# Modeling and Analysis of Shanghai Central Tower

Yuchi Liu[1](✉), Yiwen Chen[2], and Peitong Li[3]

[1] Chang'an Dublin International College of Transportation, Chang'an University, Xi'an 710018, China
2019902246@chd.edu.cn
[2] College of Architectural Science and Engineering, Yangzhou University, Yangzhou 225100, Jiangsu, China
[3] UNITEC Institute of Technology, Auckland 1025, New Zealand

**Abstract.** Shanghai Central Tower, as China's landmark super high-rise building, has attracted wide attention since its construction. Because it is much higher than ordinary buildings, it also poses a challenge to construction and later maintenance. Therefore, the structural safety of Shanghai Center Tower needs to be highly valued. This article builds a model similar to Shanghai Central Tower by using ANSYS software. Through modal analysis, a series of analysis are carried out on the model. In the analysis process, the analysis data are compared with the actual situation, the model can be close to the real situation, and can provide some reference for the analysis of Shanghai Central Tower. At the same time, it is found that when the model is at some corresponding natural frequencies, the overall structure is more prone to dangerous states. These frequencies need to be avoided as much as possible. In addition, the effects of torsion and non-torsion of the structure are also discussed in the article.

**Keywords:** Modal analysis · Structural analysis · Shanghai Central Tower · Ansys

## 1 Introduction

Shanghai Center Tower, as a high-profile high-rise building, has its function and importance. At the same time, because it exceeds the height and design form of ordinary buildings, its architectural structure form is also extremely complex.

Shanghai Central Tower is the highest building of China and it located in Lujiazui Shanghai. The height of Shanghai Central Tower is 632 m, and the assumed weight is 800,000 tones. The land area of the project is 30,370 square meters, the above-ground construction area is 380,000 square meters, the underground construction area is 160,000 square meters. The design team is Gensler from America. It is also the newest landmark of Shanghai. Shanghai Center Tower's structural facade is a unique curved surface, with curtain walls rotating [1]. Wind load is one of the main controlling factors of Shanghai Center Tower. Due to the geographical location of Shanghai in coastal areas, typhoon weather often occurs more frequently here [2]. Some researchers have found that the ratio


E. Strauss (Ed.): ICOCE 2022, LNCE 276, pp. 128–137, 2023.
https://doi.org/10.1007/978-981-19-3983-9_12

of hourly average wind speed to gradient time average wind speed in Shanghai is about 0.68 [3]. At the same time, the use of radiosonde also helps researchers obtain the data of typhoon wind profile [4]. At the same time, in view of the external influence of high-rise buildings, the field measurement method is also used in the research. These established systems provide useful information on wind effects and the dynamic characteristics of high-rise buildings [5].

This article mainly uses ANSYS software for modeling. Compare the data obtained from the model analysis with the real measurement data, and constantly adjust the parameters to be close to the real situation as much as possible. The analysis method mainly uses modal analysis to obtain the natural frequency and other data of the model. Under some natural frequencies, the structure of the model may be affected, which needs to be avoided in reality.

## 2 Methodology

### 2.1 Modal Analysis Overview

One of the most basic and important types of structural dynamics analysis is "structural modal analysis". Modal analysis is mainly used to calculate the vibration frequency and vibration pattern of the structure, so it can also be called frequency analysis or vibration analysis. Dynamical analysis can be divided into time domain analysis and frequency domain analysis, and modal analysis is the basic analysis type of dynamical frequency domain analysis.

### 2.2 Related Theory

#### 2.2.1 Kinetic Control Equations

The kinetic control equations can be expressed as differential equations.

$$[M]\{\ddot{u}\} + [C]\{u\} + [K]\{u\} + \{F\} = 0 \tag{1}$$

where [M] = structural mass matrix, [C] = structural damping matrix, [K] = structural stiffness matrix, {F} = external load function with time, {u} = nodal displacement vector, {u} = nodal velocity vector, and {ü} = nodal acceleration vector.

