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STRUCTURAL ANALYSIS AND HEALTH MONITORING OF SHANGHAI TOWER IN CONSTRUCTION STAGE

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ABSTRACT

Located close to the Jin Mao tower and the World Financial Center, the 632-metre Shanghai Tower will be the highest super tall building in the new Lujiazui Finance and Trade Zone of Shanghai. As one of the highest buildings in China, its structure is so complicated and requires innovative construction solutions. This paper presents the construction scheme and introduces the construction simulation and structural health monitoring system. Due to the lack of theoretical research and engineering practice, traditional design method of high-rise building cannot fully grasp and control the behaviour of high-rise building during construction and operation stage. Structural health monitoring during construction and operation stage is an effective measure to guarantee the construction safety and operation stability of super high-rise buildings. This paper also introduces the functional components, technical requirements and the monitoring objectives of the structural health monitoring system. The final part of this paper presents the initial safety evaluation results of Shanghai Tower based on the monitoring data recorded in construction to illustrate the effectiveness of the structural health monitoring system.

KEYWORDS

Shanghai Tower, construction scheme, construction simulation, structural health monitoring, life cycle monitoring, performance evaluation.

INTRODUCTION

Nearby the Jin Mao tower and the Shanghai World Financial Center tower, the Shanghai Tower is a 580,000 m2 multi-use development located in the new Lujiazui Finance and the Trade Zone of Shanghai (see Figure 1). The structural height is 580m and the architectural height is 632m. The building consists of 121 floors of office and hotel space, with additional 5 stories above for MEP functions. The building is divided into 9 zones along the height (see Figure 2).The building has been designed as a soft vertical spiral to contain the vertical city slowly rising towards the sky. (Ding *et al.* 2010)

Figure 1. High-rise buildings in Lujiazui district

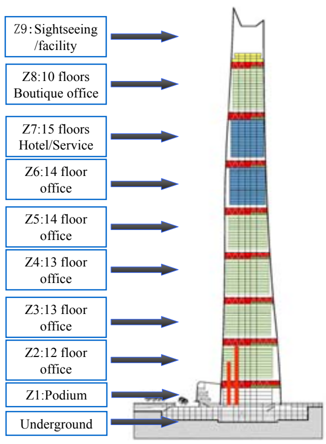


Figure 2. Shanghai Tower section

A curved triangle with a V cut in one of the angles is the basic geometry of Shanghai Tower. The triangle forms a unique façade by gradually shrinking and twisting along the height of the building (Figure 3). The overall twisting angle of the building façade is about 120。.

Figure 3. Shanghai Tower geometry

Mega frame core wall structural system is applied for the Shanghai Tower (Figure 4). A total of 6 levels of outriggers are set along the height of the building at zones 2, 4, 5, 6, 7 and 8, respectively (Figures 4a and 4b). A two-storey high belt truss is set for each zone of the building (Figure 4c). For supporting the twisting curtain wall on the building façade, radial trusses are installed at the refugee floor for each zone. The mega frame is composed of the super columns, two-storey high outriggers and belt trusses at all zones. A composite floor system is employed to support the gravity loads between the central core and the mega frame. In order to support the curtain wall support systems around the whole building, radial trusses are installed at the MEP floors (Figure 4d). All the glass curtain wall loads are transferred by the radial trusses to belt trusses, super columns and the central core walls.

