Research on the influence of frame-core tube stiffness ratio on dynamic characteristics of Super high-rise buildings

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Abstract. The frame-core tube hybrid structure is an important high-rise building structure system which is widely used in the world at present. The stiffness ratio of frame to core tube affects the dynamic characteristics of the structure. In this paper, nine models of concrete-filled steel tubular frame-concrete core tube super high-rise hybrid structure with different stiffness ratios are analyzed by subspace iteration method, and the analysis of the acceleration and displacement response spectrum value of each vibration mode under frequent earthquakes are carried out. The results show that the stiffness ratio has different effects on different modes, the fundamental frequency, natural period, acceleration and displacement response of the structure of the first mode increase with the stiffness ratio increasing, and it is feasible and significant to interpret the seismic response of structures from studying the dynamic characteristics of seismic waves and structures.

1. Introduction
Earthquake action is one of the main factors that affect the stress and deformation of high-rise buildings, especially super-high-rise buildings. In the high-rise building structure system, the frame-core tube hybrid structure is an important high-rise building structure system which is widely used in the world[1-2]. The stiffness ratio of frame to core tube has an important influence on the seismic behavior of frame-core tube structure, and affects the dynamic characteristics of the building.

At present, there are many researches on the dynamic and seismic behavior of single super-high-rise buildings[3-6], but a few on the influence of stiffness ratio. In general, the stiffness ratio of frame to core tube is changed by changing the cross-section of frame or shear wall, and then the dynamic characteristics, internal force and deformation are analyzed by numerical calculation. Using Push-over simplified analysis method, Yong Chun[7] studies the influence of stiffness ratio on the dynamic behavior, internal force and deformation of SRC frame-RC core-wall structure. The results show that the structural period decreases with decrease of the stiffness ratio of frame to core tube, except for the increase of structural period when the ratio of stiffness to weight is small. Qu Shuping et al [8] study the effect of lateral stiffness ratio between steel frame and core wall on the cracking of Shear Wall and fundamental period of structure. Nie Jianguo et al [9] study the characteristic value of stiffness in the selection of frame-core tube composite structure system. The study of stiffness ratio to the dynamic characteristics of buildings needs to be further developed.

In this paper, based on the super-high-rise mixed structure of concrete-filled steel tubular frame-concrete core tube, the calculation models of different stiffness ratios between concrete-filled steel
tubular frame and concrete core tube are established, the modal analysis of each model is carried out, and the variation of different order frequency, natural vibration period, acceleration response spectrum and displacement response spectrum under different stiffness ratio is studied.

2. Calculation model of Super high-rise structure

2.1. Engineering situation

The second phase of a project, 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 11 and 12 floors, between 26 and 27 floors, between 41 and 42 floors. The height of standard layer is 4.18 m, the distance between columns is 6 m (local is 9 m). The diameter of concrete filled steel tubular (Wall thickness 20-50mm) column is 1300-1500mm, the section of steel outer frame beam is 1000×500×16×35, 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, the thickness of inner wall is 500-600mm, with Q345GJ for steel over 35mm and C50-C60 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 and strengthened layer of the structure are shown in figure 1-2.

![Figure 1](image1.png)

Figure 1. The layout plan of the standard layer of the structure.

![Figure 2](image2.png)

Figure 2. The layout plan of strengthened layer of the structure.

![Figure 3](image3.png)

Figure 3. The three-dimensional finite element model.

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 articulated of pin-jointed system of frame-shear wall structure is given by

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

where \( y \) is lateral deformation of structure, \( p \) is the lateral force on the structure, \( \xi = \frac{z}{H} \), \( z \) is height of structure, \( H \) is total height of structure, \( \lambda \) is characteristic value of stiffness ratio.

\( \lambda \) is a parameter reflecting the stiffness ratio between frame and Shear wall, and is the main parameter affecting the force and deformation of frame-shear Wall (core wall) structure. \( \lambda \) is given by...
\[
\lambda = \frac{H}{\sqrt{\frac{C_s}{EI_t}}}
\]  
where \(C_s\) is total shear stiffness of frame; \(EI_t\) 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 of the frame-core wall structure can be determined according to equation (2).

2.3. Test scheme
In this paper, the stiffness of frame and 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 1500mm to 1900mm each time, and then decreased by 100mm from 1500mm to 1100mm 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.