There is no need to consider the effect of external forces in the modal analysis of the structure; therefore, the dynamical control equation for modal analysis can be expressed as follows:

$$[M]\{\ddot{u}\} + [C]\{u\} + [K]\{u\} = 0 \tag{2}$$

Ideally, the structure is vibrating without considering the damping effect, which is the so-called free vibration case, and the modal analysis can be described again as

$$[M]\{\ddot{u}\} + [K]\{u\} = 0 \tag{3}$$

Further analysis of Eq. 3, assuming that the free vibration is harmonic response motion, that is, u = u0sin(ωt), Eq. 3 can be further described as

$$([K] - \omega 2[M])\{u\} = 0 \tag{4}$$

Solving Eq. 4, the root of the equation is ωi2, the eigenvalue, where i ranges from 1 to the number of degrees of freedom N of the structure (in FEA, the number of degrees of freedom N generally does not exceed three times the number of nodes of the analytical model mesh).

The square root of the eigenvalue is ωi, which is the intrinsic circular frequency, so that the structural vibration frequency (structural intrinsic frequency) fi can be obtained by the formula fi = ωi/2π. Finite element modal analysis can be performed to obtain fi or ωi, both of which can be used to describe the vibration frequency of the structure.

The characteristic vector corresponding to the eigenvalues is {u}i. The eigenvector {u}i represents the vibration shape (mode) of the structure when it vibrates at the intrinsic frequency fi.

#### 2.2.2 Vibration Frequency Influencing Factors

Considering the simplest form of transformation for modal analysis (Eq. 4), its further transformation gives ω2 = [K]/([M]){u}). Thus, the modal frequency is proportional to the stiffness of the structure and inversely proportional to the mass of the structure.

### 2.3 Model Building

#### 2.3.1 Method and Tool

The finite element method is used to analyze the dynamic characteristics of the main tower section of the Shanghai Tower. For a more complex structure, it is difficult to assume the exact overall displacement function. In this case, the structure can be divided into a finite number of units, and a unified and relatively simple displacement function can be used inside the unit, while the structure is analyzed as a collection of these units. This analysis method is called the finite unit method. The CAE software we use is ANSYS, which is powerful, easy to operate, and has become the most popular FEA software in the world, and has been ranked first in the FEA competition for many years. We mainly use workbench of ANSYS to perform modal analysis.

Models according to the general dimensions in Shanghai Tower, which are relatively less precise, but easy to generate meshes and calculate results. One of them is distorted and the other one is not, other parameters are the same, and the results of our analysis are based on these two models. The geometric properties of the model is first determined and adjust it to the actual mass and frequency. To simplify the analysis, the gap at the curtain wall is ignored because we believe that it has little effect on the structure. Figure 1 shows two basic models of Shanghai Center Tower. One is the model after torsion and the other is the model without torsion. These two models are both drawn by ANSYS.