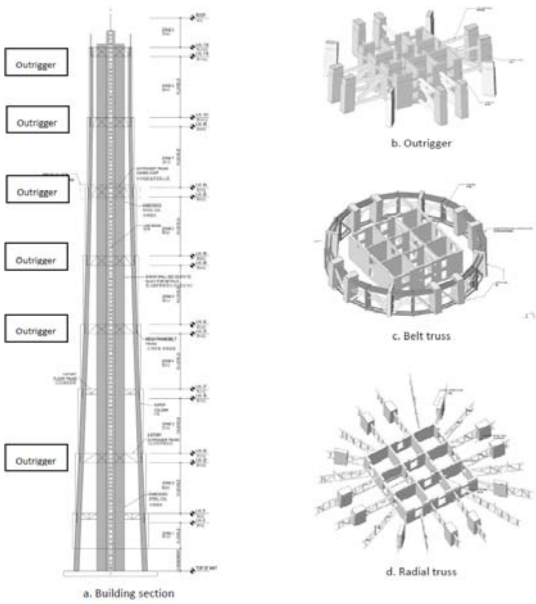


Figure 4. Structural system

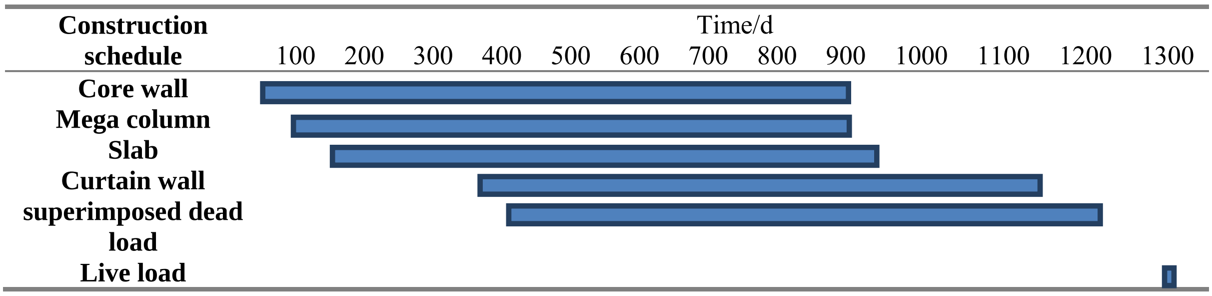
CONSTRUCTION SEQUENCE

During the construction sequence of super high-rise building, the construction of core wall commonly precedes the perimeter frame. But the number of preceding floors must be controlled to ensure the stability and stiffness of the tower, and reduce the secondary forces in the outrigger trusses caused by differential shortening between the core wall and perimeter frame. Time dependent property of structural materials, structural system and loadings will lead to significant time dependent responses of both mega columns and core walls.

Figure 5. Preceding construction of core wall

The construction progress reduces from 8d/floor in lower zone to 4d/floor in high zone. The curtain wall structure is to be installed when the frame reached 1/3 of the building height.

Table 1. Construction schedule



Upper Structure Construction

The upper structure is constructed in three steps: core wall construction, mega column and exterior floors construction and interior floors construction, as shown in Figure 6.

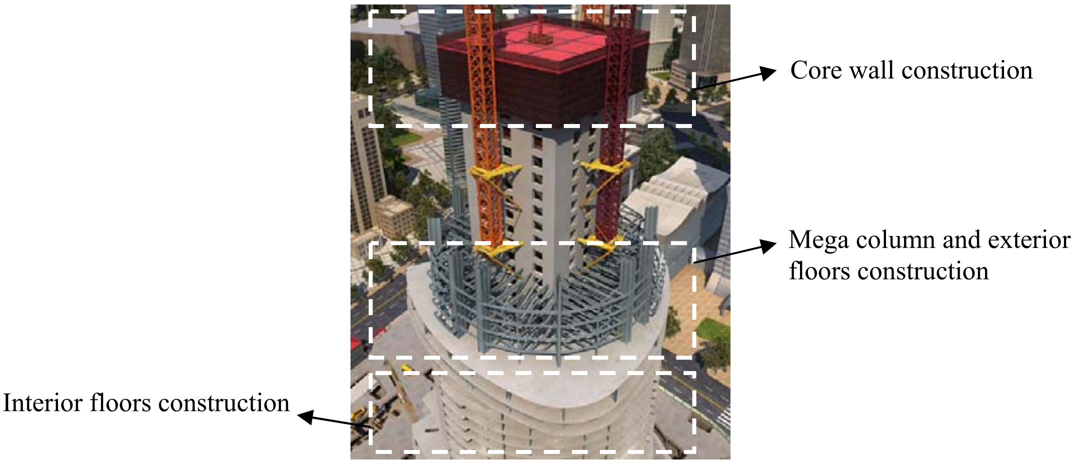


Figure 6. Upper structure construction

During the upper structural construction sequence, the distance between perimeter frame and core wall becomes closer due to the shrinkage of building plane with the progress of the construction.

