Experimental Research of Progressive Collapse Resistance of RC Frame Structure

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Abstract

In order to further study the reinforced concrete frame structure against the continuous collapse of the force mechanism, a $2 \times 2$ single-layer reinforced concrete frame model was designed and manufactured. The quasi-static test method was adopted to exert the external effect on the reinforced concrete frame structure with the failure angle column through the hydraulic jack. By using the force and displacement mixed control method, structural continuous collapse process was simulated. The failure process of the corner column and the development of the plastic hinge formation were observed, and the data of frame resistance, structural displacement, steel strain and concrete strain were collected. According to the experimental data and phenomena, the structure resistance - displacement curve, the order, quantity and collapse mechanism of the plastic hinge were analyzed. It can be seen that the frame underwent the elastic phase, the plastic phase and the failure failure stage in the failure process of the corner column failure. It is also known that the frame structure provides the anti-continuous collapse ability through the failure bearing capacity of the frame beam. Moreover, a simple plasticity method for the collapse of the frame was obtained.

Keywords: RC frame structure, progressive collapse, experiment study, flexible, plastic, failure mechanism.

1. INTRODUCTION

Local Damage of the structure may lead to the destruction of a major part of the whole structure or the overall structure. In other words, the final scope and extent of structural damage are not proportionate to the initial scope and extent of structural damage, this failure mode in structural engineering is termed continuous collapse or disproportionate collapse damage. From the damage of Ronan Point apartment in the 1960s, to the collapse of the US World Trade Center in 2001, the disproportionately collapse of a large area caused by a partial failure has brought tremendous damage to human beings. However, the research on the criterion of continuous collapse is still not perfect. The "Design Code for Concrete Structures" in China only stipulates the design principles of the concrete structure against continuous collapse and the concept of strengthening integrity. In addition, there are many reasons for the collapse of the structure, for example, there were less relevant model test, lack of both sufficient experimental verification and strong data support, and the mechanism of the structure collapse is also complex, so further study is needed. Therefore, many scholars from home and abroad have done a lot of research on this. Sasani
and Sagiroglu (2007) did a positioning blasting test to the bottom exterior column of 10-story reinforced concrete frame structure; Sasani (2014) through abstract experimental and analytical studies on a two-span fixed-end RC beam; Yi and He(2007) did a collapsing quasi-static test to a three four-span reinforced concrete plane frame in Hunan University; Zou (2011) used the method of quasi static loading to study resisting progressive collapse on a four-layer space frame without plate. Phamxuan et al., (2015) presented a simplified approach for progressive collapse assessed of RC building structures, which subjected to a penultimate column loss. By choosing proper criterion to deactivate elements and adopting appropriate contact algorithm, the models proposed are able to simulate the whole process of structural collapse(Lu et al.,2008).One approach to evaluate progressive collapse of structures is to study the effects of instantaneous removal of a load-bearing element such as a column (Sasani and Kropelnicki, 2008). An experimental program is carried out to study the behavior of a 3/8 scaled model of a continuous perimeter beam in a reinforced concrete frame structure following the removal of a supporting column; The progressive collapse of the frame structure is simulated with testing a 1/3 scale, 4×2-bay and 3-storey reinforced concrete spatial frame in this paper (Zheng et al., 2011). The experimental model was designed according to the non-seismic resistance demand; Jia et al., (2016) carried out nonlinear finite element analysis of a 3-story single span R.C. frame and a single story R.C. double shear wall shear wall test model by utilizing ANSYS; In this research, a numerical study on two reinforced RC frame structures demonstrates that the current TF method is inadequate in increasing the progressive collapse resistance(Yi et al., 2011);To study the progressive collapse-resisting mechanisms of reinforced concrete floor systems, seven 1/3-scaled one-way substructure specimens, including five beam-slab specimens and two continuous-beam specimens without slabs, were tested under a middle-column-removal scenario (Ren et al., 2016); The progressive collapse resistance of a two-story steel frame was investigated after the sudden removal of a perimeter column in the first floor through an experimental study(Chen et al., 2012). Due to the complexity of mechanical mechanism of collapse process, although many scholars at home and abroad carried out a lot of works, but in view of the framework’s continuous collapse, related research is still not perfect, it still needs to carry out the experimental study.

In this paper, a 2*2 single-layer reinforced concrete frame model was designed, the loading method of force-displacement hybrid control was adopted and the pseudo-static test of the reinforced concrete frame without corner posts is carried out to simulate the continuous collapse of the frame under the initial failure of the corner column. The deformation of the structure and the formation of plastic hinge were observed and the relevant data was collected. The collapse mechanism and internal force of the frame structure were analyzed.

