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LONG-TERM STRUCTURAL HEALTH MONITORING OF A 250M HIGH-RISE BUILDING

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This paper presents the work on long-term structural health monitoring (SHM) of a 250m high-rise building located in Shanghai, China. The structure resists lateral loads with the steel composite frame and concrete core tube. In 21/F and 36-38/F, ring-shaped trusses and outrigger trusses are used to strengthen the stiffness of the structure. Because the height of this structure is beyond the limit of existing code and its lateral stiffness in the vertical direction is non-uniform, a long-term SHM system is designed to monitor dynamic response of the structure and evaluate the structural condition. The system consists of two parts: acceleration monitoring and displacement monitoring. Based on the system, long-term ambient vibration tests in both construction and using stages were carried out to investigate the modal parameters as well as the lateral displacement of the structure. Operational modal identification methods were employed to analyze the data to determine the dynamic characteristics. The first five modes of the structure and the lateral displacement obtained in different stages are studied and discussed. The results of this paper can be applied to provide reference for the future model updating, damage detection and performance evaluation.

Keywords: Long-term structural health monitoring, modal parameters, lateral displacement, operational modal analysis, super tall building.

1 Introduction

Structural health monitoring (SHM) refers to the nondestructive field testing, such as measure the dynamic response of the structure under ambient excitation, to analyze the characteristics of the structural system and identify structural damage. Dynamic characteristics of buildings generally include the natural frequency, damping ratio and mode shape. If the excitation frequency is close to the natural frequency of a structure, it is easy to cause resonance and may produce damages to the structure. Damping ratio reflects the energy dissipation capacity while the mode shape reflects the distribution of the quality and stiffness of the structure as well as the boundary conditions.

The response of a structure under dynamic loads such as earthquakes or strong winds is determined by the property of the ground motion, the distribution of the wind, and the dynamic characteristics of the structure. However, during the service life, the structure is inevitably subjected to material aging, reinforcement corrosion and the coupling effects with long-time loads and extreme loads which will directly affect the dynamic characteristics of the structure. Through long-term SHM, the dynamic characteristics of the structure under the operational condition can be obtained to evaluate the structural performance. Much research has been carried out to carry SHM of structures. Vanik et al. (1997) put forward a Bayesian probabilistic approach to structural health monitoring and established the basic method of Bayesian modal identification. Xiong et al. (2016) presented the analytical and experimental modal analysis of the Shanghai Tower and proposed a novel sub regional least square method for horizontal displacement calculation of frame core-tube structure with strengthened stories. Lam et al. (2017) tested a 14-story factory building and updated the finite element model based on the dynamic characteristics obtained by SHM.

In this paper, the dynamic characteristics of a 250m structure in Shanghai were investigated. The structure resists lateral loads with a reinforced concrete core tube interconnected with composite frame. Two strengthened layers are vertically arranged along the structure. Therefore, the vertical stiffness is inhomogeneous. In addition, the height of the building is beyond the limits of the design code, so it is necessary to conduct long-term SHM to investigate structural performance. Accelerometers and inclinometers were used to monitor the acceleration response and displacement response, respectively. Based on these data, system identification was carried out to investigate the dynamic characteristics and deformation of this structure. The results of this paper can be applied in the future model updating, damage identification and performance evaluation.

2 Monitoring System

The objective structure is 250m high with four floors underground and 52 floors above the ground. The typical layer stands 4.2m high with the shape of rounded rectangle. The structure resists lateral loads with the composite frame and concrete core tube. In order to enhance the lateral rigidity of the structure, the outrigger truss are respectively arranged in the 21st, 21st interlayer and 36th, 37th and 38th layer as shown in Figure 1. Monitoring system consists of two parts: acceleration monitoring and displacement monitoring. All measurements were connected by cables. The cables were embedded in the pipeline during construction stage. Considering that some measurements were too far apart, five substations were set up along the height of the structure to collect data. The typical layout plan is shown in Figure 2.

