Analysis on dynamic eccentricity effect and torsional performance of steel reinforced concrete frame with special-shaped column

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Abstract. Based on the seismic simulation shaking table test of steel reinforced concrete frame model with special-shaped column, the lateral-torsional vibration response, dynamic eccentricity effect and nonlinear torsion response law of the model structure are studied. The results show that, under the action of three-way earthquake, the Y-direction and X-direction horizontal torsion coupling phenomena occur in the high-order vibration mode of the model structure, and the accidental eccentric torsion has a light influence on the seismic performance of the special-shaped column structure which does not exceed the height limit. The nonlinear torsion analysis shows that the inter-storey displacement angle of the model structure is affected by floor position, eccentricity and ground motion intensity. As the eccentricity and seismic intensity increases, the inter-storey torsion Angle of the model structure increases constantly. In case the relative eccentricity is less than or equal to 0.5 and the peak acceleration is less than or equal to 0.62g, then the amplitude of the inter-storey torsion Angle of the model increases slightly; In case the relative eccentricity is more than 0.5, then the lateral-torsional coupled effect of earthquake response of the structure is obvious, and the influence of eccentricity on torsion effect of the model structure is more obvious. The results show that steel reinforced concrete frame with special-shaped column has good ductility and torsion resistance.

1. Introduction

In recent years, researchers have done a lot of research on the mechanical properties and design methods of concrete special-shaped column structure. For the new structure system of steel reinforced concrete (SRC) frame with special-shaped column, the existing research is mostly concentrated in China [1-3], and only the quasi-static or pseudo-dynamic test research is carried out for SRC special-shaped column members or plane frame. There are few studies on the dynamic characteristics and seismic response of SRC frame structures with special-shaped columns [4-6]. Especially under the action of three-dimensional earthquake, because the stiffness center and frequency ratio of the structure change with time, dynamic eccentric effect of the SRC frame structure with special-shaped columns is obvious, which affects the elastic-plastic response of the structure. In addition to the torsion of the special-shaped column, the torsion of the special-shaped column is not only accompanied by the torsion of the cross-section of the special-shaped column, but also when the
torsion of the special-shaped column is unsymmetrical, the torsion of the column is not symmetrical. Therefore, the torsional behavior of special-shaped column members and the dynamic eccentric action of the structure are the important factors affecting the seismic performance of SRC special-shaped column frame structure.

By using the methods of simulated earthquake test, theoretical analysis and numerical calculation, the lateral torsional vibration response and torsional behavior of SRC frame with special-shaped columns are studied, which provides a theoretical reference for the torsional design of SRC special-shaped column frame structure.

2. Shaking table test

2.1. Test survey

According to the geometric similarity ratio of 1:4, the model of a five story solid web steel reinforced concrete frame structure with special-shaped column space has been designed, as shown in Figure 1. The special-shaped columns used in the model are equal limb L-shaped, T-shaped and + -shaped columns. Arrangement for beams and columns of the model is shown in Figure 2, and the cross-section form of the special-shaped column is shown in Figure 3. Q235 steel is used as column section steel, HPB300 grade reinforcement is used as stress bar, 10#3.0 galvanized iron wire is used as stirrup, and C30 micro particle concrete is used for concrete. In the test, El Centro wave, Taft wave and Lanzhou wave are respectively input as three-dimensional seismic excitation. In order to simulate the seismic response and damage of the structure subjected to small, medium and large earthquakes, the peak acceleration of the table is adjusted according to the similarity ratio of 1:0.67, and the time interval is adjusted according to the similarity ratio of 1:2. The specific test parameters and detailed test process are shown in the literature[7].