2. TEST OVERVIEW

2.1 Specimen design

The experimental model in this paper was a single-layer 2 *2 RC frame-column space model. The model was designed and manufactured in the Key Laboratory of Structural and Anti-seismic of the Ministry of Education, School of Civil Engineering, Xi'an University of Architecture and Technology, and it was in accordance with the Code for Design of Concrete Structures (GB50010-2010) and Building Seismic Design Code (JGJ101-96).

The overall dimensions of the test frame were 3.6m* 2.6m*1.75m. Longitudinal frame column grid layout spacing was 1.8m; lateral spacing was 1.3m. Column sectional dimension were 133mm*133mm; stringer cross-section dimensions were 67mm*150mm; beam cross-sectional dimensions were 67mm*117mm; floor thickness was 30mm. The clear height between the foundation beams and the floor plate column was 1200mm. Other than the load plate side corner posts, added at the higher place of the floor plate column, other frame columns project 50mm over capitals. In the lower end of the model structure,
poured the foundation beam, and the experimental model was shown in Figure 1; Reinforcement of slab was in Figure 2; Layout, size and reinforcement of beams and columns was in Figure 3. The test of frame beams force reinforcement all used HPB300 bars; stirrups and Ligament used 3mm wire; concrete design strength grade was C25. The measured values of mechanical properties of steel and concrete indicators were: steel and steel wire yield strength was 310 Mpa and 395 MPa, ultimate strength was 372 Mpa, 450 MPa, the elastic modulus was 2.08 \* 10^5 MPa; concrete cube compressive strength was 26 MPa.

![Figure 1. Model of frame structure](image1)

![Figure 2. Reinforcement layout of slab](image2)

(a) Column (b) Lengthways beam (c) Transverse beam

![Figure 3. Reinforcement layout](image3)

### 2.2 Observation design

#### 2.2.1 Test setup

In this paper, the quasi-static loading method was adopted, and the loading device adopted the portal type steel frame, and the hydraulic jack was fixed on the steel frame to apply load to the corner column. Through the dial gauge we can measure the vertical displacement of the angle column, and the value of the force measured by the force sensor can reflect changes of externally applied load during the loading process. The layout of the instrument was shown in Figure 4.
2.2.2 Layout of ganging points

The test content of the static load test included displacement and strain measurement. Therefore dial indicator measuring points arrangement was shown in Figure 5 (a); concrete frame beam strain gauge layout was shown in Figure 5 (b); measuring gage steel was mainly arranged in the proximal and distal corner post connection failure of beams bars on the top and bottom.

![Figure 5. Layout diagram of ganging points](image)

(a) D was placement meter  (b) S was strain gauges

2.3 Loading systems

Force - displacement hybrid control loading was used during test. And loading system was: before the start of loading in static test, firstly turned sensor signal acquisition channel into zero, then force was used to control load rating, increased the load 1kN by hydraulic jacks until the component part yield roughly, started use displacement to control loading, firstly down loaded 5mm each time, and loaded four times; then every time down loaded 10mm, after completion of each loading, waited 10 minutes, until the data collection instrument stabilized, then read the beams, plates and reinforced concrete tensile and compressive strain and strain beam each test-section deflection plate, while getting the value of the force sensor recorded simultaneously. After the completion of each stage, read the maximum crack width with crack microscope, measured out the cracks range with a ruler until structural failure or carrying capacity sharply decreased.
3. TEST RESULTS AND ANALYSIS

3.1 Failure modes and crack development

At the early stage of loading, when the vertical displacement of the failure column was only 2.6mm under the action of the self-weight and the external load, the C-beam distal concrete was cracked due to tension, and when the vertical displacement was 4.5mm, B beam distal side of the concrete also produced cracks. As the displacement continued to increase, the B and C beams gradually twisted inward, resulting in oblique shear cracks at the beam end and the concrete peeling at the bottom of the beam end is severely. At the same time in the P1 area of the concrete slab surface there were several cracks of 45 degrees slope, and they were cross-through, and ultimately they formed several large diagonal cracks. A small amount of oblique cracks appeared in the middle of the P2 and P4 plates, and almost no cracks were found in the other beams and the plate as shown in Figure 6(a-f).

