Research on the Effect of Stiffness Ratio Between Frame and Core Tube on Seismic Response of Super High-rise Building Under Frequent Earthquake

Gao Yanhua\textsuperscript{1,a}, Sui Zhili\textsuperscript{1}, Zhang Fenghong\textsuperscript{1}, Chen Shuaijun\textsuperscript{2,b}

\textsuperscript{1}Department of Urban Construction Beijing City University Beijing, China
\textsuperscript{2}School of Civil and Resource Engineering University of Science and Technology Beijing Beijing, China
\textsuperscript{a}gaoyanhua@bcu.edu.cn, \textsuperscript{b}chen_shuai_jun@163.com

Abstract—The stiffness ratio of frame to core tube has an important influence on the seismic behavior of frame-core tube hybrid structure which is a high-rise building structure system widely used in the world. In this paper, nine models of concrete-filled steel tubular frame-concrete core tube super-high-rise hybrid structures with different stiffness ratios are established by using finite element method, and the effect of stiffness ratio on inter-story displacement angle, top displacement and base shear force of super high-rise buildings under frequent earthquakes is studied. The results show that, with the increase of stiffness ratio, the inter-story displacement angle, the top displacement and the base shear force change complicatedly, the maximum base shear force increase, and the maximum inter-story displacement angle and the maximum top displacement first increase then peak, and that the strengthening layer with outrigger obviously improves the deficiency of lateral stiffness caused by height. This study provides a reference for reasonable determination of stiffness ratio and optimization of structural seismic design.

1. INTRODUCTION
The frame-core tube hybrid structure is an important high-rise building structure system which is widely used in the world and has a broad development prospect [1]. Under earthquake action, the frame and the core tube bear the earthquake action according to their respective stiffness, and work together through the connection of the floor. The stiffness ratio between frame and core tube has an important influence on the seismic behavior of frame-core tube structure.

At present, the research on the influence of the stiffness ratio of frame to core tube on the seismic performance mainly focuses on the theoretical analysis and numerical tests. In theory, the simplified calculation method is adopted to simplify the connection between frame and core tube into such types as rigid connection at two ends, hinged connection at two ends [2], rigid connection at one end, hinged connection at one end[3], connection with reinforced layer [4] etc., and the effect of stiffness eigenvalue on the internal force and displacement of the structure is studied. In the numerical test, the stiffness ratio of frame to core tube is changed by changing the cross-section of frame or shear wall, and the influence of stiffness ratio on the internal force and deformation of structure is analyzed by numerical calculation. Using Push-over simplified analysis method, Yong Chun [5] studied the influence of stiffness ratio on the internal force and deformation of SRC Frame-RC tube structure, and the results
show that floor shear force and bending moment borne by the frame increase with the increase of stiffness ratio, and the inter-story displacement angle of the structure also increases. Qu Shuping [6] studied the effect of lateral stiffness ratio between steel frame and core tube on cracking. To sum up, there are few time-history analysis methods by which seismic response of structures is calculated more precisely. And it is rare to study the effect of stiffness ratio on the seismic response of the concrete filled steel tubular frame-concrete core tube super high-rise structure.

In this paper, based on the concrete filled steel tubular frame-concrete core tube super-high-rise mixed structure with strengthened story, the calculation models of different stiffness ratio between concrete filled steel tubular frame and concrete core tube are established, and the influence of different stiffness ratio on the inter-story displacement angle, top displacement, base shear force of super high-rise structure is studied, which are used for reference to determine the stiffness ratio reasonably and optimize the seismic design of structure.

2. CALCULATION MODEL OF SUPER HIGH-RISE STRUCTURE

2.1. Engineering Situation
Some super high-rise building, with a building height of 263.65m, is a class B building with 61 floors above ground and 4 floors below ground. It is a composite structure of concrete-filled steel tubular frame and concrete core tube, with three strengthened floors between the 11th and 12th floor, between 26th and 27th floor, between 41th and 42th floor. The height of standard layer is 4.18 m, and the distance between columns is 6 m (Local is 9m). The diameter of concrete filled steel tubular (Wall thickness 20-50mm) column is 1300-1500mm and the section of steel outer frame beam is 1000×500×16×35. The section of member in the strengthening layer and its adjacent layer are 1000×600×35×50 and 1000×500×25×50 respectively. The thickness of outer wall of core tube is 600-1200mm, and the thickness of inner wall is 500-600mm, Q345 is used for steel over 35 mm thick, and C50-C60 is used for concrete. The seismic precautionary intensity is 8 degree, design earthquake grouping is the first group and it is on the II site. The layout plans of the standard layer of the structure are shown in Fig. 1.

