Numerical Simulation of Catenary Effect of (RC) Frame Structure Based on MSC.Marc

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Abstract. Since the collapse of Ronan point apartment in 1960s, progressive collapse has become a research hotspot in civil engineering. In order to study and verify the catenary effect on the resistance of the reinforced concrete frame structure to the progressive collapse. Based on MSC.Marc software, a single-story plane frame structure of reinforced concrete frame structure was selected to establish a finite element model for numerical simulation, and the numerical simulation results was compared with the experimental data.

1. Introduction
In China's Code for anti-collapse design of building structures [1], the phenomenon that the initial local failure, from component to component expansion, eventually leads to the collapse of a part of the structure or the collapse of the whole structure is defined as progressive collapse. NIST [2] uses the term “progressive collapse” to describe the spread of an initial local failure in a manner analogous to a chain reaction that leads to partial or total collapse of a building. Codes in different countries have pointed out the characteristics of progressive collapse, which is caused by the chain reaction of local small damage and eventually leads to partial collapse or even overall collapse. The damage degree of the whole structure is not proportional to the initial damage. The collapse of Ronan point apartment in 1960s is a typical case of progressive collapse. The collapse was attributed to the gas exploration displacing walls and initiating a progressive collapse upward and then downward through the corner of the building [3]. Reinforced concrete frame structure is one of the most common building structures in the world. Fire, gas explosion, terrorist attacks and other disasters are not rare. The occurrence of these disasters may lead to the local damage of reinforced concrete frame structure, resulting in the progressive collapse of the whole building, causing more serious casualties and economic losses. Many experts and scholars have carried out research on progressive collapse, and have made some achievements so far.

Qian Kai et al. [4] in order to study the influence of catenary effect on the progressive collapse resistance of reinforced concrete frame structure, a macro-model of reinforced concrete frame considering catenary effect was established based on OPENSEES. The rationality of the macro-model was verified by comparing the vertical bearing capacity test results of two reinforced concrete frame structures after removing the middle column, the influence of catenary effect on the progressive collapse resistance of reinforced concrete frame structure is investigated.

He Qingfeng et al [5] used the pseudo-static experimental method to complete the collapse test of a 1/3 scale, 4-bay and 3-story plane reinforced concrete frame. It is found that the collapse of reinforced concrete frame structure is ultimately controlled by the tensile failure of the steel bars of the frame beam. If the strain distribution of the tensile steel bars is more uniform, the deformation capacity of
the structure can be increased, and the bearing capacity of the catenary mechanism can be further improved.

B. Abdelwahed [6] explained the catenary effect as follows: In the case of large deflection, the axial force in the beam or plate is converted into tensile force [2], which indicates the beginning of the next stage: catenary action and the catenary effect will play the role of bearing the axial tension. Catenary action depends mainly on the tensile force of longitudinal steel bars to withstand the vertical loading [2]. In the case of high deflection of a beam or slab, the tension in the beam or slab has a vertical component. This kind of vertical component is helpful to resist the influence of the increased load on the structure after the column is removed. Catenary effect works when the displacement is large, because the vertical force is directly related to the rotation angle of the beam after deformation [2,7].

The reinforced concrete frame structure undergoes the beam mechanism when the displacement is small under the load, and then it enters the catenary mechanism when the catenary action is motivated in the stage of large deformation.

Through the research [8], it is shown that in the stage of large deformation, the load is mainly borne by catenary mechanism, which will make the structure produce nonlinear resistance and improve the resistance of reinforced concrete frame structure to progressive collapse. In this paper, the catenary action analysis and numerical simulation are carried out for a reinforced concrete frame structure with the removal of middle column. The main subject of this research is reinforced concrete frame structure, considering the catenary connection of the floor and the contribution of the floor to improve the collapse resistance of the structure. A reinforced concrete frame structure with middle column failure is taken from the main body of the study. Referring to the existing collapse test of reinforced concrete frame structure, a RC frame structure with the removal of middle column from the original structure was selected and the test models were made according to the scale of 1:3. The MSC. Marc software was used to build finite element model. The experimental results are compared with the numerical simulation results to verify the catenary effect.

