Seismic Performance Analysis on a High-rise Hidden Frame-brace Structure

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Abstract. The building No.1 project located in the district of Jinjian Yingxiyuan at the city of Taiyuan is the first high-rise steel structure building in Shanxi Province by using hidden frame-brace system with the special-shaped wide concrete-filled steel tubular (WCFT) columns. In this paper, elastic analysis and pushover analysis of the new building are carried out by using the finite element software MIDAS/Gen, which is based on the theory of equivalent sectional flexural stiffness. And the results show that the various parameters under the action of frequent earthquake and rare earthquake meet requirements of the code, the failure mechanism of the structure is reasonable, and the seismic performance is good. Finally, the hidden danger and the key problems about the new structure system are put forward.

1. Introduction

In the last few decades, in response to national policies, prefabricated steel structure buildings have been vigorously promoted in China, and a lot of new prefabricated steel structure housing systems have been proposed [1]. As a part of these systems, hidden frame steel structure is mainly composed of concrete-filled steel tube columns, H-shaped steel beams, steel plate shear walls, etc., which is mainly used in steel structure residences, and its components can be hidden in the building walls [2].

At present, there is a lack of research on hidden frame steel structure system. Fu et al. [3] used ETABS software to carry out pushover analysis on a high-rise residential project with hidden frame-brace structure system. The results show that the performance of the frame-brace system meets the requirements of "strong frame weak support" and "strong column weak beam", which means the system has good seismic performance. Fu et al. [4] carried out quasi-static analysis on seven specimens which composed of concrete-filled rectangular steel tubular column and H-shaped steel beam outer top plate joints without diaphragm in the column, concentrate on the influence of the changes of steel beam section, roof thickness and roof long side height on the seismic performance of the joints, and the results showed that the seismic performance of the joints met the requirements of "strong joints and weak members". In addition, the plastic deformation capacity of the joint can be controlled by changing the strength of the flange at the end of beam. Hong et al. [5] elaborated the manufacturing technology of wide steel tube column members in hidden frame steel structure system. The limbs of special-shaped columns can be hidden in the wall, which can not only solve the problem of exposed beams and columns in the room, make the building plane meet the aesthetic requirements, but also increase the building area and improve the land use efficiency, so it is widely used in residential structures [6].
In order to explore the seismic performance of the hidden frame-brace system with special-shaped WCFT columns used in high-rise steel structure residential projects, this paper take an elastic analysis to the system with the action of frequent earthquake, and a pushover analysis under rare earthquake by Midas/Gen, and pointed out the problems existing in the new structure system.

2. Engineering situations
The building No.1 project (Figure 1) located in the district of Jinjian Yingxiyuan at the city of Taiyuan is the first project in Shanxi Province adopts the hidden frame-braced system with the special-shaped WCFT columns. The residential building has 2 floors underground and 34 floors above ground, with a floor height of 2.9m and a structural height of 98.6m. The layout of the structure is shown in Figure 2, the upper main body mainly adopts the frame-brace system of the special-shaped WCFT columns, and the underground adopts the reinforced concrete structure. Among L-shaped columns and T-shaped columns are mainly distributed in the four corners of residential buildings and the middle of East and west walls.

The frame columns in the frame-brace system are divided into two forms: the special-shaped WCFT columns and the normal WCFT columns. The special-shaped columns are used in the position of 1-25th floors. The special-shaped columns include the L-shaped WCFT columns and the T-shaped WCFT columns, as shown in Figure 3.

3. Elastic analysis under frequent earthquakes
The finite element software MIDAS/Gen is used in this paper to model the project. The bottom of the first-floor column is considered to be connected with the foundation, so its constraint is set as rigid connection. The section equivalent bending stiffness method is used in this paper to model the special-shaped columns in the structure. Through the method, the special-shaped WCFT is converted into rectangular concrete-filled steel tubular columns by controlling the bending stiffness in X direction and Y direction are reasonably equivalent converted.

The Application of Mode-Superposition Response Spectrum Method (CQC) is used for elastic analysis of the building under frequent earthquake. When simulating the building under the action of X and Y directions, the influence of accidental eccentricity is considering. The main calculation results of vibration modal and frequent earthquakes about the residential buildings are shown in Table 1 and Table 2 respectively.
Table 1  Vibration modal results of residential buildings

| Structure type                      | Frame-braced structure |
|-------------------------------------|------------------------|
| Free vibration period of structure /s |                        |
| T₁                                  | 2.329                  |
| T₂                                  | 2.313                  |
| T₃                                  | 2.021                  |
| Calculation number of vibration modes | 0.868                  |
| Calculation number of vibration modes | 12                    |
| Modal participating mass ratio %   |                        |
| X                                   | 91.4                   |
| Y                                   | 92.7                   |

The number of the vibration mode calculation is taking 12. Table 1 shows that the ratio of T₃ to T₁ is 0.868 (T₃ and T₁ are dominated by torsion and translational motion respectively), which is less than the limit value of 0.9 specified in the Code for seismic design of buildings (GB 50011-2010) [7] (Seismic code for short). Which means that the plane layout of the structure is reasonable, the shape is regular, the lateral force resisting components are continuous and effective, the structure does not appear excessive torsional deformation, and all this means the seismic performance is good. In the 12th mode state, the modal mass participation coefficients in X and Y directions of the structure are 91.4 % and 92.7 % respectively, which all meet the limit value of 90 % specified in Seismic code.