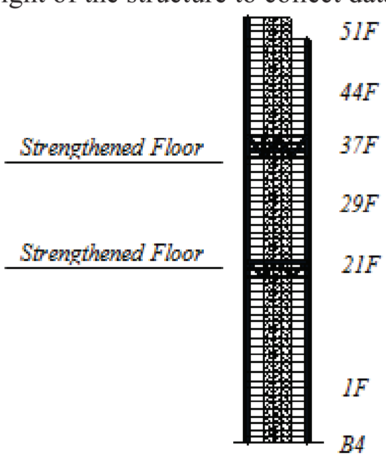

Figure 1. Structural Façade

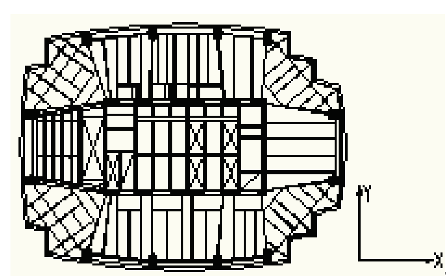

Figure 2. Structural Plane

As shown in Table 1, along the height of the structure, acceleration sensors were installed in some key floors, such as B4, 1st, 21st, 37th and 51st floor with one measuring point for each floor. As for 21st and 37st floors, each measuring point arranges two acceleration sensors to monitor the X and Y directions, respectively. Besides, three acceleration sensors are installed at each measuring point on the B4, the first and the 51st floors to monitor the X, Y and Z directions respectively. The sensors in X-direction and Y-direction mainly monitor the horizontal vibration of the structure, while Z-direction sensors monitor possible vertical vibration. The measuring points are located in the weak electricity rooms along the height of the structure, which facilitates the laying of the wire on the one hand and the acquisition of mode shape on the other hand.

Table 1. Acceleration sensor arrangement

Layers	Elevation/m	Numbers	Direction
B4	-18.800	3	X/Y/Z
1F	-0.050	3	X/Y/Z
21F	89.395	2	X/Y
37F	159.045	2	X/Y
51F	219.095	3	X/Y/Z

In addition to accelerometers, inclinometers were also arranged to monitor the inter-story displacement angle and obtain the horizontal displacement of critical layers.

For convenience, inclinometers were installed in the same equipment room as accelerometers. Each measuring point arranges one inclinometer to monitor the X and Y directions at the same time. Because the vertical stiffness of the structure changes at the strengthened layers, the story drift curve as well as the horizontal displacement curve would be different from those of structures without strengthened layers. Considering the reliability of the monitoring results, an additional measuring point is set up between adjacent strengthened layers. The final layout is shown in Table 2. The instrumentation used in the test is shown in Figure 3.

Table 2: Inclinometer sensor arrangement

Layers	Elevation/m	Numbers	Direction
21F	89.395	1	X/Y
29F	125.295	1	X/Y
37F	159.045	1	X/Y
44F	188.495	1	X/Y
51F	219.095	1	X/Y

Figure 3: Instrumentation in the test

3 Acceleration Monitoring

The accelerometer used is a piezoelectric acceleration sensor with a built-in IC amplifier. The internal spring vibrator senses tiny ambient excitation and converts the vibrations into voltage signal by micro-amplifier and signal conditioner.

Taking into account the possible extreme loads such as strong winds and earthquakes, two types of accelerometers are used for long-term monitoring. One is with higher sensitivity with the frequency range of 0.05~500Hz but smaller measurement range of 0.1g. The other is a less sensitive one with a frequency range of 0.1 ~ 1500Hz but larger measurement range of 1g. To ensure that the accelerometer can capture the dynamic response of the structure and minimize the effects of human activities, all accelerometers were mounted to the ground through a mounting base.

The acceleration response of the structure at different stages was collected. Software ARTeMIS Modal V4.0 was used to analyze dynamic characteristics. A simplified model that can reflect the structure size and boundary conditions was established. The test data was corresponded with the measuring points in the model, and the modal parameters were analyzed by the Enhanced Frequency Domain Method (EFDD). The dynamic characteristics of the structure at different stages are shown in the following Table 3.