2. Introduction of the experiment

2.1. Prototype

The prototype structure is a 7-story reinforced concrete frame structure with 6 spans in both directions. The seismic fortification intensity is 8 degrees (0.2g), the bottom floor height of the structure is 4.2m, the rest floor height is 3.6m, and the vertical and transverse spans are 7.5m, as shown in Figure 1.

![Prototype](image1.png)

![Prototype plan](image2.png)

**Figure 1.** Structure model

2.2. Research content

In the test, a single-story plane frame structure of prototype structure in the red wire frame shown in Figure 1(b) is selected. Referring to the existing collapse test research, the test models are made according to the scale of 1:3 as the test research object. After the middle column of the structure is
removed, the monotonic vertical pseudo-static loading experiment is carried out, and then the catenary action analysis is carried out by the method of numerical simulation based on the MSC.Marc software. The experimental device is shown in Figure 2. When loading, the jack above the middle column is loaded downward, and the loading displacement is 500mm. Considering that the horizontal tension transmitted by the floor and frame beam is the main cause of the failure of the frame column, the effective flange width of the floor is made in the test models to consider its force transmission contribution. The research results of Bredean, L.A. and Botez, M.D. [9] show that the floor slab plays a great role in improving the collapse resistance of the structure and influencing the internal forces transmission in numerical model. Considering the contribution of floor slab, not only the economy can be improved, but also the anti-collapse ability of the structure will not be underestimated.

2.3. Design of Reinforcement Mode

Reinforcement details are demonstrated in figure 3. The starting position of transverse steel bars at the top of flange is 125mm away from the edge, 58 steel bars in total. The starting position of 6 longitudinal steel bars on the top of flange is 15mm away from the edge. The distance between the vertical distribution steel bars of the wall is 200mm, which each unit in double row arrangement, 4 steel bars in total. The concrete cover depth of beam L1, L2, columns and walls measure 8mm, the concrete cover depth foundation beam measures 25mm, and the concrete cover depth of slab measures 7mm. The foundation beam, upper beams and upper columns of the test frame are poured in two times, among which C50 concrete is used for the foundation beam and C30 concrete is used for the beams and columns. HRB335 steel bars are used as the longitudinal steel bars in the beams and columns. HPB300 steel bars are used as the stirrup. HPB300 steel bars are used as the steel bars in the flange plates.

(a) Reinforcement details for joints
2.4. Material properties
The material properties of all test models are shown in Table 1.

| Types of steel | Yield stress (MPa) | Ultimate stress (MPa) | Elastic modulus (GPa) | Elongation δ (%) | Cubic compressive strength of concrete (MPa) |
|----------------|-------------------|----------------------|----------------------|-----------------|-------------------------------------------|
| A6             | 394               | 519                  | 220                  | 20              |                                           |
| B10            | 419               | 617                  | 219                  | 18              | 29.2                                      |
| B12            | 625               | 685                  | 171                  | 10.2            |                                           |

The strength test of concrete is carried out with 150 mm *150 mm *150 mm cube blocks, and the average compressive strength of the blocks is obtained.
2.5. Loading and measuring methods
The test model is loaded by a hydraulic jack with a stroke of 500mm above its middle column. Considering that the side column may shift to a large extent during the test, slide plates with a displacement of ±175mm are installed on the jack. The 530kn load is pressurized on the top of the side column to simulate the gravity load from the above structure. Then, the axial force is kept unchanged, and the top of the middle column was loaded by the method of displacement loading.

3. Numerical simulation

3.1. MSC.Marc software
Msc.marc is a full-featured advanced nonlinear finite element software with strong structural analysis ability. It can deal with many kinds of linear and nonlinear structural analysis. Msc.marc is used to build the finite element model for calculation. In the process of building the model, the influence of material nonlinearity and geometric nonlinearity on the calculation results are taken into consideration. Through the establishment and analysis of the finite element model, the numerical simulation of the progressive collapse under the action of concentrated force is carried out.