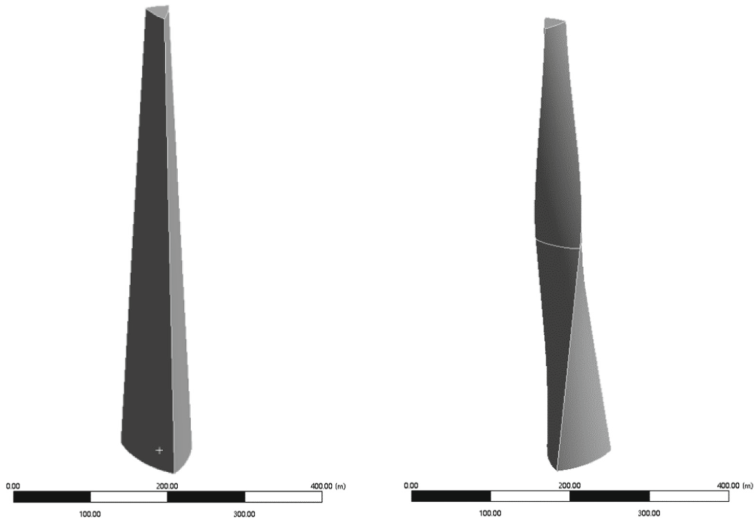


**Fig. 1.** Shanghai Central Tower basic model

# 3 Result and Discussion

Model analysis method is used in the analysis of Shanghai Central Tower model. Before using the first mock exam function of ANSYS, the basic parameters of the model need to be modified through engineering data module. Taking the density of the model as an example, the whole model needs to be selected first and the software will automatically identify the total volume of the model. The total weight of Shanghai Central Tower is eight hundred thousand tons [6]. According to the mass volume formula, the density value of the model can be roughly obtained. After obtaining the density value, the density value should be input into the corresponding module for subsequent analysis.

After adjusting the parameters required by the model, the software can automatically start the analysis. In this analysis, the default mode order is 6, which means only the first six modes have to be analyzed. Through the software display window, the vibration modes and corresponding specific values of the model under different modes are provided. In the process of comparing the value obtained from the analysis of the model with the real value, there may be a large gap compared to the real value. Therefore, in this case, the elastic modulus of the model needs to be adjusted. If the period is too large, it reflects that the material stiffness is small, and the elastic modulus needs to be increased [7].

## 3.1 Model Analysis of Torsional Model

Figure 2 mainly shows the vibration of the torsional model under different modes. According to the Fig. 3, and compared with the natural frequency of Shanghai Central Tower in reality, the first order frequency deviation is less than 1%, and the second frequency deviation is about 8%. Basically, within the acceptable range of deviation, it shows that the model can reflect the situation of Shanghai Central Tower approximately.