![Figure 1. The layout plan of the standard layer of the structure.](image-url)
2.2. Characteristic Value of Stiffness Ratio

The stiffness ratio of frame to core tube can be expressed by the stiffness eigenvalue of the structure, which can be calculated by referring to the stiffness eigenvalue of frame-shear wall structure. The differential equation for the hinged system of frame-shear wall structure is given by [7]

\[ \frac{d^4y}{d\xi^4} - \lambda^2 \frac{d^2y}{d\xi^2} = \frac{pH^4}{EI_i} \]  

where \( y \) is lateral deformation of structure, \( p \) is the lateral force on the structure, \( \xi = \frac{z}{H} \), \( z \) is the height of structure, \( H \) is total height of structure, and \( \lambda \) is characteristic value of stiffness ratio. \( \lambda \) is a parameter reflecting the stiffness ratio between frame and shear wall, and affecting the force and deformation of frame-shear wall (core wall) structure. \( \lambda \) is given by

\[ \lambda = H \left( \frac{C_s}{EI_i} \right)^{1/2} \]

where is \( C_s \) total shear stiffness of frame, and \( EI_i \) is total flexural stiffness of shear walls.

In this paper, the frame-core wall structure is simplified as a hinged connection between frame and core tube, then the stiffness eigenvalue can be determined according to equation (2).

2.3. Test Scheme

The stiffness ratio of frame to core tube is changed by keeping the wall thickness and changing the column section size. Specifically, at the bottom of the structure, the outer diameter of concrete filled steel tubular columns is increased by 100mm from 1000mm to 1900mm each time, in the meantime, on the upper layers of the structure, the cross sections of concrete filled steel tubular columns change along the vertical direction. Nine models are established, as shown in table 1.

| Structural Model Code | Characteristic Value of Stiffness Ratio (\( \lambda \)) | Outer Diameter of Concrete Filled Steel Tubular Columns [mm] | Core Wall Thickness [mm] | Total Weight [N] |
|-----------------------|-----------------------------------------------|--------------------------------------------------|----------------|-----------------|
| 1100E                 | 4.58                                          | 900-1100                                         | 500-1200       | 2.22E09         |
| 1200E                 | 5.34                                          | 1000-1200                                        | 500-1200       | 2.26E09         |
| 1300E                 | 6.15                                          | 1100-1300                                        | 500-1200       | 2.30E09         |
| 1400E                 | 7.02                                          | 1200-1400                                        | 500-1200       | 2.35E09         |
| 1500E                 | 7.94                                          | 1300-1500                                        | 500-1200       | 2.39E09         |
| 1600E                 | 8.92                                          | 1400-1600                                        | 500-1200       | 2.45E09         |
| 1700E                 | 9.95                                          | 1500-1700                                        | 500-1200       | 2.51E09         |
| 1800E                 | 11.0                                          | 1600-1800                                        | 500-1200       | 2.57E09         |
| 1900E                 | 12.2                                          | 1700-1900                                        | 500-1200       | 2.63E09         |

2.4. Computational Model of Structural Member

Under earthquake action, the structure is in the elastic deformation stage, therefore the linear elastic constitutive model is adopted in the calculation model of each structural member, as shown in table II. The structural model is established by the finite element method. The whole three-dimensional finite element model, the models of frame and waist truss and the models of core tube and outrigger truss are shown in Fig. 2.
Figure 2. Calculation model of super high-rise structure. (The whole three-dimensional finite element model is shown in figure a, frame and waist truss models are shown in figure b, and core tube and outrigger truss models are shown in figure c.)

| Structural Element                          | Unit Type              | Calculation Model      |
|---------------------------------------------|------------------------|------------------------|
| Concrete filled steel tubular column        | Concrete, Beam element | *MAT_ELASTIC           |
| Frame beam                                 | Steel tube, Beam element | *MAT_ELASTIC         |
| Reinforce concrete shear wall               | Shell element          | *MAT_ELASTIC           |
| Steel plate in composite steel plate shear wall | Shell element        | *MAT_ELASTIC           |
| Coupling beams                              | Beam element           | *MAT_ELASTIC           |
| Belt truss and outrigger truss              | Beam element           | *MAT_ELASTIC           |