![Figure 1. Test model](image1)

![Figure 2. Arrangement for Structure](image2)

![Figure 3. Section of special-shaped columns](image3)

2.2. Translation-torsion vibration characteristics

The natural frequency, damping ratio and mode shape distribution of steel reinforced concrete model with special-shaped column structure under three-dimensional earthquake action are shown in Table 1.
2.3. Translation-torsion response of model

Figure 4 is the envelope diagram of the acceleration amplification coefficient of the model, and Figure 5 is the envelope diagram of the model interlayer displacement. It can be seen from the figure that: the acceleration amplification coefficient increases with the increase of the floor, and decreases continuously with the increase of the peak acceleration. As the steel ratio of the lateral force resisting member at the bottom layer of the model is greater than that of the upper structure, the stiffness of the bottom layer of the model is greater than that of the upper structure, which is reflected in the figure, that is, the curve is concave at the position of the first floor. With the increase of the peak acceleration, the interlayer displacement of each floor of the model is increased. The interlayer displacement decreases in the following order, such as 2nd floor, 3rd floor, 1st floor, 4th floor, 5th floor. After 0.40g seismic wave input, 1st floor and 2nd floor of model enter the elastic-plastic stage, and the maximum value of interlayer displacement angle of model 2 reaches 1/39.

Table 1. Natural frequency, damping ratio and vibration mode shape of model structure

| Mode order | Before the test | 0.14g | 0.20g | 0.62g | 1.00g |
|------------|----------------|-------|-------|-------|-------|
|            | Frequency/Hz   | 7.305 | 6.719 | 6.875 | 5.430 | 5.039 |
|            | Damping ratio  | 0.037 | 0.080 | 0.061 | 0.086 | 0.155 |
| Mode of vibration | X-Translation | Y-Translation | Torsion | Z-Vibration | X-Translation | Y-Translation | Torsion | Z-Vibration | X-Translation | Y-Translation |

Figure 4 shows the relationship curve between Y-direction acceleration $ay$ and X-direction acceleration $ax$ of the top layer of the model. Because the structure is completely symmetrical (the center of stiffness coincides with the center of mass), the bidirectional input of seismic wave is equivalent to unidirectional input along a specific angle, and the $ay$-$ax$ curve should be linear in theory. However, the $ay$-$ax$ relationship curve in the figure constitutes an irregular region, and with the increase of the peak acceleration of seismic wave, the irregular area expands continuously. The reason
is that the moment of the model component entering the elastic-plastic stage is different in the loading process, resulting in the acceleration response not completely along the excitation direction.

3. Nonlinear torsional response analysis

3.1. Fiber model based on finite element flexibility method

Through the above theoretical analysis and shaking table test, it is found that the dynamic torsional effect of SRC special-shaped column frame structure is obvious due to the constant change of the stiffness center, horizontal torsion period ratio and frequency ratio of the model structure under earthquake action, which affects the frequency spectrum characteristics and dynamic response of the structure. Therefore, it is necessary to analyze the plane torsion response of SRC special-shaped column space frame structure on the basis of shaking table test. In this section, based on the OPENSEES platform, the fiber model beam column element based on the finite element flexibility method is used to study the plane torsion coupling elastic-plastic response law of SRC special-shaped column space frame structure with different eccentricities.

The concrete constitutive skeleton curve of the model adopts Kent park model extended by Scott et al. [9]. And the stress-strain relationship of steel and reinforcement adopts the constitutive model proposed by Menegotto, Pinto and Filippou et al. [10]. Considering the strong influence of the torsional stiffness of steel reinforced concrete special-shaped columns, the torsional stiffness values of column members in this paper are: 0.75 $K_{0t}$ before cracking, 0.125 $K_{0t}$ after cracking, $K_{0t}$ is the section torsional stiffness calculated according to elastic theory, and the values are shown in reference [8].