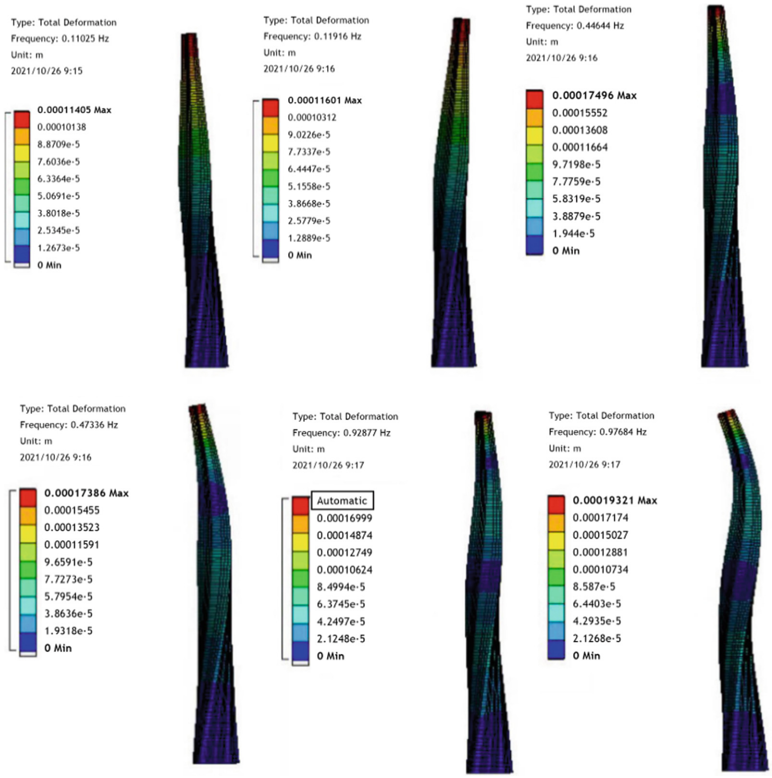


**Fig. 2.** Vibration of different modes of torsional model

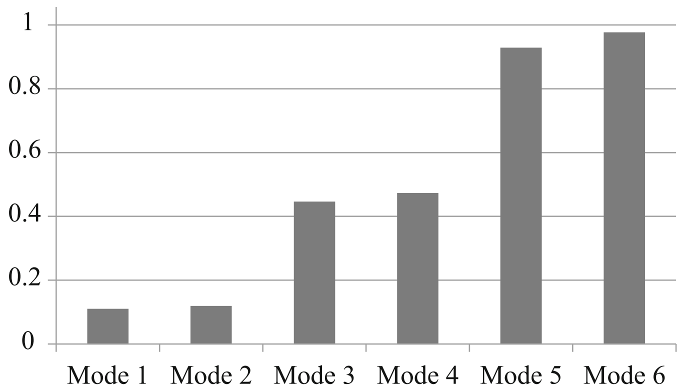


**Fig. 3.** The value of the natural frequency of torsional model

The natural frequency of the model is the largest at the sixth order. However, only from the digital images, it cannot fully reflect the vibration of the model. At this time, the more comprehensive vibration of the model through the solution information table of ANSYS becomes a better choice.

Vibration of the model can be judged through three different directions. These three directions are automatically divided into x, y and Z axes in the software. Generally speaking, the change severity of the model along the Y axis can reflect the possible results of the model under the wind. By comparing the modes of different orders to determine, people can avoid the building reaching this frequency in future design.

The participation factor can be also used as a good parameter to reflect the vibration severity of the building in this mode. As shown in the following Table 1, the absolute value of the participation factor is the largest in forth mode, and the ratio is larger than that of other modes. The results reflect that the frequency obtained in the fourth mode of the model needs to be avoided as much as possible, and it is more likely to be affected by the wind in reality. The building may be in dangerous condition.

**Table 1.** Y-axis participation factor of torsion model

| Model | Participation factor | Ratio |
|---|---|---|
| 1 | 35.563 | 0.1882 |
| 2 | −91.197 | 0.4826 |
| 3 | 152.77 | 0.8084 |
| 4 | −188.98 | 1.0000 |
| 5 | −96.645 | 0.5114 |
| 6 | 39.675 | 0.2099 |

For the x-axis and z-axis, these two axes can mainly reflect the possible impact on the foundation of the building due to vibration. In the y-axis direction, the changes caused by vibration can be clearly displayed, while the changes of X and Z-axes are not easy to detect directly. In this case, the change of effective mass can be analyzed and shown in the Table 3. When the model vibrates, the internal structure and materials will swing, resulting in changes in the partial mass. The change of effective mass refers to the change of forces on different parts of the model due to the deviation of the building during vibration. If the force changes too much at this frequency, the building may be in danger of overturning. This situation should be avoided in engineering design and manufacturing.

Table 2 shows that the effective stress of the building is the largest in the second mode in the X direction. The maximum effective stress in Z direction appears in the first mode. Therefore, the frequencies in model 1 and model 2 need to be avoided as much as possible. The building may be dangerous at these two frequencies.

**Table 2.** The value of the effective stress

| Effective mass | | | |
|---|---|---|---|
| X-DIR | Ratio% | Z-DIR | Ratio% |
| 0.6849E + 08 | 8.57 | 0.2584E + 09 | 32.33 |
| 0.2521E + 09 | 31.55 | 0.7368E + 08 | 9.22 |
| 0.1156E + 09 | 14.46 | 0.2717E + 08 | 3.40 |
| 0.2409E + 08 | 3.02 | 0.1185E + 09 | 14.82 |
| 0.7694E + 08 | 9.63 | 0.5712E + 07 | 0.71 |
| 0.6422E + 07 | 0.80 | 0.7240E + 08 | 9.06 |

## 3.2 Model Analysis of Model Without Torsion

Shanghai Central Tower has a special torsional structural character compared to the general structure. Therefore, an untwisted model is established and compared it with the previous twisted model.

