Experimental study on seismic performance of frame flat columns with high axial compression ratio

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Abstract. When the lateral stiffness of the frame flat column is relatively small, the strength of the frame flat column is not enough to resist the large horizontal earthquake force and seriously deformed, which leads to the structure fail and could not work normally. In order to study the bearing capacity and the deformation capacity, experiments of three specimens of high axial compressive ratio under frequency cyclic loading were conducted, in which the failure process were observed in detail and the failure mechanism of the specimens were researched, the failure type, the hysteretic characteristic were studied, and the effect of the axial compressive ratio, the ties type and the stirrup ratio on the ductility of the members were analysed.

1 Introduction

The code for seismic design of buildings (GB50011-2010) [1] stipulates that the frame structure of seismic fortification or the frame structure houses with more layers in the non-seismic area should be designed as rigidly connected frames horizontally and longitudinally and calculated accordingly. In this way, the frame column should be calculated in the longitudinal direction in addition to the bearing capacity and deformation calculation in the transverse direction. It is often considered that there are more columns in the longitudinal direction, the lateral stiffness is larger, the load on the longitudinal frame is small, and the seismic action should also be small, and its bearing capacity and deformation ability are relatively easy to meet [2]. However, the main structure of large thermal power plant, high-rise reinforced concrete structure and other heavy industrial structures are generally subjected to large vertical load, so the action in the longitudinal direction of the frame of the total horizontal seismic action is relatively large [3]. And the column section is different from the general column section, and the height of the section is far greater than the width of the section, forming a flat column. For the convenience of narration, the frame column with section height less than 2 times of section width is called frame flat column. Because of the above two reasons, whether the bearing capacity and deformation capacity of the frame flat column can meet the requirements of seismic resistance has not been tested and studied so far. In this paper, three long flat columns of reinforced concrete frame with high axial compression ratio are tested under repeated periodic load, and the

effects of hoop form, hoop ratio and axial compression ratio on the failure form, bearing capacity, hysteresis and ductility of reinforced concrete flat columns are studied.

2 Experiment design

2.1 Specimen design

The prototype of the specimen was taken from the third phase project of Zouxian Power Plant in Shandong Province (built). According to the characteristics and practical engineering experience of the frame flat column in the frame bent system of the main workshop, the parameters of the specimen design are as follows [4,5]:

(1) The test column is a cantilever loading column with a calculated aspect ratio of 22; the cross section size is 315×140 and the geometric ratio of the model to the prototype is 1:6;

(2) The concrete strength grade is C30;

(3) Steel bar strength grade: stirrups are grade I hot rolled steel bar and longitudinal bars are grade II, the relation between axial compression ratio n_t and design axial compression ratio n is: $n = 1.616n_t$ [1].

(4) The specimen C-1 is taken from the actual engineering with the same volumetric hoop ratio and longitudinal reinforcement ratio as the frame column in the actual engineering.

(5) A stirrups infill zone is set up in the 200mm range of the top of the column to prevent local pressure damage. The stirrups spacing of the stirrups is 50 mm.

All columns are designed for strong shear bending, and the specimen size and reinforcement are shown in the table 1.

Table 1. Specimen Size and Reinforcement

Test specimen	$b \times h$ (mm)	Slenderness ratio	Test axial compression ratio n_t	Column height H (mm)	Axial force N (t)	Shear level Force V (t)	Bending level Force V (t)	Form of stirrups	Diameter of stirrups and spacing	Volumetric hoop ratio ρ_v (%)	Actual longitudinal bars A_s (mm)	Actual reinforcement ratio ρ_s (%)
C-1	315×140	22	0.557 (0.9)	1540	66.32	8.70	1.82	S-1	$\phi 6@80$	1.05	452 4 $\phi 12$	1.37
C-2	315×140	22	0.557 (0.9)	1540	66.32	9.81	1.99	S-2	$\phi 6@80$	1.57	678 6 $\phi 12$	2.05
C-3	315×140	22	0.557 (0.9)	1540	66.32	11.22	2.56	S-3	$\phi 8@100$	2.44	904 8 $\phi 12$	2.73

Note: The shear horizontal and flexural horizontal forces in the table are the values calculated according to the formula in the Code for the Design of Concrete Structures (50010-2010) [6].

2.2 Mechanical properties of materials

The measured value of concrete standard cube compressive strength is 31.2 N/mm^2 . Each steel bar is tested in three groups, and the average value is taken as the measured value of its mechanical properties, as shown in the literature [4, 5]. The test piece is poured by prostrate and the concrete by manual stirring.

