CTBUH Research Paper

ctbuh.org/papers

Title:	**Structural Health Monitoring of Shanghai Tower Considering Time-dependent Effects**
Authors:	Qilin Zhang, Tongji University Bin Yang, Tongji University Tao Liu, Tongji University Han Li, Tongji University Jia Lv, East China Architectural Design and Research
Subjects:	Building Case Study Structural Engineering
Keywords:	Construction Life Safety Structural Health Monitoring
Publication Date:	2015
Original Publication:	International Journal of High-Rise Buildings 2015 Number 1
Paper Type:	1. Book chapter/Part chapter 2. **Journal paper** 3. Conference proceeding 4. Unpublished conference paper 5. Magazine article 6. Unpublished

© Council on Tall Buildings and Urban Habitat / Qilin Zhang; Bin Yang; Tao Liu; Han Li; Jia Lv

International Journal of High-Rise Buildings
March 2015, Vol 4, No 1, 39-44

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

Structural Health Monitoring of Shanghai Tower Considering Time-dependent Effects

Qilin Zhang[1], Bin Yang[1,†], Tao Liu[1], Han Li[1], and Jia Lv[2]

[1]*Department of Structural Engineering, Tongji University, No.1239 Siping Road, 200092, Shanghai, China*
[2]*East China Architectural Design & Research Institute Co., Ltd, No.151 Hankou Road, 200002, Shanghai, China*

Abstract

This paper presents the structural health monitoring (SHM) of Shanghai Tower. In order to provide useful information for safety evaluation and regular maintenance under construction and in-service condition, a comprehensive structural health monitoring (SHM) system is installed in Shanghai Tower, which is composed of a main monitoring station and eleven substations. Structural responses at different construction stages are measured using this SHM system and presented in this study. Meanwhile, a detailed finite element model (FEM) is created and comparison of results between SHM and FEM is carried out. Results indicate that the time-dependent property of concrete creep is of great importance to structural response and the measured data can be used in FEM updating to obtain more accurate FEM models at different construction stages. Therefore, installation of structural health monitoring system in super-tall buildings could be considered as an effective way to assure structural safety during the construction process.

Keywords: Structural health monitoring, Shanghai Tower, Construction process, Time-dependent effect, FEM

1. Introduction

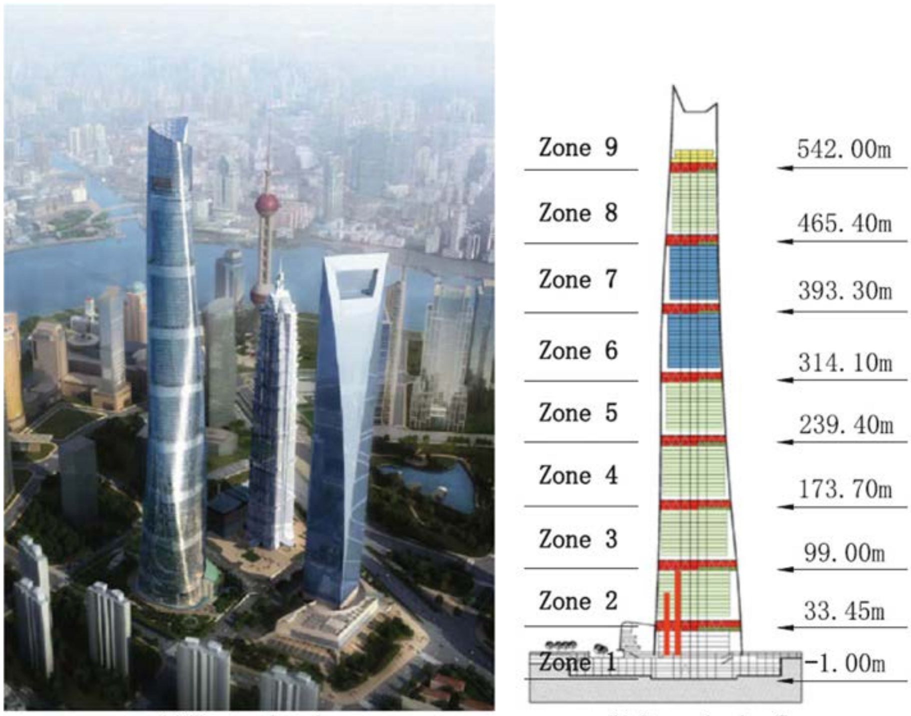
The Shanghai Tower is a super-tall building with a structural height of 580 m and an architectural height of 632 m , which will be the tallest structure in China after completion in 2015 (Fig. 1(a)). The depth of embedment is 31.2 m. The groundwater level is generally 1.0~1.7 m below the ground surface. The piled raft foundation is in the shape of an octagon. A triangular outer facade encloses the entire structure, which gradually shrinks and twists clockwise at approximately 120 degree along the height of the building. The Shanghai Tower is mainly used for office, hotel, commerce, tourism and other purposes. According to the requirement of building function, the building is divided into nine zones along its height separated by eight independent strengthening floors (Fig. 1(b)).