3. Seismic Wave Input, Calculated Parameter and Analysis Method

3.1. Seismic Wave History and Reaction Spectrum
Under frequent earthquake action, the time history of input earthquake wave of the structure is shown in Fig. 3. The peak acceleration of the seismic wave is 0.7 m/s² at 11.94 second. According to the definition of response spectrum, the seismic wave acceleration response spectrum is given in Fig. 4, compared with the response spectrum given in “code for seismic design of buildings” [8]. As can be seen from Fig. 4, the change trend and the shape of the curve are similar.
3.2. P-Δ Effect
The p-Δ effect of high-rise structure is obvious, so the influence on the internal force and displacement of structure should be considered. In this paper, finite element method for large displacement is adopted, and the dynamic equilibrium equation of the structure is established on the geometric state of the structure after deformation.

3.3. Damping Model
Damping is one of the most important factors that affect dynamic response of structures. In this paper a frequency-independent constant damping model is used. In the frequency range where participation coefficient of vibration mode quality is more than 90%, the damping ratio of composite structures is 0.04 under frequent earthquake action, according to the recommendation of term 11.2.18 in “technical specification for concrete structures of tall building” [9].

3.4. Numerical Method for Solving Dynamic Equation
The basic problem of structural seismic response analysis is to solve the dynamic equation (3) of multi-degree-of-freedom system,

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = -\mathbf{MI}_\mathbf{u}_{\text{g}}$$

(3)

Where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are mass matrix, damping matrix and stiffness matrix of structural system respectively; $\mathbf{I}$ is unit matrix; $\ddot{\mathbf{u}}$, $\dot{\mathbf{u}}$ and $\mathbf{u}$ are the acceleration vector, the velocity vector and the displacement vector of the structural system respectively; $\mathbf{u}_{\text{g}}$ is the ground acceleration under earthquake action.

4. THE EFFECT OF DIFFERENT STIFFNESS RATIO ON SEISMIC RESPONSE OF SUPER HIGH-RISE BUILDING

4.1. The Effect of Stiffness Ratio on Inter-story Displacement Angle of Structure
The inter-story displacement angle is an important index to measure the structural deformation ability. According to “code for seismic design of buildings” [8], the limit value of the elastic inter-story displacement angle is 1/500. Change curves of inter-story displacement angle of structures with different stiffness ratio under frequent earthquake action are shown in Fig. 5.

Several points can be seen from Fig. 5:

a) With the increase of stiffness ratio, the inter-story displacement angle increases gradually at the bottom and middle of the structure (Less than 2/3 of the structure height), especially the middle, but the increasing ratio decreases.
b) As the stiffness ratio increases, at the top of the structure (about 1/3 of the height of the structure), the inter-story displacement angle increases from 1100E to 1600E, decreases from 1600E to 1900E, and it is very close from 1400E to 1900E.

c) In 1100E model, because the stiffness of the frame is small, the shear deformation of the whole structure is not obvious, especially in the middle of 30 to 45 stories, the deformation of the structure appears bending deformation, while in 1900E model, because the stiffness of the frame is large, the shear deformation is obvious in the whole structure deformation.

d) The 60th and 61th floor are the core tubes of the prominent roof, and the curves of model with greater rigidity appear inflexion points in the 60th floor.

e) The strengthening layer obviously improves the deficiency of lateral stiffness of the structure due to height. The 11th-12th floors of the structure have waist trusses in the middle of the frame columns, and the 26th-27th and 41th-42th floor have waist trusses and four outrigger trusses. Outrigger trusses provide a good connection between the frame and the core tube, significantly improving the lateral displacement resistance of the structure. And, with the increase of frame column stiffness, the function of outrigger especially in the middle of the structure is more obvious.

![Inter-story Displacement Angle of X Direction](image)

**Figure 5.** Inter-story displacement angle of the structure with different stiffness ratio.

### 4.2. The Effect of Stiffness Ratio on Maximum Inter-story Displacement Angle of Structure

The maximum inter-story displacement angle is an important index in structural design, which reflects the ratio of the maximum inter-story displacement to the story height. Maximum inter-story displacement angle is list in table III.