2.3 Test methods and contents

The experiment was carried out on the pseudo static test of a counter force frame device at North Workshop in the structure laboratory of Xi'an University of Architecture and the loading system is cantilever column. A displacement meter installed in the column tops, which measure the horizontal displacement of column top under the horizontal action V_1 , and then the $V - \Delta$ curve of column top is obtained. First, a predetermined axial force vertical load was applied to the specimen, and remained constant, and then horizontal load was applied. The horizontal loads are adopted by load and displacement control method. Specimens are controlled according to the load value before yielding. After the specimen yield, specimens are controlled according to multiple recorded specimen yield displacement control cyclic loading Δy . At the same time, as the degradation capacity, each displacement amplitude was 2 ~ 3 times until the bearing capacity of the specimen is reduced to the maximum load of 80%.

3 The main test results and analysis

3.1 The failure process and the failure form of description

The cracking loads of columns C-1, C-2 and C-3, the load of shear oblique cracks and the load of vertical cracks are shown in the literature [4, 5]. C-1, C-2 and C-3 column fractures develop and develop according to the following law: with the increase of the load, new horizontal cracks appear at the left and right edge of the front or back of the column from the bottom to the top, the original cracks continue to extend, the bottom cracks have been extended to the middle axis, some cracks have been extended from the original horizontal cracks from the top to the bottom, but the angle of the lower

extension is not large; several horizontal cracks have appeared at different heights on the left or right side of the column through and through the cross section. There were several vertical cracks immediately at the lower left edge or right lower edge of the front or back of the column, as well as at the lower left or right edge of the column; after entering the yield stage,

Fig. 1. Damage map of C-1

the cracks in the column expanded further with the cyclic loading, and then a number of vertical cracks appeared near the root of the left or right edge of the column, and the original vertical cracks

Fig. 2. Damage map of C-2

continued to extend upward and spread wider and wider in the middle of the column. The vertical crack gradually penetrates with the original horizontal crack, forming a mesh, and the concrete begins to peel off, which indicates that the compressed area concrete has been crushed to reach the ultimate load. With the repeated load, there are a large number of vertical and horizontal cracks around the column, these cracks are intertwined, the width of the cracks is increasing, the concrete is gradually becoming crisp, the concrete at the left and right edge of the front or back of the column appears partial shedding, and the concrete is partially shedding at the lower part of the left and right side of the column. Finally, when the horizontal load is reduced to 85% limit load, the cracks in the surrounding concrete have made the concrete crisp and crack and the column is considered to have been completely destroyed at this time. The cracking and yielding loads of the C-1 column are close, the load of the oblique crack, the load of

Fig. 3. Damage map of C-3

the vertical crack and the ultimate load are close, that is to say, the column has obvious brittle failure, when the ultimate load is reached (see Fig.1), it begins to load repeatedly, because the column reinforcement ratio is less and the hoop ratio is less, the load suddenly decreases greatly at the time of push, and the concrete falls off seriously at the back of the column, the vertical crack extension is longer, and there are many horizontal cracks running through the cross section on the left side of the column. When the C-2 and C-3 columns were finally destroyed (see Fig. 2 and Fig. 3), the vertical cracks did not extend very long, and there were several horizontal cracks running through the cross section on the left and right side of the column, and the concrete around the root of the column was shed, but the C-3 column was more severe than the C-2 concrete, which was mainly caused by the high reinforcement ratio and hoop ratio of the C-3 column and the large spacing of the stirrups.

The failure form of the column mainly depends on the axial compression ratio, the hoop ratio (or the characteristic value of the hoop), the form of stirrups, the content of longitudinal bars and the strength, etc. Because the test columns are designed with strong shearing and weak bending, the failure form is finally bending failure. The stirrups of column C-1 are in the form of ordinary rectangular hoop, and the volumetric hoop ratio is small, the ductility is poor, and the sudden brittle failure occurs. The stirrups of column C-2 and column C-3 are rectangular hoops with strips and well hoops, which can meet the ductility requirement. The stirrups of column C-3 are in the form of well hoops with tension bars, the reinforcement ratio of longitudinal bars and stirrups with hoop ratio are higher, the strain values of stirrups are smaller when the final failure, only individual longitudinal bars have yield phenomenon, therefore, when the column is finally destroyed, the concrete falls off more seriously and the ductility is relatively better.

3.2 Experimental results

The main test data and the hysteresis curves and skeleton curves of columns C-1 to C-3 are shown in the literature [4, 5].