The structural plan layouts of typical floors in each zone are shown in Fig. 2. The steel-concrete composite superstructure resists lateral loads with a central reinforced concrete shear wall core interconnected with the composite mega frame through six two-story high outrigger trusses. Gravity loads are resisted by steel-concrete composite floor system.

[†]Corresponding author: Bin Yang
Tel: +86-21-6598-0644; Fax: +86-21-6598-0644
E-mail: yangbin@tongji.edu.cn

In the past decades, numerous super-tall buildings have been built across the world to meet the economic and social needs of communities, especially in Asia. The new generation of super-tall buildings, such as the Shanghai Tower, is designed to be more flexible, slender and visually exciting. However, these features call out special challenges for the safety and performance of super-tall buildings. Although numerical analysis and scaled laboratory experiments could be conducted to predict the structural response of super-tall buildings under certain loading conditions, the performance of super-tall buildings under actual construction and service conditions is a key issue that has not been comprehensively investigated. Therefore, the structural performance should be monitored in real-time to ensure the safety and serviceability during the construction and service stages.

In traditional design, loads are applied to the whole model for one time without considering the construction process, which is different from the actual mechanical behavior of structure during construction. The construction period of Shanghai Tower is 1573 days. Due to the long construction cycle, the time-dependent property of structure, material and load will impact the behavior of structure during the construction. So, it is essential to carry out the construction process analysis of high-rise building, and adjust the construction process according to on-site monitoring data (Brownjohn, 2007; Dundar et al., 2008; Ye et



(a) Perspective view (b) Strengthening floors

Figure 1. The Shanghai Tower.

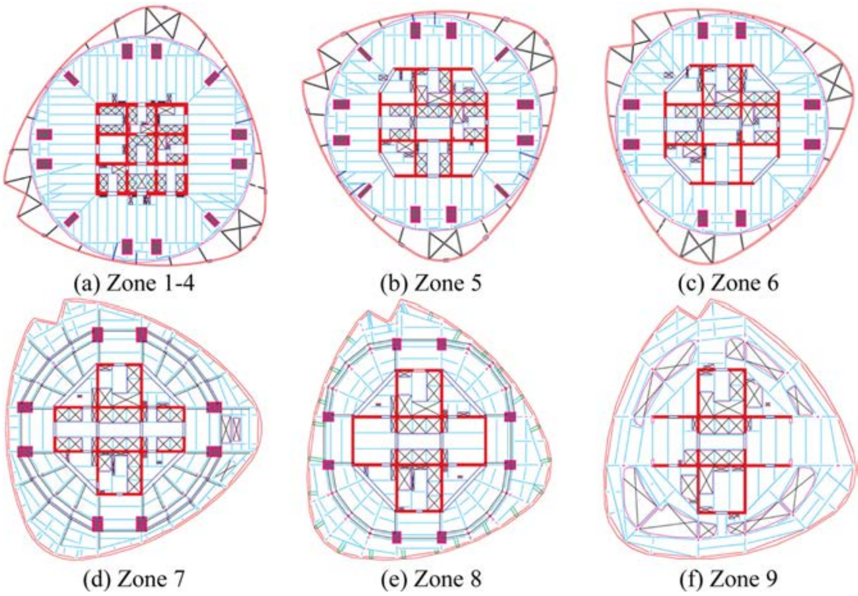


Figure 2. Structural plan layout of typical floors in each zone.

al., 2012; Zhou, 2003).