3.2. Floor displacement and inter story displacement angle

Figure 7 shows the maximum floor displacement of eccentric structure models with different masses under the earthquake action of basic acceleration and above peak acceleration. It can be seen from the figure that: with the increase of the peak acceleration of the seismic input wave, the floor displacement of the model structure gradually increases, and the distribution along the height is "shear type". Under the same peak acceleration earthquake action, with the increase of eccentricity, the floor displacement increases significantly, especially when the eccentricity $e/l>0.3$. As shown in Figure 10, under the same eccentricity condition, when $a_{\text{max}} \geq 0.62g$, the floor displacement is 4 times of that of $a_{\text{max}}=0.40g$; under the same acceleration peak earthquake action, for different eccentricity models, the increase of floor displacement is small.

Figure 8 shows the maximum value of inter story displacement angle of eccentric structure model with different mass under the earthquake action of basic acceleration and above peak acceleration. It can be seen from the figure that: with the increase of the peak acceleration of the seismic input wave, the floor displacement of the model structure gradually increases, and the distribution along the height is "shear type". Under the same peak acceleration earthquake action, with the increase of eccentricity, the floor displacement increases significantly, especially when the eccentricity $e/l>0.3$. As shown in Figure 10, under the same eccentricity condition, when $a_{\text{max}} \geq 0.62g$, the floor displacement is 4 times of that of $a_{\text{max}}=0.40g$; under the same acceleration peak earthquake action, for different eccentricity models, the increase of floor displacement is small.

Figure 7. Inter-story displacement envelope in the X direction
maximum value of the inter story displacement angle of the model structure appears in the bottom layer. With the increase of the center distance, the effect is obvious. Which indicates that the structure has entered the plastic state, and its vibration mode is mainly high-order mode.

3.3. Floor torsion angle and Inter-story torsion angle

Figure 8 shows the envelope diagram of the torsion angle between layers of the model. It can be seen from the figure that: with the increase of eccentricity and seismic intensity, the model story torsion angle increases continuously. When $a_{\text{max}} \leq 0.62g$, the maximum value of the model interlayer torsion angle appears in the second floor. When $a_{\text{max}} \geq 0.80g$, the maximum value of the model interlayer torsion angle appears in the first floor, which is mainly because the bottom layer column has entered the plastic stage, and the lateral displacement of the column increases significantly. When $e/l \leq 0.5$ and $a_{\text{max}} \leq 0.62g$, that is, when the seismic intensity input is small and the eccentricity is small, the variation range of the interlayer torsion angle is small. But when $e/l > 0.5$, the contribution of eccentricity to torsion is obviously greater than that of seismic intensity. According to the envelope diagram of inter story displacement angle, it can be seen that the correlation between displacement response and torsional response of the model is relatively high, and the response law is relatively close, which is mainly caused by the horizontal torsional coupling in the vibration mode. Generally speaking, when $a_{\text{max}} \leq 0.62g$, the torsional response of the model is greatly affected by eccentricity and seismic intensity, but when $e/l > 0.5$, the influence of eccentricity on torsional response is obvious.

4. Conclusion

1) Based on shaking table test and numerical analysis, the torsional response law of steel reinforced concrete frame with special-shaped columns is analyzed. The conclusions are as follows: shaking table test shows that Y-direction and X-direction horizontal torsion coupling phenomena occur successively in the high-order vibration modes of the frame structure with special-shaped columns.

2) Through the numerical analysis, it can be seen that after 0.80g earthquake action, the model enters into plastic state. At this time, the maximum total displacement angle of the structure is 1/12,
and the maximum interlayer displacement angle caused by horizontal torsion coupling is 1/39, which exceeds the limit value of elastic-plastic interlayer displacement angle.

3) The nonlinear torsional response analysis shows that the story displacement angle of SRC frame structure with special-shaped columns is affected by floor position, eccentricity and seismic intensity. With the increase of eccentricity and seismic intensity, the interlayer torsional angle of the model increases continuously. When $e/l \leq 0.5$ and $a_{\text{max}} \leq 0.62g$, the increase range of story torsional angle is small. When $e/l > 0.5$, the displacement response relates to the torsion response significantly, and the influence of eccentricity on torsion effect of model structure is obvious.

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