Chinese frames, as shown in Fig 7 and Fig 8. The ground storey is 4.2m high and all the other stories are 3.6m high. The sections of columns, longitudinal beams and transverse beams are 550 × 550mm, 300mm×500mm and 300mm×550mm respectively. The columns have a fixed end on the ground.

3.2 Material parameters

The selected parameters for the materials are as follows. For concrete material, Young's Modulus E_0=30GPa, peak compressive strength f_c=30MPa, peak compressive strain ε_0=0.002, ultimate compressive strength f_u=20MPa and ultimate compressive strain ε_u=0.004. For the reinforcement, Young's Modulus E_s=200GPa, yield strength=335MPa and the broken tensile strain=0.1.

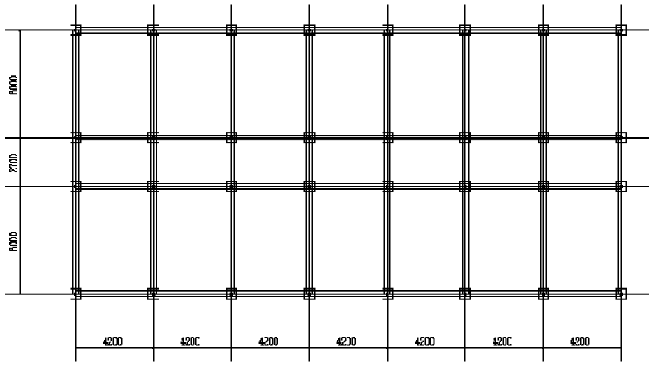


Fig.7 Plan view of standard story of 8-stories RC frame

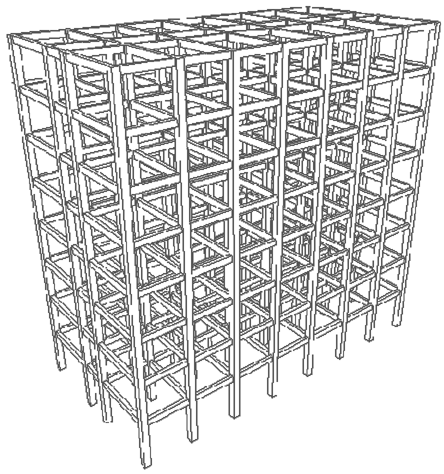


Fig.8 Perspective view of the 8-stories RC frame

3.3 Slabs modeling

In order to study the influence of slabs on the progressive collapse behavior of RC frames, the numerical models of the frame with and without slabs are compared:

Model A: Frame model with columns and beams only;

Model B: Frame model including columns, beams and slabs. When progressive collapse happens, slabs are usually in large deformation stage, and therefore, the bending bearing capacity of slabs can be ignored comparing with their suspending capacity. So in this paper, the reinforcement in slabs is modeled with truss elements to consider the tensile effect of rebars, and the concrete in slabs is not taken into account. And moreover, when tensile strain of reinforcement reaches 10%, the reinforcement is considered to be broken, and then the procedure will delete it automatically. Thus, the contribution of slabs is conservatively considered by means of this method.

4 Analysis procedure

4.1 Load case

According to the specification in DoD2005 [2], the following factored load combination is applied to the entire structures for nonlinear dynamic analyses:

$$1.2G_k+0.5Q_k+0.2W_k \qquad (2)$$

where, G_k =standard value of dead load; Q_k =standard value of live load; W_k =standard value of wind load.

4.2 Analysis procedure

Alternate Path (AP) method based on the dynamic nonlinear analysis is used in this paper to analyze the progressive collapse resistance capacity because of its high accuracy. In AP method, one vertical load-bearing element is removed instantaneously from Model A and Model B in every load case to check the bridge over capacity of the residual structures. The columns are near the middle of the short side, near the middle of the long side and at the corner of the building at each floor are removed. Besides, an internal column at ground floor is also removed, as shown in Figure 9.

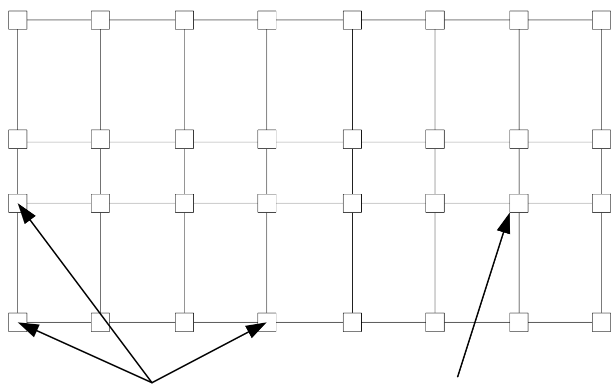


Fig.9 Column removal locations

According to the DoD2005 [2], the beams are considered to be failed (or collapsed) when their deflections reach 10% of their spans or the tensile strain of reinforcement in them exceeds 10%. If collapse area exceeds the value specified in DoD2005 [2], the structure will be considered that its progressive collapse resistance is insufficient and the collapsed part need be strengthened. Both the results of collapse resistance and strengthening reinforcement of Model A and Model B are compared to analysis the effect of slabs in collapse process.