In order to monitor the response of Shanghai tower in construction stage, Tongji University, Hong Kong Polytechnic University and Tongji architectural design institute conduct a long-term structural health monitoring system, which includes the following items: wind velocity, displacement, internal force, temperature, corrosion, crack and earthquake.

The outline of this paper is presented as follows. Section 2 describes the SHM systems installed in Shanghai Tower. Finite element model of Shanghai Tower is shown in section 3, which considers the time-dependent effect of

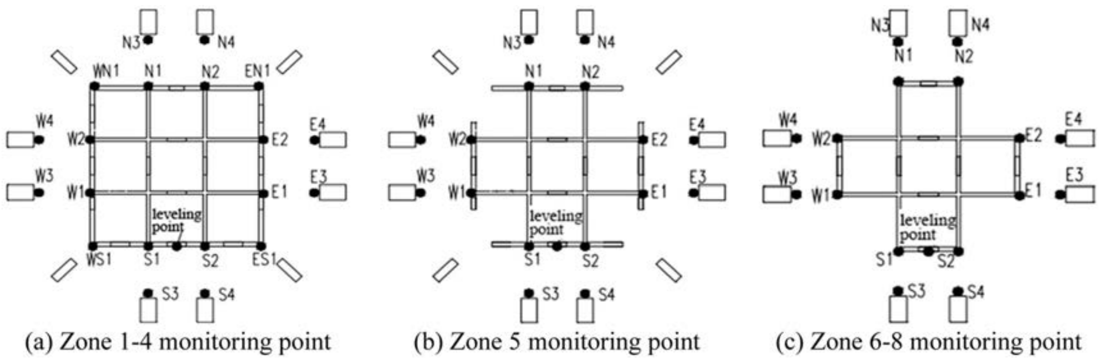


Figure 3. The position of deformation measure points.

material and construction stage. In section 4, comparison of results between SHM and FEM is carried out in terms of deformation and stress. Based on the obtained results, conclusions are drawn in section 5.

2. Structural Health Monitoring (SHM) System

On-site monitoring of high-rise building can provide the real-time data of structure behavior during the construction. Through the comparison between monitored and computed results, the structural behavior under subsequent construction stages can be predicted by adjusting the finite element model (Wu et al., 2012; Peng et al., 2009).

Based on the cooperation between Tongji University, Hong Kong Polytechnic University and Tongji architectural design institute, a long-term structural health monitoring system is installed in Shanghai Tower, which is composed of a main monitoring station and eleven substations. Displacement control points (+ 0.500 m) are used as the starting point of deformation of Shanghai Tower. Hanging steel tape and precision level gauges are used for deformation transmission and the effects of temperature, self-gravity and tension of steel tape are also taken into account when calculating deformation. The measure points are arranged in the super columns and core-tube wall of each monitored floor, as shown in Fig. 3. Deformation measurements are initiated when the slabs of the monitored floor are completed, and the time-dependent vertical deformation of monitored floor can be calculated.

Vibrating wire sensors are used to measure the deformation, stress and strain of key members in the building. The location of the measured points in each zone could be found in Fig. 4. This study examines the measured stress and strain of super column in external frame and concealed column in core-tube. The detailed arrangement of installed gauges is presented in Fig. 5.

3. Numerical Simulation

The finite element model of Shanghai Tower is created in MIDAS/GEN 7.8 software, which is comprised of two main components, i.e., steel structure (including mega frame and outriggers) and concrete structure (core-tube). Concrete and steel section of super columns are modeled separately using plate and beam elements, with core-tube using wall elements and other parts using beam elements. The master-slave constraints are used to simulate the cooperation between steel and concrete elements of super