3.3 The hysteretic curves and skeleton curves

The specimens C-1~ C-3 are all frame flat columns. The design axial compression ratio of the three columns is the same, the hysteresis ring shows the phenomenon of pinching, the ductility is low, because of the increase of hoop ratio and reinforcement ratio in turn, the hysteresis ring of each column becomes more and more plump, the ductility of the specimen increases, the energy dissipation capacity increases, and the seismic resistance increases accordingly. However, it can be seen from the hysteresis curve that the hysteresis curve of C-1 column is extremely asymmetrical. Because the ratio of hoop and reinforcement of C-3 column is higher than that of C-2 column, its bearing capacity and ductility are higher. In fact, it can be seen from the hysteresis curve that the

bearing capacity of C-3 and column C-2 is not much different, and the hysteresis ring of column C-3 is not very full, which may be mainly due to the large spacing of stirrups of column C-3 under the condition of high axial compression ratio, and the high hoop ratio and reinforcement ratio do not improve the bearing capacity and energy consumption. But in general, the ductility of C-3 column is better than that of C-2 column. This is mainly because the C-3 column adopts the form of S-3 stirrups, while the C-2 column adopts the form of S-2 stirrups, and the form of S-3 stirrups can effectively restrain the core concrete and improve its strength and deformation performance. Although the longitudinal reinforcement ratio of the two columns is not the same, the flexural bearing capacity is not much different, which is mainly due to the high reinforcement ratio of the latter. Compared with the general frame column, the ductility and bearing capacity of the frame flat column are poor, and the failure has obvious brittle property.

In the case of high axial compression ratio, the falling section of the skeleton curve is steep, the bearing capacity of the specimen lost is large, and the capacity of energy consumption is poor. It can be seen from the literature [4, 5] that the $v-\delta$ curve difference of the three specimens is quite obvious, which is mainly due to the influence of longitudinal reinforcement ratio, stirrups form and hoop ratio, and the influence of hoop spacing cannot be ignored. The longitudinal reinforcement ratio and hoop ratio of the three columns increase in turn, and the skeleton curve becomes gentler. Because the stirrups spacing of the C-3 column is larger than that of the C-2 column, the decrease section of the skeleton curve between the C-3 column and the C-2 column is not very different. For the C-1 column, the form of S-1 stirrups is adopted, and the ratio of longitudinal reinforcement and volumetric stirrups is small, so its deformation performance is also poor, which cannot meet the requirements of seismic ductility. The test also shows that when the composite stirrups with a certain volumetric reinforcement ratio are used, the plastic zone after the steel bar yield can be developed in a fairly long section, and there is still a certain plastic section, and the deformation ability of the specimen is obviously improved. For example, C-2 and C-3 columns have better ductility.

3.4 Ductility of specimens

Ductility is an important index to evaluate the seismic performance of structures. The ductility coefficient of this test column is shown in the literature [4, 5]. Column C-1, column C-2 and column C-3 three columns are designed for strong shear and weak bending, which should occur bending failure. The test results show that the last three columns were destroyed by large bias voltage and the stirrups did not yield. The hysteresis curves of the three columns in the literature [4, 5] are all arched and plumper in turn, indicating that the absorption energy is larger and the ductility is better and better. For the C-1 column, the form of stirrups is S-1, and the ratio of volume and longitudinal bars is also small, so its

deformation performance is also poor, so it is no longer suitable for the frame long flat column with high axial compression ratio. From the above analysis, it can be seen that the ductility of the long flat column of the frame increases gradually with the increase of the volumetric hoop ratio and the longitudinal reinforcement hoop ratio, and the ductility of the composite hoop column with the tension strip of the well hoop is better than that of the composite hoop column with the rectangular band cross strip, and the ductility of the rectangular hoop column is extremely poor. That is to say, the ductility of the long flat column of the frame is not only related to the volumetric stirrup ratio and the longitudinal stirrup ratio, but also has a great relationship with the form of stirrups and the spacing of stirrups. This test found that the design of C-2 column and C-3 column with a axial compression ratio of 0.9 can also meet the requirements of ductility under high axial compression ratio by increasing the hoop ratio and adopting the form of composite stirrups^[5].

4 Conclusions

(1) The test columns are all caused by the large eccentric compression failure, and the concrete on the surface of the column falls off more seriously when the failure occurs. The ductility of ordinary rectangular hoop column is poor, and the brittle failure occurs, while the composite stirrups column is ductile failure.

(2) The hysteresis curves of each column are arched. With the increase of hoop ratio, the hysteresis curves of each column become more and more full, the absorption of seismic energy increases, and the seismic performance and ductility increase accordingly. The high axial compression ratio of the skeleton curve of the rectangular hoop column is steep and the ductility is poor, which cannot meet the requirements of seismic performance. The high axial pressure is longer than the skeleton curve of the composite hoop column and the slope is gentle, the hysteresis curve is plump, the plastic deformation ability is strong, and finally the failure occurs because the side shift is too large, and the bending ductility failure can meet the requirements of seismic performance.

(3) The ductility of the long flat column of reinforced concrete frame increases gradually with the increase of volumetric hoop ratio and longitudinal reinforcement ratio; the ductility of the composite hoop column with the tension strip of the well hoop is better than that of the composite hoop column with the cross strip of the rectangular hoop, and the ductility of the rectangular hoop column is very poor. By increasing the ratio of stirrups and adopting the form of composite stirrups, the ductility can also be satisfied under the high axial compression ratio.

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