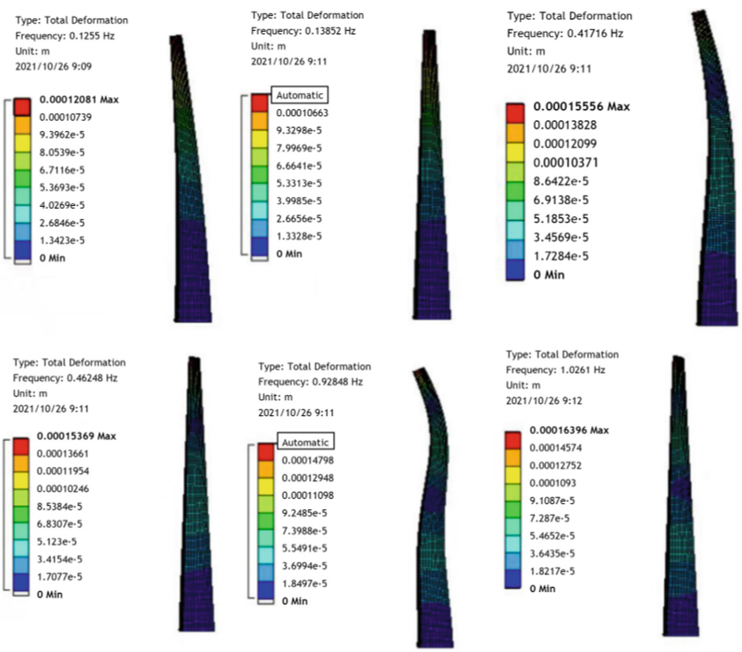


**Fig. 4.** Vibration of different modes of untwisted model

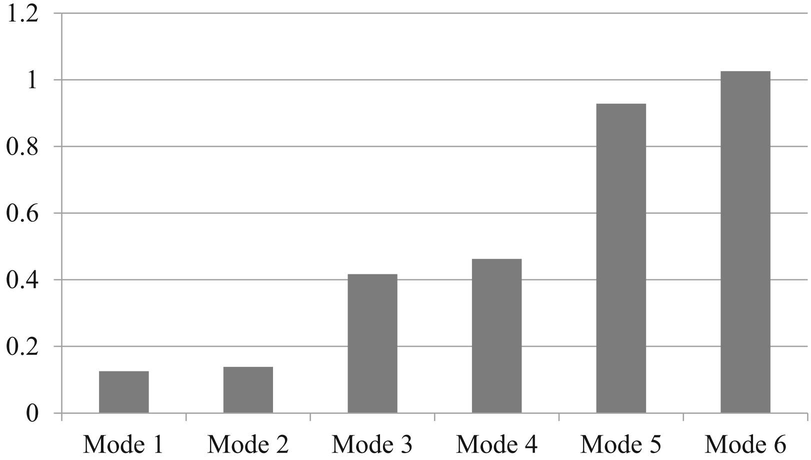


**Fig. 5.** The value of the natural frequency of untwisted model

Figure 4 mainly shows the vibration of the untwisted model in different modes. Moreover, in Fig. 5, to make a more intuitive comparison with the torsional model analyzed before, the first six modes are selected in this study when analyzing the non-torsional model. The analysis data show that the natural frequency of the model without torsion is greater than that of the model after torsion.

**Table 3.** Y-axis participation factor of untwisted model

| Model | Participation factor | Ratio |
|---|---|---|
| 1 | −49.250 | 1.0000 |
| 2 | 40.180 | 0.8158 |
| 3 | 36.801 | 0.7472 |
| 4 | −28.820 | 0.5852 |
| 5 | −23.116 | 0.4694 |
| 6 | 17.582 | 0.3570 |

**Table 4.** The value of the effective stress of untwisted model

| Effective mass | | | |
|---|---|---|---|
| X-DIR | Ratio% | Z-DIR | Ratio% |
| 153.0 | 0.00 | 0.3250E + 09 | 36.79 |
| 0.3276E + 09 | 37.08 | 130.1 | 0.00 |
| 86.29 | 0.00 | 0.1855E + 09 | 21.00 |
| 0.1869E + 09 | 21.16 | 76.57 | 0.00 |
| 41.47 | 0.00 | 0.1030E + 09 | 11.66 |
| 0.1037E + 09 | 11.74 | 40.77 | 0.00 |