![Figure 6. Failure modes of structure](image-url)
3.2 Relationship between resistance and vertical displacement

Figure 7 showed the relationship between the resistance and the vertical displacement of the failure column. From the figure, with the increase of vertical column corner displacement, the whole collapse process can be divided into three stages. 1) OA: Elastic phase. As the load increased, the displacement increased. When the load was 5kN and the displacement was about 2.6mm (point A), a crack appeared in the upper part of the beam away from the corner column, which marked the end of the elastic stage. 2) AB: plastic hinge formation stage. When reached to point B, the vertical displacement was about 25mm, the bearing capacity reached the maximum value of 16.4kN, and the beam connected with the failure angle column was gradually formed. End of the other cross-section also had a plastic hinge. 3) BC: failure stage. After point B, a plastic hinge was formed at the beam end, and the structure became a maneuvering system and began to enter the failure stage. In this process, with the vertical displacement continued to increase, the plastic hinge region deformation increased sharply, the pressure area of the concrete was crushed, and constantly peeling. Because the frame beam connected with the failure column lacked the horizontal constraint of the frame column, it can only be carried by bending. When the vertical displacement reached 130mm, the deformation of the structure was quite serious. The load of the top of the failure column was mainly transmitted by the toughness of the reinforcement in the frame beam and plate. The deflection of the frame beam has exceeded 10% of the beam span. According to DoD(2005) Appendix B that the framework has collapsed.

![Resistance and vertical displacement](image)

**Figure 7.** Vertical displacement curve

3.3 Concrete strain curve

Figure 8 (a) is relationship curve between upper and lower surfaces of concrete stain of the far end on the beam B, C and vertical displacement of failure corner posts. From the figure, at the start of loading, the concrete at position 4 of the beam C was in tension. Under its own weight and external loads, when the prism displacement decreased only 2.6mm, the concrete of this position has cracks due to tension, indicating an elastic frame Force stage’s end. With the prism vertical displacement continued to increase, the concrete tensile strain at position 1 of the beam B also increased. When the prism vertical displacement was approximately 4.5mm, strain increased to 214 micro-strain, then a crack was found in the concrete position, after that, deformation gradually intensified, sustained rally has also been increased, but the crack passed through resistance strain gages, so strain after that can’t accurately reflected the true state of the position by force. The concrete in the lower was under pressure initially, when the load exceeded the limit of the structure, the upper steel was severely deformed, plastic hinge was gradually destroyed, concrete is crushed and spalling, the lower steel tended to be in tension, concrete strain decreased gradually, with the tension trend. Figure 8 (b) is relationship curve between concrete stain at position 1 of the beam A and vertical displacement of the corner posts. The figure shows that with the increase in vertical displacement of the corner posts, on the A side of the beam,
concrete strain was in tension, the lower side was under pressure, indicating a trend upward movement of the beam, which is the midpoint of the beam A No 4-5. It is consistent with the measured displacement movement trend. It is also proved from the side that structure has the trend to close to failure prism.

![Graph](image1.png)

(a) Concrete stain of the far end on the beam B, C (b) Concrete stain at position 1 of the beam A

**Figure 8.** Concrete stain of the beam

### 3.4 Strain of steel and development of plastic hinge

By the strain change of the steel in the test, the order that steel within the framework of the beam yields can be inferred. From the data measured in the test, the side of the steel girder 5-1 C 4 was the first to yield, almost at the same time a beam on the B side reinforced 5-3 also began to yield, these two steel strain has been increasing in line with the actual stress situation. In the lower part of the collapse process, it has been in a state of compression, with the increase of the vertical displacement of the failure corner posts, its compressive strain has been increasing. The lower reinforced 5-6 of the beam C at the position 3 and the lower reinforced 5-8 of the beam B at the position 2, which laid near end on the load post have been in tension, the upper 5-5 and 5-7 reinforced were in compression, and it increased with the increase of vertical displacement. Relationship between steel stains of near end on the beam of frame structure and vertical displacements of failure corner posts is shown in Figure 9.

![Graph](image2.png)

(a) Steel’s far end stains of beam (b) Steel’s near end stains of beam

**Figure 9.** Relationship between steel stains and vertical displacements of failure corner posts
4. THE FORCE MECHANISM OF FRAME BY COLLAPSE

There are two kinds of collapse modes of frame structure: vertical continuous collapse and vertical and horizontal mixed continuous collapse mode. Vertical continuous collapse mode generally is, after the demolition or failure of the corner column, only the upper part of the local parts have continuous collapse but other parts’ relative damage is not large, this paper belongs to this form of destruction. Regardless of the failure mode, the failure mode of the RC frame starts from the vertical deformation of the failure site, so the frame beam plays a key role in the anti-continuous collapse mechanism of the whole structure. In the small deformation stage, the frame beams provide the ability to withstand continuous collapse through their bending capacity, which is the beam mechanism. In the large deformation stage, only the reinforcing bars in the beams with support on both sides can provide continuous anti-collapse capacity, this is the catenary mechanism.