Table 2  Calculation results under frequent earthquakes

| Structure type                      | Frame-braced structure |
|-------------------------------------|------------------------|
| Base shear/kN                       |                        |
| X                                   | 1956.4                 |
| Y                                   | 2091.4                 |
| Overturning moment/(kN*m)           |                        |
| X                                   | 120378.9               |
| Y                                   | 132099.7               |
| Maximum inter-story drift angle     |                        |
| X                                   | 1/792                  |
| Y                                   | 1/771                  |
| Top displacement/mm                 |                        |
| X                                   | 102.5                  |
| Y                                   | 107.8                  |

Figure 4 shows the response of lateral stiffness, overturning moment, floor shear force, shear-gravity ratio, layer displacement and inter-story drift angle on the different floors under frequent earthquakes. Figure 4(a) shows that the lateral stiffness of the structure under frequent earthquakes is not only greater than 70 % of the adjacent upper layer, but also greater than 80 % of the average lateral stiffness of the adjacent three floors, which meets the requirements of Seismic code, indicating that the structure is regular in vertical and without weak layers. Figure 4(b) and (c) show that the overturning moment and floor shearing force of the residential building under frequent earthquakes have a continuous and uniform decreasing trend with the increase of the floor. In addition, Figure 4(e) shows that the layer displacement of the residential building presents a trend of approximately linear increase with the increase of the floor, indicating that the layout of the lateral force resisting components of the residential building structure is reasonable. Figure 4(d) shows that the layer minimum shear-weight ratio of the residential building under frequent earthquakes is 0.044, which meets the requirements of Seismic code. Figure 4(f) shows that the inter-story drift angle of the residential building under frequent earthquakes increases with the increase of the floor, and the overall increase first and then decrease, which reflects that the structure has good ductility performance. Although the original special-shaped columns of 26th floor and above are replaced by normal WCFT columns, which take the changes in structural stiffness and small inflection points in the curve, the maximum inter-story drift angle of the structure is still less than the limit specified in the code.
4. Pushover analysis under rare earthquakes

As a novel structural system that the hidden frame-brace system of special-shaped WCFT columns used in this building project for engineering practice. It is necessary to explore its seismic performance under rare earthquakes. Now, the corresponding pushover analysis of the residential building is carried out by the finite element software MIDAS/Gen. Triangle and uniformity load distribution are selected to investigate the stress and deformation performance of the structure [9]. The triangle loading mode is modality loading mode, and the corresponding load conditions are push-Mx and push-My. The uniform load loading mode is the constant acceleration loading mode, and the corresponding load conditions are push-Ax and push-Ay. In the process of structural analysis, the trilinear hinge is used to distribute the plastic hinge of beam, column and support.

4.1. Structure analysis

Figure 5 shows the changes of shearing force and inter-story drift angle with the floor increase under rare earthquake. Figure 5(a) shows that the shearing force of the residential building under two loading modes decreases continuously and uniformly with the increase of the floor. Compared with the loading mode of uniform distribution, the shear slope of the floor below 20 floors in the inverted triangle distribution loading mode is increases and the floor shear is decreases.
Figure 5(b) shows that the inter-story drift angle of the structure under the two loading modes is first increased and then decreased with the increase of the floor, which means that the structure has good ductility performance. Because of the original special-shaped columns above 26th layers are replaced by normal WCFT column, the stiffness of the structure changes, so that the curves under the two loading modes have a small inflection point. The stiffness of the residential building structure under the inverted triangular distribution loading mode is lower than that under the uniform distribution loading mode, but the maximum story drift angle of the structure is still less than the limit value of 1/50 specified in technical code for concrete filled steel tubular structures.

4.2. Performance at performance point
The structure can obtain the performance point under two loading modes, and the structure still has good ductility after the performance point. Each parameter value of the structure at the performance point is shown in Table 3. The ratio of elastic-plastic base shear under rare earthquake and elastic base shear under frequent earthquake is between 3 and 5, which means structural system design is reasonable.

| Load pattern | Working condition | Spectral acceleration (mm/s²) | Spectral displacement (mm) | Base shear (kN) | Ratio of base shear to minor earthquake | Top displacement (mm) | Structural equivalent period (s) |
|--------------|-------------------|-------------------------------|---------------------------|----------------|----------------------------------------|-----------------------|-------------------------------|
| Inverted     | push-Mx           | 0.2434                        | 362.0                     | 7610           | 3.89                                   | 544.1                 | 2.447                         |
| Uniformity   | push-My           | 0.2707                        | 402.3                     | 8092           | 3.87                                   | 623.3                 | 2.314                         |
|              | push-Ax           | 0.3048                        | 304.7                     | 9530           | 4.87                                   | 458                   | 2.006                         |
|              | push-Ay           | 0.3478                        | 301.4                     | 10400          | 4.97                                   | 467                   | 2.314                         |