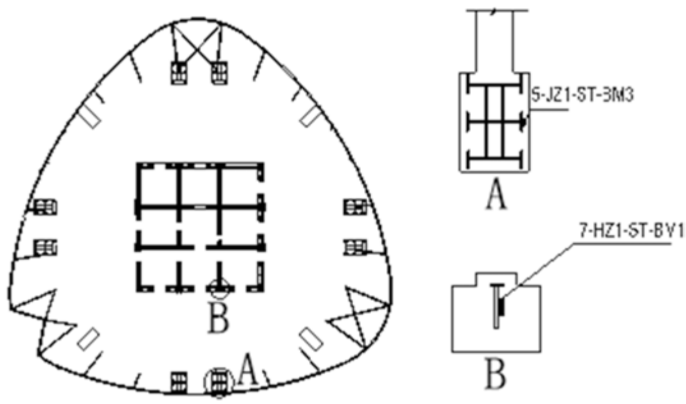
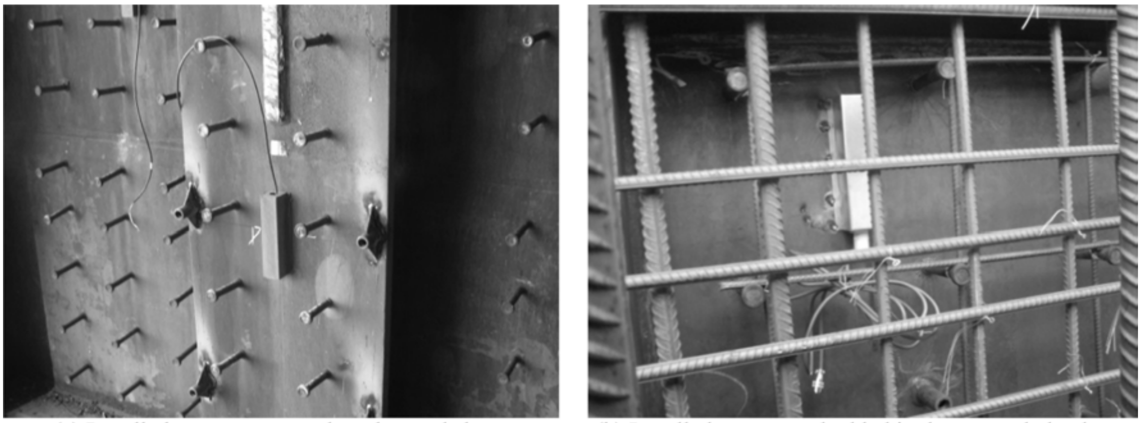


Figure 4. The position of stress measure points.



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

Figure 5. Vibrating wire strain gauge.

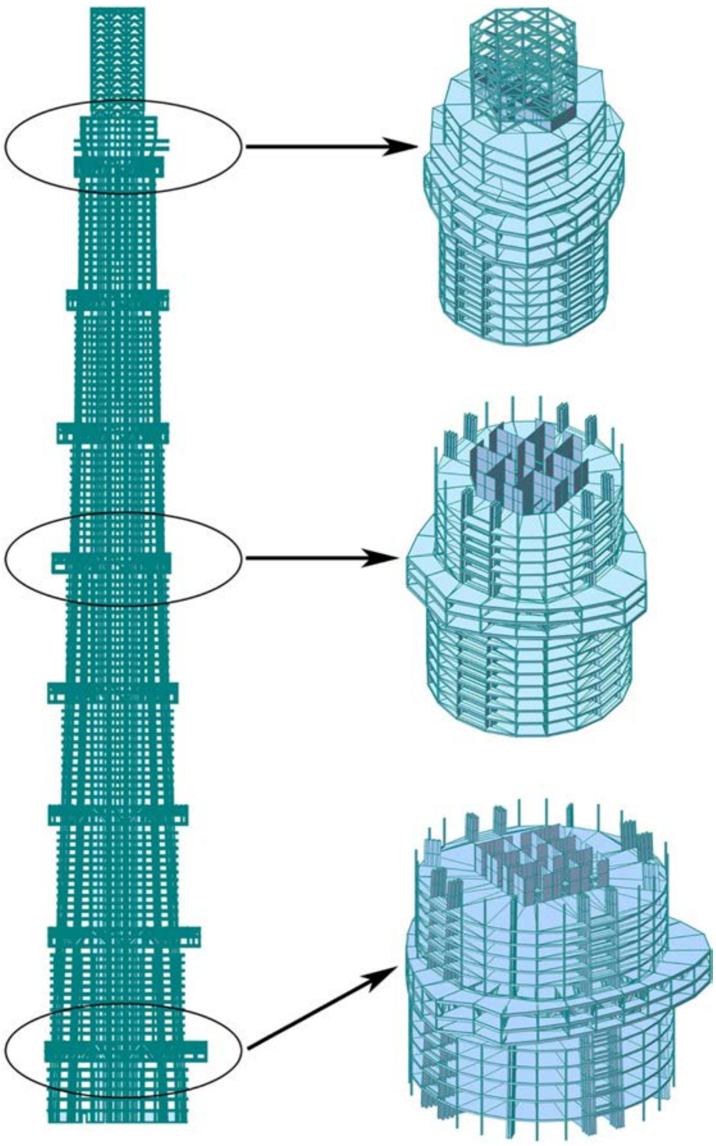


Figure 6. Finite element model of Shanghai Tower.