In this paper, experimental framework collapse is due to the initial failure of the prism’s position, and from relationship between resistance and vertical displacement of failure corner posts, its progressive collapse resistance force process has two stages: stage elastic and plastic phases.

4.1 Flexible stage

According to the relationship between resistance and vertical displacement of failure corner posts, when failure prism vertical displacement was approximately 2.6mm, frame enter elastic-plastic stage, the resistance was about 5kN, at this time, bending moment diagram and axial force diagram of frame are shown in Figure 10-11. The bending moment figure shows lengthways beams’ span was larger than cress beam, but the far end bending moment was not as large as transverse beam and cracks appeared slightly later, and the destruction of transverse beam was more serious, it is because the transverse beam span was small, and it can produce large angle at the same vertical displacement of failure prism corner posts, The forming order of plastic hinges can be seen approximately. These results were in agreement with the experimental results. As what can be seen from the axial force diagram, the tension force was generated in the side beam after the corner column’s failure. The frame model moved toward the corner column as a whole, and the two columns near the failure angle column withstand the pressure of most of the structure, both sides of the side column and the column also bear part of the pressure, but the force of the other part is not big. In the upper corner of the failure angle column, the upper part of the corner column was under pressure, and the lower end column was not subjected to the force. It can be seen that, when the corner column failure, the load born by angle column went through the two cantilever beam to the remaining structure, the stress area mainly concentrated in the corner column area and that was connected to the side beam, other areas had little influence, and it reflects the load transfer path.

![Figure 10. Bending moment diagram](image1)

![Figure 11. Axial force diagram](image2)
4.2 Plastic stage

According to the theory of yield line, it is assumed that the ultimate load $P$ is applied above the failure angle column and the downward displacement of the corner element by the unit virtual displacement is 1, it will cause the downward displacement of the whole plate surface, and the load $P$ does the external work. At the same time, the plate along the negative bending moment of the plastic hinge line to produce the corner, the bending moment along the plastic hinge line works. According to external work and internal work equal, there is functional equation:

$$ P \times \frac{L}{2} = m_{un} \times L $$

(1)

$L$ is the length of the diagonal concrete; $m_{un}$ is resisting moment unit width limit of the concrete slab.

In plastic stage, internal Reinforced of frame beam attached failure prism yielded by tension, gradually plastic hinge formed. After the nip concrete is crushed, the core areas of reinforced concrete and steel of beam section mainly shared external force, then the whole cross section of the beam enter the plastic stage. The bending moment value of the beam section reached the limit value $M_p$, and a certain degree of rotation can take place. When all the ends of the frame beam formed plastic hinges, the structure changed to a geometrically variable system. The structural plasticity analysis method can be used to calculate the resistance value of the frame beam when the plastic hinge forming:

$$ F_{u1} = \frac{M_{p1}}{L_1}, F_{u2} = \frac{M_{p2}}{L_2} $$

(2)

On behalf of the cross-section parameters available:

Overall ultimate load of model structure:

$$ F_u = F_{u1} + F_{u2} + P = 12.65KN $$

(3)

Compared with the experimental value, the theoretical value is smaller, with a difference of about 4kN, and it is more conservative. In the formula, $M_{p1}, M_{p2}$ represent plastic bending moment of the long side and the short side beam, $L_1, L_2$ represent net length of long span and short span beam of slab.

5. CONCLUSION

Through the continuous collapse of the column failure frame, the resistance displacement curve, the strain curve of the concrete strain and the reinforcement strain and the sequence and quantity of the plastic hinge formation are obtained. The collapse failure process and the force characteristic of the initial failure of the corner column are revealed.

In the process of collapse, failure prism frame model has undergone elastic stage, plastic stage and failure stage. The mechanism of frame collapse is analyzed. It is pointed out that when the corner column failure, frame beams in the failure region resist external loads by bending and provided resistance to continuous collapse.

The plasticity method of the frame collapse failure is given by the yield line theory. And the plastic limit load of the frame model calculated by plasticity theory is smaller than that of the experimental value.
Using a mixed load control quasi-static test to research into progressive collapse process of framework, we didn’t consider the impact of the collapse of the role of power in the process, for the role of multi-frame in space, interactions of the upper and lower structure and load path’s impacts to structural progressive collapse, and the multi-position also require further analysis.

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7. REFERENCES