Table 3: Results of natural frequency, damping ratio and modal shapes

Modes	2016.07.16		2017.03.04		2017.12.14		Mode shapes
	Frequency	Damping	Frequency	Damping	Frequency	Damping	
1	0.246Hz	1.658%	0.242Hz	2.487%	0.243Hz	2.504%	1st lateral mode in Y direction
2	0.265Hz	1.593%	0.258Hz	2.42%	0.258Hz	2.417%	1st lateral mode in X direction
3	0.424Hz	1.313%	0.409Hz	1.741%	0.411Hz	1.476%	1st torsional mode
4	0.892Hz	0.920%	0.850Hz	1.300%	0.856Hz	1.198%	2st lateral mode in X direction
5	0.975Hz	0.746%	0.954Hz	1.148%	0.956Hz	1.033%	2st lateral mode in Y direction

The first five modes including four translational modes and one torsional vibration mode of the structure can be obtained. The first basic frequency is rather low in both construction (0.246Hz) and usage stage (0.244Hz), because the height-to-width ratio of the structure is large, which making that the bending stiffness is comparatively small. Compared with the test results of July 2016, the basic properties of the first five modes (four translational modes and one torsional mode) measured in March 2017 are the same while the frequency of the structure is slightly reduced because as the construction completed, mass and stiffness of this structure were all changed. However, from March 2017 to December 2017, the natural frequencies have small variations and the difference may be due to the identification error. This is because during this stage, the main structure has been finished for some time and the mass and stiffness of the whole structure tend to be stable. In addition, the damping ratio of the structure increases compared with the test result of July 2016. Note the fact that the excitations of ambient vibration are mainly composed of wind, micro tremors and other ambient incentives. Since the amplitude of the excitation is rather small, the uncertainty in identifying damping ratio would be great. Another implication is that the energy dissipation capability increase following the completion of the structure.

4 Displacement Monitoring

For super high-rise structures, horizontal loads usually play a controlling role. Therefore, monitoring the horizontal displacement of structures is an important part of SHM. The angle of the measuring point related to the Earth's gravity baseline can be measured by the inclinometer and then the horizontal displacement in the interval can be obtained. The inter-story drift angle and the horizontal displacement are important indexes to measure the structural rigidity and deformation capacity as well as to check the structural lateral resistance performance.

The displacement response of the structure at using stage was collected. The sampling frequency was 500Hz and each test lasted 10min. The time history of the inter-story displacement angle is shown in Figure 4.

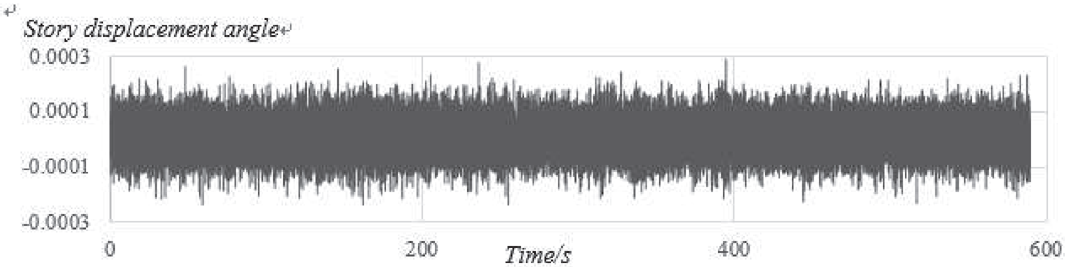

Figure 4: The time history of the story displacement angle (unit: degree)

Due to the limited number of inclinometers, the inter-story displacement angle of the floor without the inclinometer is obtained by the trapezoidal method. That is, the inter-story displacement angle of floors between adjacent inclinometers is obtained by linear interpolation based on the measuring points. The story drift angle curve is shown in Figure 5. The curve is integrated to obtain the lateral displacement curve of the structure as shown in Figure 6.