Outrigger Lock-in Scheme

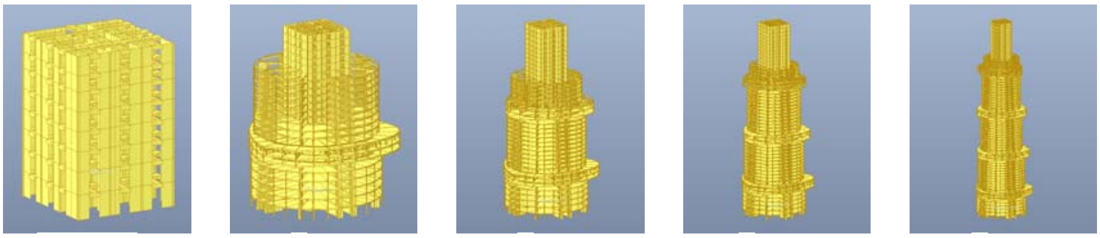
The tower is divided into 9 zones along the building height. The construction sequence can be accordingly divided into 9 structural states, which include the state from the foundation to tower crown. The outrigger lock-in scheme should consider the two requirements: Firstly, the outrigger lock-in has to satisfy the stability and stiffness requirements, and secondly the outrigger lock-in should reduce the secondary forces in the outriggers trusses to minimum. The optimum outrigger lock-in scheme which can balance both requirements is listed in Table 2. (Liu *et al.* 2011)

Table 2. Outrigger lock-in scheme

Lock-in position	Zone 7 Construction	Zone 8 Construction	Top-out	Tower crown
Zone 2	■			
Zone 4	■			
Zone 5	■			
Zone 6		■		
Zone 7			■	
Zone 8			■	

The including of construction sequence in structural analysis of super tall building structure may cause significant change on the structural responses (Wu *et al.* 2012). The construction sequence is core wall, mega frame, floor, curtain wall and secondary structure. The self weight of curtain wall and secondary structure are imposed on the main structure as dead load, and the live load during construction is considered to be $1kN/m^2$.

The construction stage is divided into 53 steps during numerical simulation. The structural situation was monitored at the time of 1 year, 1.5 year, 3 years, 10 years, 30 years, 50 years and 100 years after the structural topping out. The schedule periodic table is shown in Table 1. The structural states of different construction stages are shown in Figure 7.



a. Zone 1 b. Zone 2 c. Zone 3 d. Zone 4 e. Zone 5

f. Zone 6 g. Zone 7 h. Zone 8 i. Structural top-out j. Tower crown

Figure 7. Construction sequence

LIFE CYCLE MONITORING

Over the last decade, with the continuous development of China's social economy, high-rise building in China has been developing rapidly with increasing height. On the one hand, traditional high-rise building design method cannot fully control and know the behaviour of the high-rise building during construction and operation stage due to the lack of theoretical research and engineering practice. On the other hand, the development of super-high-rise building for decades, even centuries, disasters factors such as environmental erosion, material aging and loads long-term effects, fatigue effect and the mutagenic effect will inevitably lead to the accumulation of structural system damage and resistance attenuation, thereby reducing the ability of the structure to resist natural disasters, and even its normal ability, in extreme cases leading to catastrophic incidents. In order to guarantee the construction safety and operation health of super high-rise building, safety monitoring of high-rise building during construction and use stage can is essential.

Ground Motion

Seismic ground motion was monitored using strong motion seismograph. In order to realize the advance warning of seismic disaster and damage identification and behaviour evaluation under seismic action, seismic ground motion monitoring and seismic response monitoring should be recorded simultaneously.

Wind Loading

Velocity and direction of wind can be obtained through monitoring sensors of wind velocity at the top of the structure in different directions. In order to realize the advance warning of wind disaster and damage identification and behaviour evaluation under wind load, wind loading monitoring and wind response monitoring should be recorded simultaneously.

Displacement

Displacement monitoring of structure is used to obtain the absolute value of horizontal displacement of main structure under wind load and seismic action. Horizontal displacement and structure response of super-high-rise building can be obtained by setting tiltmeter in critical floors along the structural height. Real-time respond of structure and its overall behavior can also be obtained by combining with accelerograph.

Acceleration

Dynamic Characteristics of structures is one of the most significant and effective performance indexes reflecting the structural behaviour. The natural vibration period, frequency, damping of structures, structural response at the wind loads and earthquake loads can be obtained by setting accelerograph in the critical floors.

Due to the construction environmental restrictions, the structural accelerate response is monitored regular monthly. Structural accelerate response is small in the early construction stage and impressionable. To ensure its effectiveness, the accelerate response was monitored after finishing19th floor of outer frame in zone 2 and 37th floor of core wall in zone 3.