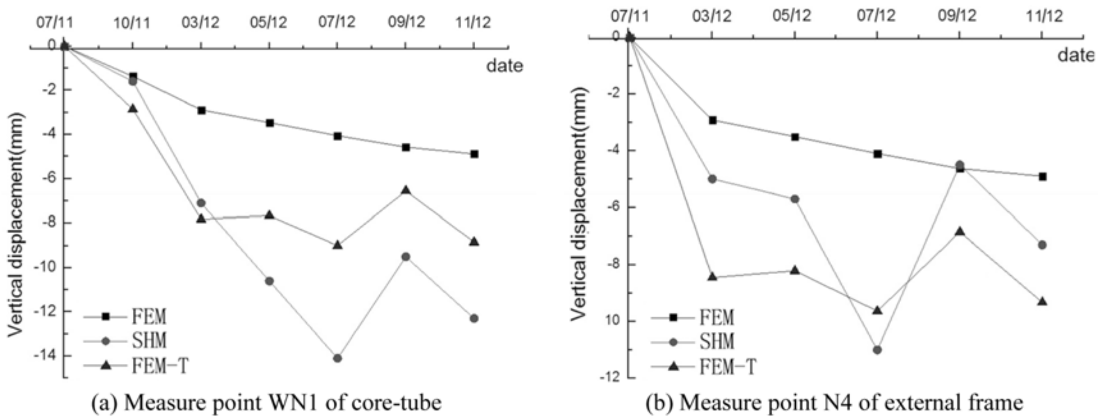


Figure 7. Comparison of vertical deformation between the measured and computed results.

columns. The bottom end is set as fixed constraint considering the deep foundation effect.

The construction sequence of Shanghai Tower is summarized as follows: (a) core-tube, (b) frame and (c) slab. The construction period of a typical floor is reduced gradually from 8 days in lower zones to 4 days in the upper zones. The installation of curtain wall starts when the structure constructs to 1/3 height, and it is always behind the construction of floors. Vertical deformation, concrete creep and shrinkage are considered in the simulation of construction process (Zhao et al., 2011).

The time-dependent properties of concrete elements mainly involves shrinkage and creep, where are affected by loading age, relative humidity, member size, reinforcement constraint effect and so on. In this paper, PCA (Fintel et al., 1987) and ACI models (ACI 1997) are selected to simulate the effects of shrinkage and creep of concrete, and the CEB-FIP model (CEB 1993) is chosen to consider the time-dependent effect of concrete compression strength.

4. Results Comparison between SHM and FEM

4.1. Deformation Monitoring

In this paper, numerical analysis of construction process is conducted in accordance with the actual construction scheme of Shanghai Tower, and the results are compared with the results obtained from SHM system. The effects of vertical loads, concrete shrinkage and creep, and seasonal temperature difference are considered in numerical simulation so as to get more accurate results. Due to the limitation of paper space, only some typical results are presented as follows.

Measure point WN1 of core-tube and measure point N4 of external frame in the fourth floor (zone 1) are selected to study the deformation change from July 2011 to November 2012, as shown in Fig. 7. Here, the results obtained from FEM when considering seasonal temperature difference are identified as FEM-T.

As can be observed in this figure, the maximum vertical deformation of measure point WN1 is 14.1 mm and that of N4 is 11 mm. In general, the vertical deformation increasing as time goes by. Without considering seasonal temperature difference, the vertical deformation is significantly underestimated, which could be adverse to structural design. However, the predicted results with consideration of seasonal temperature difference are more compatible with the monitored results. Therefore, the vertical deformation of Shanghai Tower is remarkably affected by the seasonal temperature difference, which should be also considered in numerical analyses of other high-rise buildings.