**TABLE 3.** Maximum Inter-story Displacement Angle Under Different Stiffness Ratio.

| Model | Maximum interlayer displacement angle | On the floor |
|-------|--------------------------------------|--------------|
| 1100E | 1/658                                | 57-58        |
| 1200E | 1/637                                | 56-59 61     |
| 1300E | 1/613                                | 53-58        |
| 1400E | 1/599                                | 52-57        |
| 1500E | 1/588                                | 53-55        |
| 1600E | 1/585                                | 53-55        |
| 1700E | 1/588                                | 52-56        |
| 1800E | 1/592                                | 34 38 53-55  |
| 1900E | 1/581                                | 36           |

From table III, several points can be seen that:

a) Under frequent earthquake action, the maximum inter-story displacement angle of the structure occurs on the upper floor of the structure.

b) With the increase of stiffness ratio, the position of maximum inter-story displacement angle decreases gradually from high to low.
c) The maximum inter-story displacement angle first increases then tends to be consistent with the increase of stiffness ratio.

4.3. The Effect of Stiffness Ratio on the Top Displacement of Structure

Under earthquake action, the top displacement response of high-rise building is generally large. Therefore, the top displacement of high-rise structures is concerned in seismic design of engineering. In frame-core wall structure, the change of stiffness ratio between frame and core wall has an effect on the top displacement of structure, as shown in Fig. 6.

![Figure 6. The top displacement time history of structures with different stiffness ratio.](image)

From Fig. 6, two points can be seen:

a) At about 14s, when the acceleration of the seismic wave increases to the maximum acceleration, the displacement response of structures with high stiffness ratio is smaller than that of structures with low stiffness ratio. On the contrary, after 14 seconds, the displacement response of the structure with high stiffness ratio is greater than that of the structure with low stiffness ratio.

b) The displacement between the structure with small stiffness ratio and the structure with large stiffness ratio is basically synchronous in about 1/3 of the total input time of seismic wave. However, in the later period of earthquake, the structure with high stiffness ratio first reaches the peak value of displacement response. In the total duration of seismic wave, the structure of 1900E model has 12 peak displacements, and the structure of 1100E has 11 peak displacements.

4.4. The Effect of Stiffness Ratio on the Maximum Top Displacement of Structure

The maximum top displacement is also an important value in structural design. The maximum top displacement of the structures with different stiffness ratios occurs at different time. Table IV shows the maximum top displacement under different stiffness ratio and the time when it occurs. From table IV, it can be seen that the maximum top displacement increases and the occurrence time advances with the increase of stiffness ratio.

| Model  | Maximum top displacement of structure[m] | When it happened[s] |
|--------|------------------------------------------|---------------------|
| 1100E  | -0.257                                   | 18.76               |
| 1200E  | -0.282                                   | 18.68               |
| 1300E  | -0.301                                   | 18.62 18.64         |
| 1400E  | -0.315                                   | 18.58               |
| 1500E  | -0.326                                   | 18.52               |
| 1600E  | -0.333                                   | 18.48 18.50         |
| 1700E  | -0.337                                   | 18.46               |
| 1800E  | -0.340                                   | 18.44               |
| 1900E  | -0.340                                   | 18.42 18.44         |
4.5. The Effect of Stiffness Ratio on Structural Base Shear Force

Fig. 7 shows the base shear forces of structures with different stiffness ratios under frequent earthquake action. It can be seen from Fig. 7 that, with the increase of the stiffness ratio of frame to core tube, the base shear force increases.

![Figure 7](image)

**Figure 7.** The base shear time history of the structure with different stiffness ratio.

4.6. The Effect of Stiffness Ratio on Structural Maximum Base Shear Force

Table V shows the maximum base shear force of the structure with different stiffness ratio and its occurrence time in time history curves. It can be seen from table V that the time for the model with small stiffness to reach the maximum base shear force is 5 second earlier than that of the model with large stiffness, which is also shown in comparison between the Fig. 8 and Fig. 9.

| Model | Maximum base shear of structure [MN] | When it happened [s] |
|-------|--------------------------------------|---------------------|
| 1100E | 48.039                               | 12.84               |
| 1200E | 51.177                               | 12.84               |
| 1300E | 53.541                               | 12.84               |
| 1400E | 55.179                               | 12.84               |
| 1500E | 56.241                               | 12.84               |
| 1600E | 59.492                               | 17.84               |
| 1700E | 64.229                               | 17.84               |
| 1800E | 68.292                               | 17.84               |
| 1900E | 71.298                               | 17.84               |