Table 1. Experimental scheme and its parameters.

| 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) |
|-----------------------|---------------------------------|-------------------------------------------------|----------------------|-----------------|
| 1100                  | 4.58                            | 900-1100                                        | 500-1200             | 2.22 E09        |
| 1200                  | 5.34                            | 1000-1200                                       | 500-1200             | 2.26 E09        |
| 1300                  | 6.15                            | 1100-1300                                       | 500-1200             | 2.30 E09        |
| 1400                  | 7.02                            | 1200-1400                                       | 500-1200             | 2.35 E09        |
| 1500                  | 7.94                            | 1300-1500                                       | 500-1200             | 2.39E09         |
| 1600                  | 8.92                            | 1400-1600                                       | 500-1200             | 2.45 E09        |
| 1700                  | 9.95                            | 1500-1700                                       | 500-1200             | 2.51 E09        |
| 1800                  | 11.0                            | 1600-1800                                       | 500-1200             | 2.57 E09        |
| 1900                  | 12.2                            | 1700-1900                                       | 500-1200             | 2.63 E09        |

2.4. Computational model of Structural member
According to the calculation scheme, the linear elastic constitutive model is adopted in the calculation model of each structural member. The calculation model of the structural member is shown in table 2.

Table 2. List of structural component calculation models.

| Structural Element                          | Unit Type                | Calculation Models   |
|--------------------------------------------|--------------------------|----------------------|
| Concrete filled steel tubular columns      | Concrete Beam element    | *MAT_ELASTIC         |
| Frame beam                                 | 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 and modal analysis method

3.1. Seismic wave input

3.1.1 Seismic wave history
The time history of the input frequent earthquake wave is shown in figure 4. The peak acceleration of the seismic wave is 0.7 m/s² at 11.94 second.
3.1.2 Fourier Spectrum

Fourier spectrum of frequent earthquake wave from Fourier transform is shown in figure 5. Among the frequencies contained in a seismic wave, the frequency corresponding to the maximum amplitude of the Fourier spectrum is called the dominant frequency of the seismic wave. If the amplitude of the dominant frequency is set to 1, that is $A(f)=1$, the difference between $f_1$ and $f_2$, corresponding to the frequency values of $A(f)=0.707$, is the bandwidth within which the main energy of the seismic wave is concentrated.

In this paper, the main frequency of the input seismic wave is 2.539 Hz and the frequency bandwidth is 0.073 (2.515~2.588). The frequency in this range is called the predominant frequency of the seismic wave. If the natural frequency of the structure is close to the predominant frequency of the earthquake, it will cause resonance, which is very disadvantageous to the structure. Therefore, the natural frequency of the structure should avoid approaching the predominant frequency of the seismic wave. In addition, the other large peak frequency of Fourier spectrum is 0.394, and the corresponding bandwidth is 0.050 (0.360~0.410), which effect on the seismic response of the structure is considered.

3.1.3 Reaction Spectrum

The response spectrum in the Chinese code for seismic design of buildings is given in the form of a seismic influence curve as shown in figure 6[10]. According to the definition of response spectrum, the acceleration response spectrum of seismic wave is given in this paper, and is compared with the response spectrum given in "code for seismic design of buildings", as shown in figure 7. As can be seen from the diagram, the change trend and the shape of the curve are similar, but in general, the amplitude of the response spectrum of the input seismic wave is larger than that in the code, which is beneficial to the analysis of the structural seismic response.
3.2. Characteristic equation of modal analysis and its solution

The natural frequency and vibration mode are the inherent characteristics of the structure. The modal analysis is based on the motion equation of the undamped free vibration of the structure. By solving the characteristic equation, the eigenvalues and eigenvectors are obtained. The eigenvalues are the natural frequencies of the structure, and eigenvectors corresponding to them are the mode shapes of the structure.

The motion equation of the undamped multi-degree-of-freedom system is given by
\[ M \ddot{u} + Ku = 0 \]  \hspace{1cm} (3)

where \( M \) and \( K \) are mass matrix and stiffness matrix of structure system respectively; \( u \) is displacement vector of structure system. If the structure moves in simple harmonic motion, displacement vector is written as
\[ u = \Phi \cos(\omega t - \alpha) \]  \hspace{1cm} (4)

where \( \omega \) is the natural frequency of structure, \( \Phi \) is mode vector of structure. By taking the equation (4) into the equation (3), the characteristic equation (5) of the structure is obtained.
\[ |K - \omega^2 M| = 0 \]  \hspace{1cm} (5)

It can be seen from the equation (5) that the eigenvalues \( \omega^2 \) depend only on the stiffness matrix \( K \) and the mass matrix \( M \) of the structure. Therefore, the natural frequency \( \omega \) of the structure is the natural value of the structure, and the eigenvector \( \Phi \) corresponding to each eigenvalue is the modal of the structure.