5 Results

5.1 Collapse resistance capacity

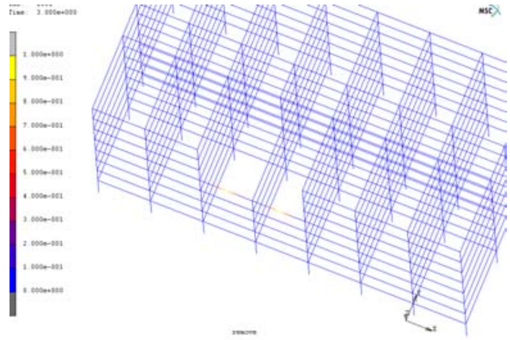
The results of simulations for collapse of Model A and Model B are listed in Table 1. It can be indicated that Chinese typical RC frames have insufficient collapse resistance. For the columns in different stories located at the same planar position, the columns in higher stories have more collapse possibility, as shown in Table 1, because the higher floor the removed column

Table 1 the results of simulations for collapse of Model A and Model B

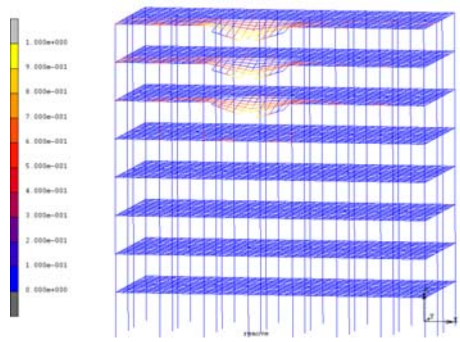
Floor	Column removal location	Model A	Model B
ground	Corner	survive	survive
	Long side	survive	survive
	Short side	survive	survive
	Internal	survive	survive
1 th	Corner	survive	survive
	Long side	survive	survive
	Short side	survive	survive
2 th	Corner	collapse**	survive **
	Long side	survive	survive
	Short side	survive	survive
3 th	Corner	collapse	collapse
	Long side	survive	survive
	Short side	survive	survive
4 th	Corner	collapse	collapse
	Long side	collapse **	survive **
	Short side	survive	survive
5 th～7 th	Corner	collapse	collapse
	Long side	collapse	collapse
	Short side	survive	survive

locates, the less alternate loading paths the residual frame has. In addition, slabs enhance the resistance of progressive collapse (the examples marked by "**").

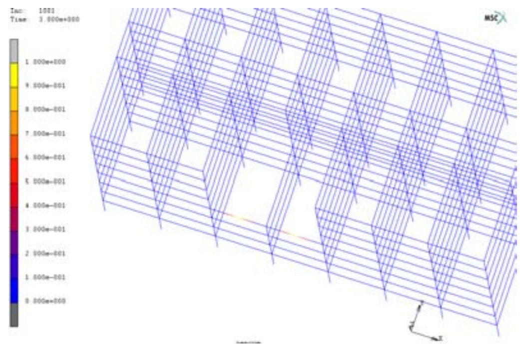
According to the simulation results as shown in Figure 10, it can be concluded that the tensile effect of slabs improves integrated load-bearing capacity which enhances the collapse resistance. Actually, the slabs still hold the broken beams though collapse happens, as shown in Figure 10(b).



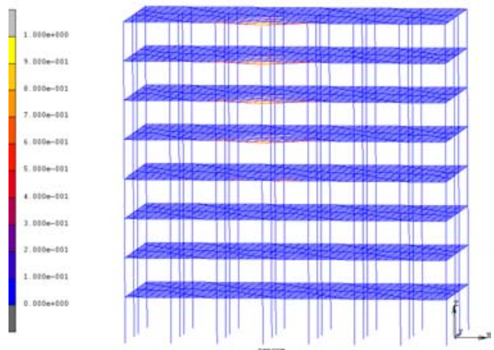
(a) Model A: collapse happens after column at long side of 5th floor is removed



(b) Model B: collapse happens after column at long side of 5th floor is removed



(c) Model A: collapse happens after column at long side of 4th floor is removed



(d) Model A: collapse does not happen after column at long side of 4th floor is removed

Fig.10 Failure models of structures after different columns are removed

Table 2 Comparison for consumption of longitudinal reinforcement in beams

Floor	Original frame	Strengthen frame			
		Model A		Model B	
	Consumption (ton)	Consumption (ton)	Increase	Consumption (ton)	Increase
Ground	5.43	5.57	2.58%	5.43	0.00%
1th	5.36	5.50	2.61%	5.36	0.00%
2th	4.87	5.00	2.67%	4.87	0.00%
3th	4.26	4.39	3.05%	4.26	0.00%
4th	3.64	3.78	3.85%	3.64	0.00%
5th	2.91	3.04	4.47%	2.91	0.00%
6th	2.33	2.75	18.03%	2.33	0.00%
7th	2.00	2.64	32.00%	2.40	20.00%
Total	30.80	32.67	6.07%	31.20	1.30%

5.2 Consumption of strengthening reinforcement

Both Model A and Model B are redesigned until they do not collapse after any column is removed. Then the consumption of strengthening reinforcement in frames including original frame and strengthened frames of Model A and Model B are compared, as shown in Table 2. Columns are strong enough but the reinforcement in beams should be increased. And moreover, Model A, which considers the contribution of slabs, just cost 21.4% of the strengthened reinforcement in the Model B, which ignores the effect of slabs. That means that slabs greatly enhance the collapse resistance of frame. It is also indicated that the design method in DoD2005 [2] which does not take the contribution of slabs into account is conservative but has some redundancy.

6 Conclusions

Fiber beam model is a high efficient element to simulate the columns and beams in collapse. In this paper, THUFIBER model embedded in commercial software MSC.MARC is developed. Because of the accurate constitutive laws of fibers and suitable discretization on section, THUFIBER performs well in simulating the collapse process of RC frames. And the simulation also shows that the slabs will obviously enhance the progressive collapse resistance of the structure.

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