![Figure 8](image)

**Figure 8.** Time history of base shear force of 1500E model structure.
4.7. The Effect of Stiffness Ratio on Shear Force Distribution Between Frame and Core Tube

In frame-corewall structure, the corewall, as the first anti-seismic line and the main anti-lateral member of the structure, bears most of the shear force of the structure under the earthquake action, while the frame column shares a small part of the shear force according to the stiffness ratio. Taking the 1500E model as an example, Fig. 10 shows the comparison between the total base shear force and the shear force borne by the frame columns which is about 3%-5% of the total shear force.

Fig. 11 shows that the base shear forces of frame columns with cross sections of 1100mm, 1500mm and 1900mm under frequent earthquake action. As the stiffness of the frame column increases, the base shear force of the frame column also increases. In contrast to Fig. 7 and Fig.11, the ratio of base shear of frame column to total base shear increases, which indicates that the ratio of base shear of frame column to total base shear increases with the increase of stiffness ratio.
5. CONCLUSION
In this paper, a concrete-filled steel tubular frame-concrete core tube super-high-rise hybrid structure is taken as the background, and the stiffness ratio between the frame and the core tube is changed by keeping the core tube wall thickness and changing the cross-section size of the frame column. 9 models of super-high-rise structure with different stiffness ratio are established, and the effects of stiffness ratio on inter-story displacement angle, top displacement and base shear force of super-high-rise structure are studied under frequent earthquake action. The conclusions are as follows:

a) Under frequent earthquake action, with the increase of stiffness ratio, the inter-story displacement angle increases gradually at the bottom and middle of the structure (Less than 2/3 of the structure height), and at the top of the structure (Above 2/3 of the structure height), the inter-story displacement angle of the structure increases first and then decreases. With the increase of the stiffness ratio, the maximum inter-story displacement angle increases first and then tends to be consistent, and it is located at the top floor and decreases from high to low.

b) The strengthened story with outrigger obviously improves the deficiency of lateral stiffness caused by height, and the function of outrigger becomes more and more obvious with the increase of column stiffness.

c) At the beginning of the earthquake motion, the displacement response of the structure with high stiffness ratio is less than that of the structure with low stiffness ratio, and after that, the displacement response of structures with high stiffness ratio is greater than that of structures with low stiffness ratio.

d) With the increase of the stiffness ratio, the base shear force, the maximum base shear force and the proportion of the base shear force to the total base shear force increase.

ACKNOWLEDGMENT
The authors acknowledge assistance and concrete proposal from Professor Pan Danguang from University of Science and Technology Beijing and senior engineer Tan Jinpeng from Capital Engineer & Research Incorporation Limited.

REFERENCES
[1] X. Y. Fu, Practical High-rise Building Structural Design, China Architecture & Building Press, Beijing,1999.
[2] L. C Fan, L. Y Nie, J. Z. Li, “Discussion on standard of critical angle of seismic wave in seismic analysis of complicated structures,” Journal of Tongji University, vol.31, pp.631-636, June 2003.
[3] J. G. Nie, S. M. Tian, J. G. Jiao, “Stiffness regularity in option of frame-corewall composite structure systems,” Journal of Architecture and Civil Engineering, Vol. 25, pp. 10-17, March 2008.
[4] J. G. Nie, Mid-term report on key projects of National Natural Science Foundation of China, Tsinghua University, Beijing, 2006.
[5] C. Yong, Effect of rigidity ratio and height-width ratio on seismic behavior of hybrid strcture of SRC frame & RC core-wall by analysis of push-over method, Xi'an University of Science and Technology Master's thesis, Xi'an, 2007.
[6] S.P. Qu, Analysis to the matching rationally of resisting earthquake of high-rise mixed steel concrete structure, China Agricultural University Master's thesis, Beijing, 2003.
[7] P. S. Shen, Structural Design of High-rise Building, China Architecture & Building Press, Beijing, 2017.
[8] Ministry of Housing and Urban-Rural Development of the People's Republic of China, Code for seismic design of buildings, China Architecture & Building Press, Beijing, 2016.
[9] Ministry of Housing and Urban-Rural Development of the People's Republic of China, Technical specification for concrete structures of tall building, China Architecture & Building Press, Beijing, 2010.