Table 3 and 4 show the information of untwisted model especially in Y axis and the value of the effective stress of untwisted model. The maximum value of the participation factor in the Y direction of the non-torsional model appears in the first mode, which is different from the torsional model. At the same time, the numerical value of participation factor is generally smaller than that of twisted model. In terms of effective quality, the results are also significantly different from the previous model. The maximum value appears in the second-order mode in X direction and the first-order mode in Z direction respectively. The foundation part of the non-torsional model may be affected in these two natural frequencies.

### 3.3 Comparison of Torsional and Non-torsional Models

When the model is not twisted, the natural frequency of the structure is greater than the twisted model. The natural frequency of the structure is related to the stiffness and mass of the object. It is the inherent characteristic of the structure itself and is not affected by external forces. This shows that the torsion of the structure may affect the stiffness, resulting in the change of natural frequency. At the same time, in terms of the participation factor in the Y direction, the value of the participation factor of the untwisted model is too small, indicating that the untwisted model may have a stronger ability to resist the wind in reality. The effective mass of the model without torsion is also different from that after torsion. It indicates that torsion may change the properties of the structure to a great extent.

## 4 Conclusion

Shanghai Central Tower as a landmark super high-rise building, its completion represents the advanced level of construction technology. In this research, model analysis method is used to analyze the natural vibration characteristics of Shanghai Central Tower model and the following conclusions are drawn. Compared with the natural frequency of Shanghai Central Tower in reality, it is basically within the acceptable range of deviation. It shows that the model can reflect the situation of Shanghai Central Tower approximately. In the fourth mode, the vibration of the model changes greatly along the y-axis direction, and the wind may have a great impact on this frequency. In the torsion model, the effective mass change of X and Z axes reflects that the foundation part is more vulnerable to the influence of these two axes frequencies and reaches the maximum in the second-order mode and the first-order mode respectively. By comparing the torsion and non-torsion of the model, the natural frequency of the model will change after torsion. It indicates that torsion may lead to deviation of the natural frequency by affecting the structural stiffness.

In future research, the model can still be improved to obtain more accurate data. If the basement is not considered in the model, the pile-soil area is equivalent. The internal force and deformation of pile-soil area cannot be obtained. Therefore, the model can be further improved in the future research, so as to strengthen the research on each structural part.

**Acknowledgement.** Y. Liu, Y. Chen and P. Li contributed equally to this work and should be considered co-first authors.

## References

1. Xin, Z., et al.: The wind resistant design of Shanghai Center Tower. J. Build. Struct. **32**(7), 1–7
2. Katagiri, J., Marukawa, H., Ohkuma, T., Fujii, K.: Effects of natural frequency ratio of across-wind to torsion on wind-induced responses of a high-rise building. Nihon Kenchiku Gakkai kōzōkei ronbunshū **63**(507), 21–27 (1998)
3. Xu, H., Lin, N., Huang, M., Lou, W.: Design tropical cyclone wind speed when considering climate change. J. Struct. Eng. **146**(5), 4020063 (2020)
4. Kepert, J.: The dynamics of boundary layer jets within the tropical cyclone core. Part I: linear theory. J. Atmos. Sci. **58**(17), 2469–2484 (2001)
5. Fu, J.Y., Wu, J.R., Xu, A., Li, Q.S., Xiao, Y.Q.: Full-scale measurements of wind effects on Guangzhou west tower. Eng. Struct. **35**, 120–139 (2012)
6. Jiemin, D., et al.: Critical issues of structural analysis for the Shanghai Center project. J. Build. Struct. **31**(6), 1–3 (2010)
7. Wu, J., Xu, H., Zhang, Q.: Dynamic performance evaluation of Shanghai Tower under winds based on full-scale data. Struct. Des. Tall Spec. Build. **28**(9) (2019)