There are many methods to solve the eigenvalues and eigenvectors of characteristic equation (5). The subspace iteration method, which repeatedly uses the matrix iteration method and the Rayleigh-Ritz method, is suitable for the solution of low order natural frequencies and modes of large multi-degree-of-freedom structures[11]. In this paper, the method is used to solve the characteristic equation for modal analysis.

4. Dynamic characteristic of Super high-rise structure under different stiffness ratio

4.1. Vibration mode

Based on the assumption of linear elasticity and small deformation, the modal analysis of 9 finite element models of frame columns with different cross-sections is carried out by using the subspace iteration method and the finite element software.

The results show that the first two orders of the vibration modes are translation and the third order is torsional vibration. The first, second and third order modes are shown in figure 8, 9, and 10.
4.2. Natural frequency and natural period

The first 25 modes are obtained from modal analysis. Since the response of the structure does not depend entirely on the fundamental frequency of the structure, but on the superposition of the modes with different contribution ratios, attention should be paid to the first frequencies which have a great influence on the structure. The first 10 natural frequencies and the first 10 natural periods are given in Table 3.

Table 3. Comparison of natural frequency (Hz) and natural period (s) of structures with different stiffness ratios

| Mode | Dynamic characteristics | Model with different stiffness ratio ($\lambda$ value) |
|------|-------------------------|--------------------------------------------------|
|      | 1100 (4.58) | 1200 (5.34) | 1300 (6.15) | 1400 (7.02) | 1500 (7.94) | 1600 (8.92) | 1700 (9.95) | 1800 (11.00) | 1900 (12.20) |
| 1    | Frequency   | 0.1728     | 0.1770     | 0.1805     | 0.1835     | 0.1859     | 0.1878     | 0.1893     | 0.1904     | 0.1911     |
|      | Period      | 5.7880     | 5.6507     | 5.5392     | 5.4493     | 5.3784     | 5.3234     | 5.2821     | 5.2529     | 5.2340     |
| 2    | Frequency   | 0.2393     | 0.2413     | 0.2427     | 0.2436     | 0.2439     | 0.2438     | 0.2434     | 0.2426     | 0.2415     |
|      | Period      | 4.1797     | 4.1437     | 4.1195     | 4.1053     | 4.0995     | 4.1012     | 4.1090     | 4.1224     | 4.1403     |
| 3    | Frequency   | 0.3256     | 0.3277     | 0.3279     | 0.3268     | 0.3246     | 0.3217     | 0.3183     | 0.3146     | 0.3106     |
|      | Period      | 3.0716     | 3.0520     | 3.0497     | 3.0603     | 3.0805     | 3.1081     | 3.1413     | 3.1788     | 3.2196     |
| 4    | Frequency   | 0.6770     | 0.6823     | 0.6860     | 0.6881     | 0.6891     | 0.6889     | 0.6879     | 0.6860     | 0.6834     |
|      | Period      | 1.4772     | 1.4657     | 1.4578     | 1.4532     | 1.4512     | 1.4515     | 1.4538     | 1.4578     | 1.4633     |
| 5    | Frequency   | 0.7131     | 0.7185     | 0.7219     | 0.7234     | 0.7236     | 0.7226     | 0.7206     | 0.7179     | 0.7145     |
|      | Period      | 1.4024     | 1.3918     | 1.3853     | 1.3823     | 1.3820     | 1.3839     | 1.3877     | 1.3930     | 1.3996     |
| 6    | Frequency   | 0.9320     | 0.9426     | 0.9470     | 0.9464     | 0.9424     | 0.9359     | 0.9276     | 0.9179     | 0.9074     |
|      | Period      | 1.0730     | 1.0609     | 1.0560     | 1.0566     | 1.0611     | 1.0685     | 1.0781     | 1.0894     | 1.1020     |
| 7    | Frequency   | 1.2552     | 1.2641     | 1.2686     | 1.2698     | 1.2682     | 1.2649     | 1.2598     | 1.2534     | 1.2464     |
|      | Period      | 0.7967     | 0.7911     | 0.7883     | 0.7875     | 0.7885     | 0.7906     | 0.7938     | 0.7978     | 0.8023     |
| 8    | Frequency   | 1.5221     | 1.5265     | 1.5267     | 1.5237     | 1.5184     | 1.5108     | 1.5020     | 1.4919     | 1.4808     |
|      | Period      | 0.6570     | 0.6551     | 0.6550     | 0.6563     | 0.6586     | 0.6619     | 0.6658     | 0.6703     | 0.6753     |
| 9    | Frequency   | 1.6279     | 1.6415     | 1.6461     | 1.6439     | 1.6364     | 1.6247     | 1.6100     | 1.5936     | 1.5758     |
|      | Period      | 0.6143     | 0.6092     | 0.6075     | 0.6083     | 0.6111     | 0.6155     | 0.6211     | 0.6275     | 0.6346     |
| 10   | Frequency   | 1.8389     | 1.8464     | 1.8484     | 1.8467     | 1.8420     | 1.8349     | 1.8262     | 1.8159     | 1.8051     |
|      | Period      | 0.5438     | 0.5416     | 0.5410     | 0.5415     | 0.5429     | 0.5450     | 0.5476     | 0.5507     | 0.5540     |