4.3. Change of hinge state
For the deformation state of beams, columns and braces under rare earthquakes, the deformation of plastic hinges of members can be checked according to the given capacity state (Linear, 1st yield, 2st yield) of trilinear hinges. Linear indicates that the member is in elastic stage, 1st yield indicates that the member begins to appear plastic hinge, 2st yield indicates that the member completely loses the bearing capacity. Since the distribution of plastic hinges of each component is basically the same under the inverted triangle distribution loading mode and the uniformity distribution loading mode, only the change state of plastic hinges of components under the inverted triangle distribution loading mode (push-Mx and push-My) is analyzed.

Figure 6 shows the yield hinge state diagram of the axial force components of each component under push-Mx loading mode in the inverted triangle distribution. In the 7th step, on the axis C of 12-16 layers, the plastic hinge appears on the brace between the axes, and the hinge is on the 2st yield state, which means the bearing capacity is lost and the failure has been destroyed. In the 10th step, the plastic hinges of the structure increase, mainly concentrated in the brace between the intersection point of axis 4-6 and axis C of the 2-20 layers. In addition, plastic hinges also appear in the brace between the intersection point of axis 1-3 and axis C of the 2-6 layers and the brace between axis 7-9 and axis C of the 3-15 layers and the hinges is in the state of 2st yield. At the 13th step (performance point), the yield state of the overall structure brace is intensified, and about 25% of the brace failure.

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The hinge state of the structural details at the performance point can be observed more carefully from Figure 7. The buckling of the beam hinge can be observed from the hinge state of the bending moment hinge. The bending moment hinge of a small part of the beam is in the 1st yield state, and a small part of the beam is in the 2st yield state. In the push-Mx loading process, the buckling failure order of the component is: the brace first appeared, then the beam began to appear, and the column never appeared. When the performance point is reached, the buckling failure of the brace is the most serious, and some braces have been completely destroyed. The degree of buckling failure of the beam is lower than that of the brace. Only a small part of the beam is completely destroyed, and most of the beam is in a low degree of buckling state (1st yield). The column hinge in the whole structure is basically in linear elastic state, and there is no buckling failure.

Figure 8 shows the yield hinge state of the axial force of the structure under the push-My loading mode in the inverted triangle distribution. In the 9th step, a few braces in the 12-16 layers of the structure yield. At the 13th step, the brace that yields presents a distribution state of upper, middle and lower, mainly concentrated in the middle and lower parts of the structure, and the yield axial force hinges are mostly in the 2st yield state. By the 17th step, when the performance point is reached, the range of the yield member is expanded, mainly on the axis A of the even layer of 2-26 layers, and the yield hinge is in the 2st yield state.
5. Conclusions
As a new type of structural system, the hidden frame-brace system of special-shaped WCFT columns is applied to residential structures. It is necessary to analyze its seismic performance. In this paper, the finite element software Midas/Gen is used to carry out the elastic analysis of a high-rise steel structure residential test project of a hidden frame-brace structure under frequent earthquakes and the pushover analysis under rare earthquakes. The following conclusions and suggestions are drawn on this study:

1) The indicators about the building under the action of frequent earthquakes all meet the specification requirements, indicating that the structural design is reasonable and the structural system can be used in high-rise steel structure residential buildings.

2) Through the pushover analysis, it can be seen that the most unfavorable interlayer displacement angle at the performance point is $1/114$ under various loading modes, which meets the requirements of each specification, and the structure has good ductility performance. Under rare earthquake, the brace in the structure first buckling failure, and consume a lot of seismic energy, playing the role of the first line of defense. Subsequently, with the buckling failure of the beam, columns did not buckle during the whole loading process, which means the failure mechanism was reasonable. Therefore, the structure has good seismic performance under rare earthquake, which meets the design concept of “no collapse under large earthquake” and has broad application prospects in the field of high-rise steel structure residence.

3) Up to now, the Midas/Gen, PKPM or YJK or other large structural analysis software still can’t complete the modeling analysis of special-shaped column structure. Although some software can be used to model, which cannot carry out relevant checking calculation. In order to analyze this kind of structure, equivalent substitution method was used by the engineers. In this paper, the section equivalent bending stiffness method is also used to convert the special-shaped column into a rectangular concrete filled steel tube column, and the relevant calculation and analysis are carried out. The above conclusions are obtained on this basis, and the rationality of the equivalent substitution needs to be further verified. In addition, the existing codes do not specify the design method of bearing capacity of special-shaped columns, which remains to be studied.

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