3.2. Geometric characteristics
Solid element is used for concrete. The mechanical behaviour of concrete is simulated by defining three-dimensional constitutive equation. Truss element is used for steel bars.

3.3. Constitutive equation of materials
The compressive strength of concrete cube ($f_{cu}$) is 29.2Mpa. In structural calculation, the standard value of strength is 22.5Mpa. Von Mises yield surface is selected for calculation. The hognestad curve is used for the uniaxial constitutive curve of concrete under compression. Because the curve has considered the restraint effect of stirrup on concrete, the stirrup part is ignored in the process of analysis. The curve image is shown in figure 4 (a), and the curve equation is as follows:

$$\sigma = \sigma_0 \left( \frac{2\varepsilon}{\varepsilon_0} - \left( \frac{\varepsilon}{\varepsilon_0} \right)^2 \right), \ \varepsilon \leq \varepsilon_0$$  \hspace{1cm} (1)

$$\sigma = \sigma_0 \left[ 1 - 0.15 \left( \frac{\varepsilon - \varepsilon_0}{\varepsilon_u - \varepsilon_0} \right)^2 \right], \ \varepsilon > \varepsilon_0$$  \hspace{1cm} (2)

In the actual calculation, the equivalent plastic stress-strain curve is input. Taking $f'_t = \frac{1}{3}$ as the boundary point of elasticity and elastoplasticity, the strain corresponding to the boundary point is
calculated as \( (1 - \frac{\sqrt{3}}{3})e_0 \). The standardized modulus of elasticity is the secant modulus \( E_c = \frac{1}{(3-\sqrt{6})e_0} \) at the boundary between elasticity and elastoplasticity. The equivalent plastic strain is \( \varepsilon_{pl} = \varepsilon - \sigma/E_c \).

Tensile constitutive curve of concrete is showed in the figure 4(b). The theory of fixed crack model is used for the tensile constitutive model of concrete. After the cracking of concrete element, the main stress direction of the cracking element changes in the subsequent calculation. At this time, the main stress direction and the crack direction may be inconsistent, so the fixed crack model can be used to deal with it. Fixed crack model is the most commonly used form of smeared crack model, the original crack angle will not change after the crack appears [10]. The bilinear model based on fracture energy is used in the tensile constitutive model, and four parameters (critical stress, softening modulus, crushing retain and shear retention) need to be input. Critical stress can be calculated by \( f_c = 0.26(f_{cn})^{2/3} \), which is 2.2MPa. The softening modulus, which can be calculated according to the fracture energy, is set as 1000MPa. Regardless of collapse, the collapse strain is set to 1. Shear transfer coefficient which affects the results of shear calculation and program convergence, is set to 0.5. The yield point, peak point and residual point of the reinforcement are found out according to the given material property data. The simplified bilinear model is used as the reinforcement constitutive model. The yield criterion is von Mises criterion.

3.4. Finite element division

In order to facilitate the calculation between different elements of the concrete part, the model not only ensures the division accuracy, but also adheres to the conditions of the common nodes of the concrete elements, making parts well connected. At the same time, the eight-node hexahedron element is selected for division, which conforms to the general rule of the modeling. The divided concrete element is shown in figure 5(a).

The steel bars are simulated by space truss elements in figure 5(b). The stirrup mainly plays a restraining role in the flexural components. However, it has a minor effect on the bearing capacity of the flexural components. Thus, modeling by defining the constitutive curve of concrete which takes stirrup restraint into consideration rather than modeling the stirrup is conducive to the convergence of the program.
3.5. Boundary conditions
The left margin is the beam column joint area. Considering the large stiffness of the shear wall on the right side, the boundary condition on the right side can be considered as fixed support boundary. The bottom boundary condition can be treated as fixed support. The elastic block is used to simulate the cushion block when it is loaded in reality, and at the same time, the phenomenon of stress concentration caused by loading directly on the concrete element is prevented. At the top of the left column, a uniform surface load of 8.48N/mm² is applied to simulate the load from the structure above. Displacement loading is carried out in the middle of the span. The target displacement is 500mm, which is divided into 2000 steps. The node at the top of the loading block is directly selected to exert displacement, and the loading position is showed in figure 6(a). In the extraction of the results, the reaction forces of the whole top region are output and summed to get the stress-displacement curve. The loading method and boundary conditions are shown in figure 6(a) and figure 6(b) respectively. The top force of the left end column is not shown in the figure 6.