Temperature

Temperature variation including daily and seasonal temperature differences of the tower environmental was observed. Temperature monitor was setting every 100m along the elevation height of building to monitor temperature variation. Stress and strain monitoring sensors are used to monitor the stress and strain of key components. The key components of super-high-rise building are shown below: belt truss, top and bottom chord and tilted belly poles of outrigger, column base of mega column and core wall members, basement and embedded steel of core wall, steel reinforced of wall and concrete.

Elevation

In order to make the final floor elevation be consistent with the design elevation, elevation compensation measures adopted to modify building's floor elevation are indispensable. Elevation compensation makes use of elevation prediction and monitoring technology to compensate the elevation deviation. First, it can get the real floor elevation through monitoring technology. Second, the long-term deformation including creep and shrinkage and foundation settlement obtained by considering material's time-dependent effect was set as the elevation compensation of the super-high-rise building.

Elevation control points (+ 0.500 m) were used as the starting point of elevation transmission in the elevation measurement of Shanghai tower. Hanging steel tape and precision level gauges were used for elevation transmission, and the effects of temperature, self-gravity and tension of steel tape should be corrected when calculating elevation. Elevation measure points were arranged in the super columns and core wall of the monitoring floor, as shown in Figure 8. Elevation measurements were initiated when the slabs in monitoring floor inside and outside the core wall completed, and the time-varying vertical displacement of monitoring floor is calculated.

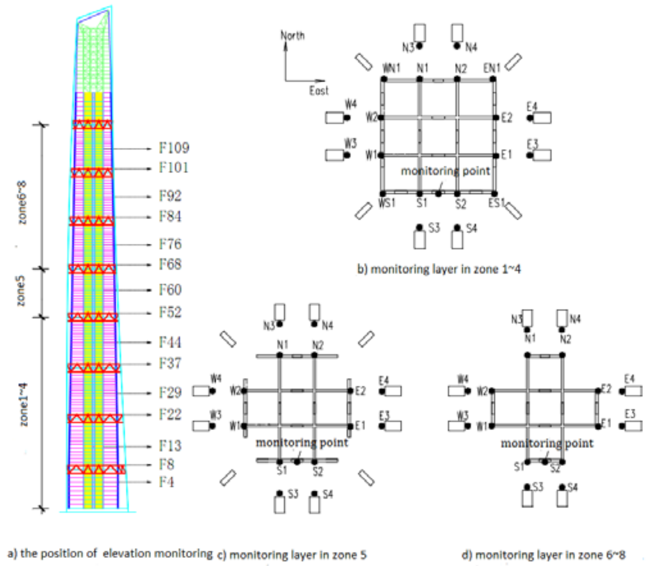


Figure 8. The position of elevation measure points

Inclination

In order to accurately know and control the tower verticality, inclination of the tower in every construction stage should be monitored. When consider the layout of vertical monitoring network, typical points should be chosen to make sure the stability of the datum mark.

On-site monitoring of super high-rise building can provide the real-time data of structure behavior during the construction. Through the comparison between monitoring and numerical analysis, the structural behavior of subsequent construction stage can be predicted by modify the calculation model. In this way, technical measures can be taken timely to adjust the construction technology and scheme, and then the construction sequence of super high-rise building can be in control (Yu 2006; Peng *et al.* 2009).The flow diagram of construction sequence analysis is shown in Figure 9.