Note: underlined values are extremum.

From Table 3, it can be seen that:

1. Combined with the Fourier spectrum of frequent earthquake wave in figure 5, the first 10 frequencies of 9 models are concentrated at 0.1728-1.8051 Hz away from the main frequency 2.539 Hz and 0.394 Hz which corresponds to another large peak in the Fourier spectrum. It can be concluded that the natural frequencies of each structure are not near the peak of the seismic wave and will not cause resonance.

2. With the increase of stiffness ratio of the outer frame to the inner core tube (the cross-section of the frame column increases from 1100mm to 1900mm), the basic frequency of the structure increases and the first natural vibration period decreases.

3. With the increase of the stiffness ratio of the outer frame to the inner core tube, the second-to-tenth-order frequency of the structure appears a peak value (indicated by the underlined words in Table 3). The frequency increases to the peak value and then decreases gradually, and the change of natural vibration period is the reverse. The peak value concentrates in certain scope, and concentrates in the model 1300mm-1500mm in this project.

4.3. Analysis of seismic wave response spectra of structures with different stiffness ratios

In order to better understand the seismic response of frame-tube structures with different stiffness ratios, the acceleration response spectra value corresponding to the natural vibration periods of each mode are given in Table 4.
Table 4. Comparison of the acceleration response spectra value (m/s²) of different modes under frequent earthquakes

| Mode | Model with different stiffness ratio (α value) |
|------|---------------------------------------------|
|      | 1100 (4.58) | 1200 (5.34) | 1300 (6.15) | 1400 (7.02) | 1500 (7.94) | 1600 (8.92) | 1700 (9.95) | 1800 (11.00) | 1900 (12.20) |
| 1    | 0.2723 | 0.2924 | 0.3177 | 0.3501 | 0.3622 | 0.3701 | 0.3760 | 0.3796 |
| 2    | 0.4467 | 0.4472 | 0.4472 | 0.4471 | 0.4471 | 0.4471 | 0.4473 | 0.4473 |
| 3    | 0.3624 | 0.3596 | 0.3610 | 0.3638 | 0.3679 | 0.3719 | 0.3772 | 0.3822 |
| 4    | 0.6077 | 0.5794 | 0.5793 | 0.5793 | 0.5793 | 0.5793 | 0.5794 | 0.5794 |
| 5    | 0.5921 | 0.5913 | 0.5905 | 0.5905 | 0.5905 | 0.5905 | 0.5913 | 0.5921 |
| 6    | 0.6486 | 0.6428 | 0.6428 | 0.6728 | 0.6728 | 0.6480 | 0.6544 | 0.6565 | 0.6586 |
| 7    | 0.5776 | 0.5785 | 0.5785 | 0.5785 | 0.5785 | 0.5785 | 0.5785 | 0.5776 | 0.5776 |
| 8    | 0.7146 | 0.7146 | 0.7146 | 0.7146 | 0.7146 | 0.7146 | 0.6400 | 0.6400 | 0.5650 |
| 9    | 1.2614 | 1.2614 | 1.2614 | 1.2614 | 1.2614 | 1.2614 | 1.1404 | 1.1404 | 1.0302 |
| 10   | 1.8687 | 1.8687 | 1.8687 | 1.8687 | 1.8687 | 1.8206 | 1.8206 | 1.8206 | 1.8206 |