4.2. Stress Monitoring

Measure point (5-JZ1-ST-BM3) of the super column in fifth floor is selected to assess the stress variation from September 2011 to November 2012. Comparison of results between FEM and SHM can be seen in Fig. 8. The measured stress could be computed through multiplying the

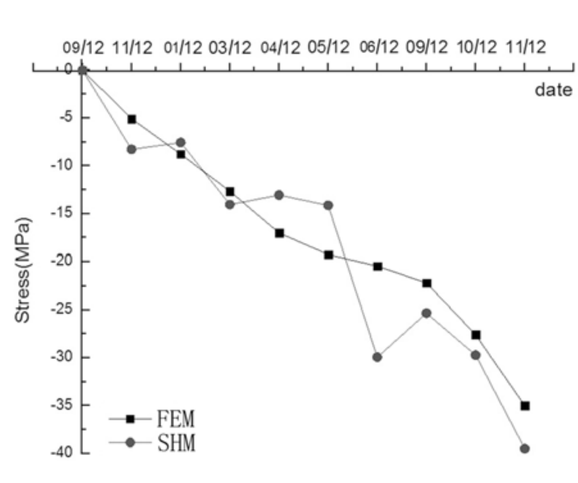


Figure 8. Comparison of stress between the measured and computed results.

measured strain by the steel elastic modulus. It can be seen that the measured results are in good agreement with the computed results. But, there are still large errors in certain dates due to measurement uncertainty, such as the environmental factors of construction site, variations of material properties and the simplified model. As the vertical load increases, the measured stress increases. Based on SHM and numerical analyses of Shanghai Tower during construction process, the variation of member stress could be predicted, thereby used for construction control of the whole building.

5. Conclusions

The structural health monitoring (SHM) of Shanghai Tower is presented in this paper. Based on the cooperation between Tongji University, Hong Kong Polytechnic University and Tongji architectural design institute, a long-term structural health monitoring system is installed to examine the changes of structural response during construction process. Due to the limitation of paper space, only the vertical deformation and stress of the key members are shown in this study. Based on the results observed in this study, the following conclusions could be drawn:

(1) The results from numerical analyses of construction process are more compatible with the monitored results considering the effect of time-dependent properties of material (such as creep and shrinkage of concrete). Hence, time-dependent effects of material should be considered in construction process analysis of high-rise composite structure.

(2) The vertical deformation of high-rise building is significantly affected by the seasonal temperature difference. The numerical results considering seasonal temperature difference are in good agreement with the monitoring results.

(3) The numerical analyses of construction process can be used to predict the variation of deformation and member forces to make a reference for design and construction.

(4) The structural health monitoring discussed in this paper not only provides valuable information on the stress and strain of the structure during construction but also represents a baseline for long-term monitoring in the near future.

References

ACI Committee 209. (1997). *Prediction of Creep, Shrinkage and Temperature Effects in Concrete Structures: ACI 209R-92*, American Concrete Institute: Farmington Hills, MI.

Brownjohn, J.M.W. (2007). “Structural health monitoring of civil infrastructure”, *Philosophical Transactions of The Royal Society A*, 365(1851), pp. 589~622.

Comite Euro-international Du Beton (1993). *CEB-FIP model code,* London: Thomas Telford Publishing.

Dundar, C., Tokgoz, S., Tanrikulu, A. K., and Baran, T. (2008). “Behavior of reinforced and concrete-encased composite columns subjected to biaxial bending and axial load”, *Building and Environment*, 43(3), pp. 1109.

Fintel, M., Ghosh, S. K., and Iyengar, H. S. (1987). *Column Shortening in Tall Buildings Prediction and Compensation*, Engineering Bulletin No. EB108D, PCA: Washington, DC.

Peng, M. X., Liu, J. J., and Wang, C. K. (2009). “Deformation monitoring technique for CCTV main tower during construction”, *Building Science*, 25(11), pp. 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), pp. 37~39.

Ye, L., Wang, J., and Zhou, J. L. (2012). “Applying research on construction simulation analysis of non-load effect of high-rise building”, *Building Structure*, 42(5), pp. 159.

Zhao, X., Liu N. X., and Sun H. H. (2011). “Structural performance assessment and control of super high-rise building during construction”, *Journal of Building Structures*, 32 (7), pp. 25.

Zhou, H. Z. (2003). “Recent advances in research on damage diagnosis for civil engineering structures”, *China Civil Engineering Journal*, 36(5), pp. 105~110.