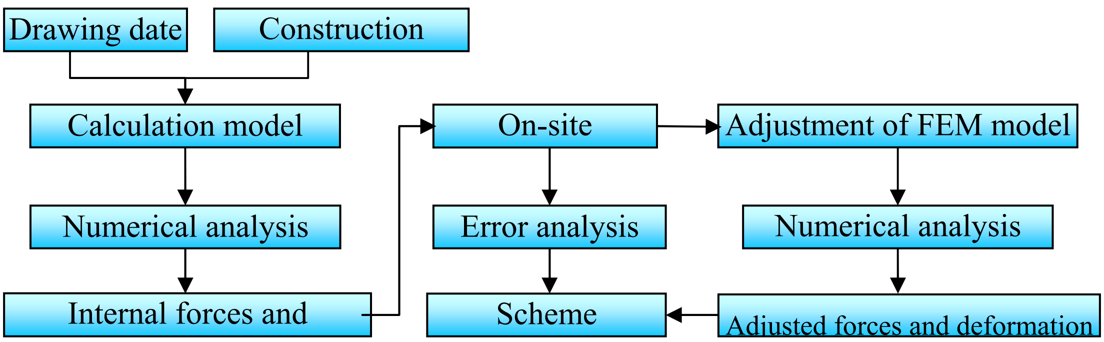


Figure 9. The construction sequence analysis

Stain and Stress

Vibrating wire sensors were used to measure the stress and strain of key members of the tower building, which measure the deformation through the change of wire resonant frequency. In each zone, a floor was chosen to arrange the measuring points of stress and strain. Gauges were mounted on the web and flange of steel shape of mega column base and installed at the reinforcing bars of column base concealed in the core wall, as shown in Figure 10. This paper analyzes the measured stress and strain of super column of external frame and concealed column in core wall. Figure 11 shows the position of measure points.

(a)Installed gauges mounted on the steel shape (b) Installed gauges embedded in the concealed column

Figure 10. Vibrating wire strain gauge

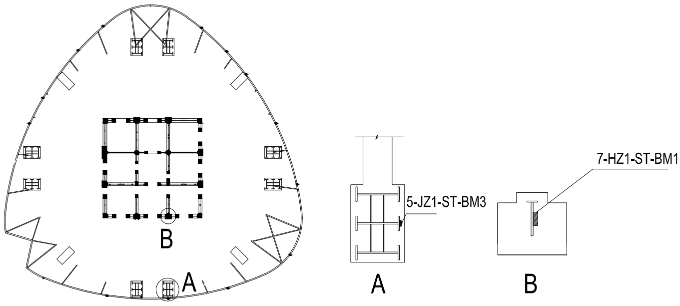


Figure 11. The position of stress measure points

ANALYSIS AND MONITORING COMPARISON

Natural Frequency

The dynamic FEM analysis shows that the first five modal is axial bending and torsion respectively and the dynamic property is very closed in two axial directions. In order to grantee the accuracy, identifying the modal parameters in two directions is necessary. Confined to the length of the thesis, only the identification result of the data acquired in 2012.08 is presented.

Table 3. Identification result comparison

Modal	1	2	3	4	5
PPK method	0.2518 Hz	0.2694 Hz	0.3123 Hz	0.7603 Hz	0.8147 Hz
SSI method	0.2558 Hz	0.2696 Hz	0.3157 Hz	0.7646 Hz	0.8156 Hz

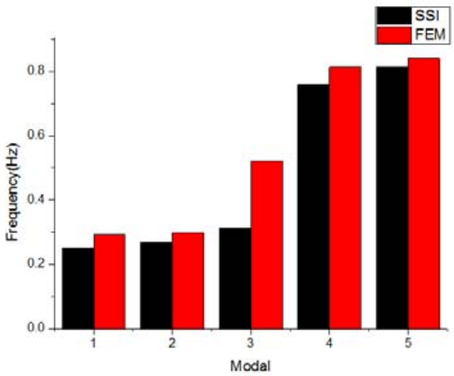


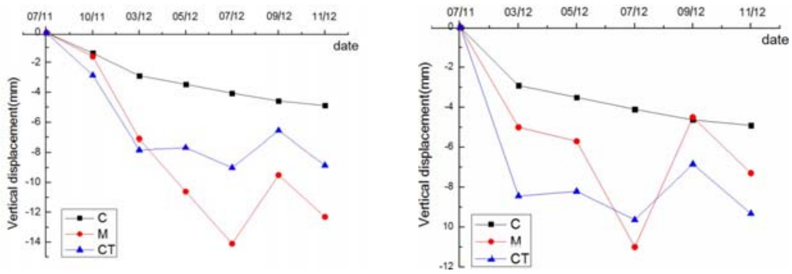
Figure 12. Frequency comparison between SSI and FEM

As shown in Table 3, the identification results of PPK and SSI are closed which means the results are reliable. From the comparison between SSI and FEM, it can be seen the identification results are lower than FEM results, especially in the third order torsion mode. After a lot of field tests analysis, it is found that FEM model cannot simulate the construction stage accurately which may be caused by construction activities, the actual structural mass is bigger than FEM.

Elevation

In this paper, numerical analysis of construction sequence is conducted in accordance with the actual construction scheme of Shanghai Tower, and the results are compared with the on-site monitoring. Numerical simulation considers the effect of vertical loads, concrete shrinkage and creep, and seasonal temperature difference to improve the result accuracy. The calculation of seasonal temperature difference considers the floor temperature when the members start the installation as the initial temperature and the measured temperature as the final temperature.