From table 4, it can be seen that:

1. With the increase of stiffness ratio, the acceleration response of the first mode of the structure increases.
2. With the increase of stiffness ratio, the acceleration response of the first several modes (3-7 order) decreases to the peak value and then increases gradually, and the after several modes (7-10 order) decreases gradually.
3. On the whole, the acceleration response of the structure increases with the increase of stiffness ratio. One of the reasons is that the participation coefficient of the previous modes is large, and the other is that the stiffness of the structure increases and the natural period of vibration is short, the corresponding acceleration response spectrum moves to the left in figure 7 and the acceleration of the structure increases.

According to the relation expression (6) between the displacement response spectrum and the acceleration response spectrum, the displacement response spectrum values of different modes with different stiffness ratios can be obtained and list in table 5.

\[ S_d(\xi, \omega) = \frac{1}{\omega^2} S_a(\xi, \omega) \]

where \( S_d(\xi, \omega) \) is the displacement response spectrum, \( S_a(\xi, \omega) \) is the acceleration response spectrum, \( \omega = \frac{2\pi}{T} \) is the natural frequency of structures, and \( T \) is the natural period of structures.

Table 5. Comparison of the displacement response spectra value (m) of different modes under frequent earthquakes

| Mode | Model with different stiffness ratio (λ value) |
|------|---------------------------------------------|
|      | 1100 (4.58) | 1200 (5.34) | 1300 (6.15) | 1400 (7.02) | 1500 (7.94) | 1600 (8.92) | 1700 (9.95) | 1800 (11.00) | 1900 (12.20) |
| 1    | 0.2311 | 0.2365 | 0.2469 | 0.2526 | 0.2565 | 0.2600 | 0.2616 | 0.2628 | 0.2634 |
| 2    | 0.1977 | 0.1945 | 0.1923 | 0.1909 | 0.1903 | 0.1905 | 0.1912 | 0.1925 | 0.1942 |
| 3    | 0.0866 | 0.0848 | 0.0847 | 0.0856 | 0.0875 | 0.0900 | 0.0930 | 0.0965 | 0.1003 |
third modes of the structure decreases first and then increases. In this project, compared with the displacement response of the first vibration mode, the change of the second and third order is very small, for example, the first order increase value is 39% of the minimum value, while the second order is 1.8% and the third order is 15.8%.

(3) In this project, the displacement response values of the other vibration modes also change, but the change is small.

5. Conclusion
In this paper, based on the assumption of linear elasticity and small deformation, 9 models of concrete filled steel tubular frame-concrete core tube super high-rise hybrid structure with different stiffness ratios are analyzed. Through subspace iteration method, the first 25 order modes of the structure are extracted, and the first 10 order modes, which have great influence on the seismic response of the structure, are analyzed:

(1) With the increase of the stiffness ratio of frame to core tube, the fundamental frequency of the structure increases, but the natural frequency of the other modes of the structure increases at first and then decreases, and the peak value appears in the range of a certain stiffness ratio.

(2) Compared the natural frequency of the structure with the frequency of the earthquake wave, the natural frequency of the structure with different stiffness ratio avoids the predominant frequency of the earthquake wave and does not cause resonance.

(3) With the increase of the stiffness ratio, the acceleration response and displacement response of the first mode of the frame-core tube structure increase, and the response of the first several modes basically follows the trend of first decreasing and then increasing, acceleration response the after order modes decreases and the displacement response the after order modes changes little.

(4) Comparing with the natural frequency of the structure and the excellent frequency of seismic wave obtained by Fourier spectrum can be used to judge whether the dynamic characteristics of the structure avoid resonance or not. The dynamic response of the structure can be judged preliminarily by the corresponding analysis of the response spectrum of seismic wave and the natural period of the structure. It is feasible and significant to interpret the seismic response of structures from studying the dynamic characteristics of seismic waves and structures.

Acknowledgments
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.

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