Figure 6. Loading position and boundary condition

3.6. Solution method
Because the concrete constitutive curve has a descending section, the stiffness matrix will appear negative when the structure is solved. Generally speaking, the finite element program has poor convergence when it is not positive definite, so the option Non-positive Definite is selected in MSC.Marc. The stiffness matrix is formed again in each calculation to ensure the convergence at the inflection point due to the large change of stiffness. The solution method is showed in figure 7.
3.7. Displacement calculation

The overall deformation diagram of the structure is shown in Figure 8. At the end of the loading, the top of the column moves sideways, the beam deforms greatly, and the final shape of the structure is the catenary shape. According to the final deformation diagram, the displacement at the bottom of the beam span is large, and the concrete has cracked. Because of the large deformation in the upper area, the concrete does not work after reaching ultimate compressive strain, and the whole structure bears the external load by the steel bars, which is the catenary mechanism.

3.8. Comparative analysis

According to the reaction force-displacement curve of the experimental data and simulation data is illustrated in Figure 9. At the beginning, the reaction force of the structure increases obviously with the increase of the displacement. When the displacement is between 35-50mm, the reaction force reaches the first peak and then decreases significantly. Then, with the further increase of the displacement, the reaction force of the structure began to rise again until the second peak. The first peak of bearing capacity occurs in the stage of beam mechanism, and the second peak of bearing capacity occurs in the stage of catenary mechanism.

The reaction force-displacement curves of simulation and test basically coincide with each other, and the overall variation trend of the curves is the same. At the early stage, with the increase of vertical
displacement in midspan, the two curves basically coincide before the first maxima. The first maximal value is about 64Kn, the difference value between experimental data and simulation data is 0.355Kn. During the descending stage, the curve of numerical simulation decreases quickly, and the test curve is slightly higher than the simulation curve, but basically within the allowable error range. The second maximal value is about 81Kn, and the difference value between experimental data and simulation data is 0.529Kn. MSc. Marc finite element model can simulate the reaction force-displacement curve of a single-story plane frame structure of reinforced concrete frame structure under the vertical loading, and also simulate the catenary effect of the structure under large deformation.

The catenary effect improves the vertical load-bearing capacity of a single-story plane frame structure after the failure of the middle column. After the beam mechanism under small deformation, the vertical bearing capacity of the structure decreases from the first maximal value, and then the catenary effect makes the vertical bearing capacity of the structure rise again to the second maximal value (about 81Kn) by 30% of the first maximal value (about 64Kn).

![Reaction force-displacement curve](image.png)

**Figure 9. Reaction force-displacement curve**

4. Conclusion

For the concrete frame beam, before entering the catenary mechanism, it first goes through the stage of beam mechanism. Under the initial load, the reaction force increases with the increase of displacement. When the load reaches its first maximum, the reaction force provided by concrete decreases due to excessive compressive stress which makes it enter the downward section of the constitutive curve. At the same time, the concrete cracks due to tensile stress on the bottom of the beam, which also causes the bearing capacity to decrease with the increase of loading displacement. Due to the continuous cumulative destruction of concrete in the compressed zone, when the load drops to its lowest point, the catenary mechanism takes effect and the load is borne by the catenary tension of steel bars. The beam-slab components of reinforced concrete frame structure deform largely and begin to provide non-linear reaction force. With the increase of deformation, the bearing capacity continues to rise until the steel bars are broken, and then the bearing capacity decreases sharply again. The finite-element-model analysis and numerical simulation of the reinforced concrete frame substructure by MSC.Marc software are in good agreement with the test of specimens, and the error between the peak bearing capacity is relatively small. This indicates that it is feasible to use the
concrete constitutive model that recommended by Hognestad, the fixed crack model, the bilinear model based on fracture energy, and the simplified bilinear model of steel to simulate reinforced concrete frame structure.

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