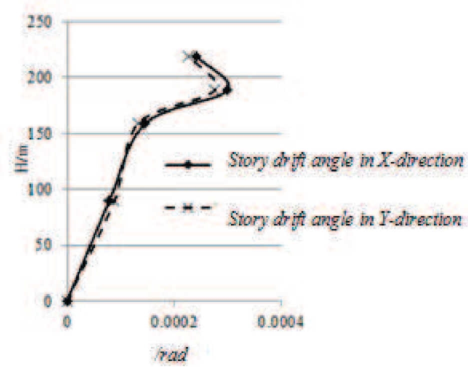

Figure 5: Story drift angle curve

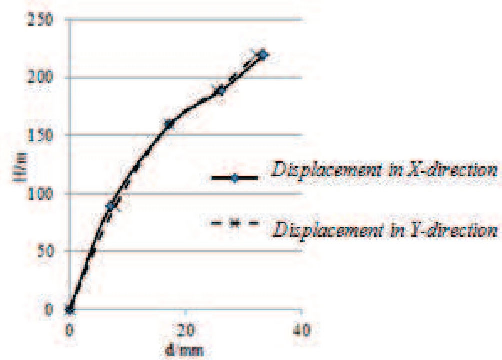

Figure 6: Lateral displacement curve

It can be seen from Figure 6 that the lateral displacement of the objective structure is mainly composed of shear and bending deformation. The shear deformation caused by the bending deformation of beams and columns is related to the inter-story shear force as well as the lateral stiffness. The shear force decreases on the upper structure leading to the shear deformation decreasing on the upper structure. Different from shear deformation, the bending deformation is caused by the axial deformation of the column, which increases on the upper structure.

5 Discussions

The first basic frequency of the structure is about 0.242Hz, and the fundamental natural period is about 4s. The adjacent translational frequencies in X and Y directions of the structures are close to each other, indicating that the distribution of mass and stiffness is approximate in the two directions. For super high-rise structures, both basic modes and higher modes are all important. The frequency of the fifth mode is 0.952Hz, which is still relatively small, indicating that the structure is sensitive to long-period components in the excitation. Shanghai is of soft ground which means the long-period components of the seismic waves will be amplified due to the characteristics of the soil layer, which will adversely affect the structure. Therefore, the modal parameters obtained through health monitoring system can be used as a reference for subsequent seismic analysis or structural optimization of the structure.

Through long-term monitoring, it is found that the natural frequency of the structure is relatively stable in using stage, but the damping ratio changes greatly. The damping ratio which represents the energy dissipation capacity of the structure is generally stable. However, the damping mechanism of super high-rise structure is complex, including structural damping and aerodynamic damping; leading to the identification of damping ratio would be different in different working conditions, with different ambient excitation or by different identification methods.

The displacement of the substructure is mainly composed of the shear deformation caused by bending deformation of beams and columns, while displacement of the superstructure is mainly composed of bending deformation caused by the axial deformation of the column. The arrangement of the outrigger truss makes the vertical stiffness change at the position of the strengthened layer causing the inter-story displacement angle decreases at the strengthened layer, which reduces the horizontal displacement of the building.

6 Conclusions

In this paper, the SHM system of a super tall building is established. Through the long-term monitoring, the natural frequency of the structure is relatively stable, but the damping ratio differs relatively large. The first basic frequency in the Y direction is 0.244Hz with the damping ratio of 2.487%, while in X direction, the first basic frequency is 0.251Hz with the damping ratio of 2.737%. The result shows that the first five modes are all below 1.0Hz. The displacement of the substructure is mainly composed of the shear deformation while displacement of the superstructure is mainly composed of bending deformation. The story drift decreases at the strengthened layer, which reduces the horizontal displacement of the building. The results in this work well reflect the dynamic response of the tested structure and provide a reference for future model updating and damage detection. In this SHM system, temperature was not measured, however, this may be an important factor that affect the accuracy of the obtained results. In the future study, this effect will be investigated.

Acknowledgments

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