Measure point WN1 of core wall and measure point N4 of external frame in zone 1 is chosen to study the elevation change from July 2011 to November 2012. The result is shown in Figure 13. In the figure, the curve of measured result, calculated result without and with considering seasonal temperature difference is identified as M, C and CT respectively.



(a) Measure point WN1 of core wall (b) Measure point N4 of external frame

Figure 13. Comparison of vertical deformation between the measured and theoretical values

The measured results show that the maximum vertical deformation of measure point WN1 is 14.1mm and N4 is 11mm, and the vertical deformation can be seen an increasing trend over time. The calculated curve without considering seasonal temperature difference shows a gentle trend with the values lower than the measured deformation, while the calculated curve considering seasonal temperature difference are more compatible with the measured result. It is found that the vertical deformation of super high-rise is significantly affected by the seasonal temperature difference and this should be considered in numerical analysis.

Strain and Stress

Measure point (5-JZ1-ST-BM3) of the steel shape of super column in fifth floor is chosen to study the stress of steel shape from September 2011 to November 2012.In the Figure14, the curve of measured result and numerical result is identified as M and C separately. Since the initial time of measured result is behind the member installation time, the time period calculating stress increment of construction simulation should be consistent with the actual measurement to make the numerical analysis in good agreement with the on-site measured results.

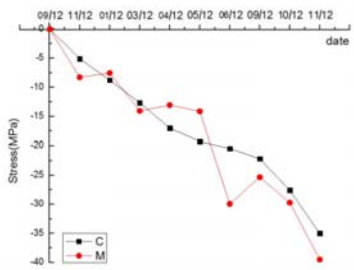


Figure 14. Comparison of stress between the measured and theoretical values

Comparison between the measured and theoretical values is shown in Figure 14. Measured strain through temperature correction multiplied by steel elastic modulus can obtain the steel shape stress. Figure 14 shows that the measured curve basically fluctuates up and down around the calculated curve. That is concerned with the environmental factors of the construction site, such as concrete mixing, steel member welding, hanging, etc., and the calculation model is simplified, it makes some difference between calculated and measured value. Steel shape stress of super column of external frame and concealed column in core wall has a tendency to enlarge with the vertical load increasing. Through numerical analysis of construction sequence, the variation of member forces can be predicted, and thus the construction can be in control.

CONCLUSION

This paper is composed of three major sections which are the construction scheme of Shanghai Tower, the life cycle monitoring and construction sequence analysis. Numerical analysis of construction sequence and on site monitoring of Shanghai Tower has been compared in this paper. The following conclusions are drawn from these studies:

(a) Structural health system monitoring program of Shanghai tower was designed based on its construction program in construction stage and the specific circumstances of the life cycle. The Shanghai Tower structural health monitoring system is composed of seismic monitoring, wind load monitoring, displacement monitoring, acceleration monitoring, temperature monitoring, and elevation monitoring. The installation of the Shanghai tower structural health monitoring system can guarantee the construction safety and operation stability of super high-rise building.

(b) The numerical analysis result of construction sequence are more compatible with the monitoring result considering the effect of time-dependent characters of material (such as creep and shrinkage of concrete) and it can be concluded that the time dependent properties of materials, structural system and loads must be considered in construction sequence analysis of super high-rise composite structure.

REFERENCES

Ding, J.M., Zhao, X. and Chao, S. (2010). "The Shanghai Tower", *2010 Conference on Structural Marvels.*

Liu, N.X, (2011). *Performance Research and Control during Construction of High-rise Mixed Structure with Outriggers*, Master Dissertation, Shanghai, Tongji University.

Peng, M.X., Liu, J.J. and Wang, C.K. (2009). "Deformation monitoring technique for cctv main tower during construction", *Building Science*, 25(11), 92-94

Wu, B.G., Wu, J.R. and Fu, J.Y. (2012). "Construction mechanics analysis of the Pearl River Building in Guangzhou", *Journal of Guangzhou University(Natural Science Edition)*, 11(2), 37-39.

Yu, D.J. (2006). *Modal Parameter Identification of Civil Engineering Structures-Theory, Implementation and Applications*, Doctoral dissertation, Fuzhou, Fuzhou University.