Dynamic characteristics of a super high-rise building using a smart monitoring system

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ABSTRACT

A smart SHM system with 46 sensors installed at 15 floors of the 492 m high Shanghai World Financial Center (SWFC) in China was developed. The efficiency of the system was validated through the analysis of the dynamic characteristics of the tall building using the measured data from a 7.2 M earthquake event that occurred in the East China Sea. Subsequently, emphasis was placed on analyzing the dynamic characteristics of the SWFC under the action of earthquake in terms of time-history responses, identifications of frequency and damping ratio, amplitude spectral ratios, and mode shapes, based on the data observed from the system.

KEYWORDS: High-rise building, structural health monitoring, seismic, dynamic characteristics, system identification

1 INTRODUCTION

New generation of high-rise buildings is becoming higher than before [1, 2], such as the Burj Dubai tower (828 m in height) in United Arab Emirates, the Shanghai Tower (632 m in height) in China, the One World Trade Center (541.3 m in height) in USA. As of 2017, there are more than 50 high-rise buildings which reach a height of 350 m or more, and in the near future the height of high-rise building will reach 1000 m, i.e. the forthcoming Azerbaijan Tower (1050 m in height). These unprecedented high-rise buildings pose new challenges for the wind and earthquake engineering.

Full-scale structural health monitoring (SHM) systems that are used for surveillance, evaluation and assessment of the condition of existing and newly built structures began to flourish to address the challenges [3-8]. The SHM system has been widely installed in many buildings in order to validate structural performance and design principles and meet high demand for life safety and rapid reoccupation in seismic regions. Kijewski-Correa et al. [9] have comprehensively introduced a SmatSync system that is installed and operated in the world’s tallest building, Burj Dubai tower.
system embedded with a sensor and acquisition subsystem, a transmission subsystem, a data management and control subsystem, and a structural health evaluation subsystem, can be utilized for the real-time monitoring and structural identification of the high-rise tower. Particularly, the system allows to observe the actions of the wind and earthquake. Xia et al. [10] have proposed a method for calculating structural deformation by using real-time data observed from a long-term SHM system, and the method has been applied to a high-rise building, Canto Tower (also known as Guangzhou TV Tower, 600 m in height) in China. Li et al. [11] have presented some selected results observed from a SHM system by using 30 accelerometers installed at six floor levels of Taipei 101 tower (508 m in height) in Taiwan where earthquakes and strong typhoons frequently occur. The effects of wind and earthquake on the supertall building have been comprehensively investigated based on field measurements and numerical simulations. Moreover, the dynamic behaviors of the building have been determined. Apart from buildings, SHM systems are widely installed on long-span bridges [12-14]. Based on data measured from SHM systems, efforts have been made on the system identification [15-18], dynamic behavior [11, 19, 20], and condition assessment [21-23] of structures. These studies have advanced our understanding in deployment and application of a SHM system. Unfortunately, there are still several issues that need to be addressed in the future, including power management, energy scavenging, fault tolerate capability, and autonomous operations data management and storage, data mining and knowledge discovery, diagnostic methods, the analyzing and modeling of the bigdata observed from the SHM system utilized for decision making on maintenance and management [24, 25].

Despite the progress in deployment and application of a SHM system on buildings, as pointed out in a previous study [9], most published full-scale observations under service conditions are derived from midrise buildings associated largely with the Japanese database and few full-scale monitoring systems have been developed for super high-rise buildings. Moreover, few seismic events have been observed by a full-scale monitoring system installed in a high-rise building. In addition, dynamic characteristics of super high-rise buildings still remain unclear. This study aims to (1) develop an unique full-scale monitoring system that is installed in the 492 m-high Shanghai World Financial Center (SWFC) in China to observe the earthquake-induced dynamic characteristics of the super high-rise building, (2) to validate the developed system, (3) to analyze dynamic characteristics of the building, and (4) to obtain the effect of earthquake on the building.

Section 1 briefly overviewed SHM systems installed on high-rise buildings; Section 2 introduces the deployment of an unique seismic monitoring system for the 492 m-high SWFC in China; Section 3 validates the effectiveness of the full-scale monitoring system by using dynamic parameters identified from a seismic event; Section 4 analyzes the dynamic characteristics of the building under the action of a seismic event, with respect to time-history responses, identifications of frequency and damping ratio, amplitude spectral ratios, and mode shapes; Section 5 summarizes the major findings of the study.

2 DEPLOYMENT OF A FULL-SCALE MONITORING SYSTEM

2.1 Structural overview

SWFC (in Fig. 1) located in Shanghai, China, was completed in 2008 and crowned the China’s tallest building then (now ranked the 9th tallest building in the world), measuring 492 m in height above the ground. The structure is diagonally symmetrical with a square base plan of 57.95 m × 57.95 m (in Fig. 2), and correspondingly the aspect ratio (height to width) is 8.49. The SWFC is made up of structural-steel and reinforced concrete. The main body consists of three parallel structural systems (1) a mega-frame structure including mega-columns, mega-diagonals, and belt trusses; (2) a reinforced concrete and braced steel service core; (3) outrigger trusses. Details can be found in a previous study [26]. A large number of forces, such as wind loads and loads of self-weight, are carried down to the ground by the main body. The coordinated system of the building is marked in Fig. 2 for convenient use in the following.
Such a high-rise building is sensitive to outer excitations, such as wind and seismic load. Although Shanghai City is not exactly located in a seismic zone, it nears to the East China sea and the Yellow Sea where earthquake frequently takes place. Therefore, the effect of earthquake on Shanghai City should be well concerned, especially for the super high-rise building. To evaluate the performance of the high-rise building under the action of earthquake, a full-scale monitoring system was developed. Important data, such as force and response, was observed during the action of several earthquakes by using the monitoring system. Details are introduced in the following.

2.2 System deployment

2.2.1 Layout of sensors

Sensors for seismic measurements were installed according to the feature of the building. For example, the effect of vibration mode on the distribution of sensor was considered to avoid being installed on the joint node of vibration mode. In order to obtain the dynamic characteristics of the building under the action of earthquake, measuring points were selected on the ground, the aforementioned steel service core, and outside of the steel service core. There were 46 sensors in total.
including 25 three-direction accelerometers, 12 two-direction accelerometers, and 9 three-direction velocimeters, installed in the 15 floors of B3, 1F, 6F, 18F, 30F, 42F, 54F, 66F, 78F, 90F, 91F, 93F, 96F, 98F and 101F, where ‘B’ and ‘F’ denote the words of ‘basement’ and ‘floor’, respectively. All the sensors were linked together by 126 electronic lines. There were two supervision centers located in 18F and 90F, respectively. The layout of the measuring points and lines is depicted in Fig. 3.

2.2.2 monitoring system

The full-scale monitoring system of SWFC consists of 4 subsystems: (1) data acquisition system; (2) data transmission system; (3) GPS time-control system; and (4) data center, as depicted in Figure 4. In the data acquisition system, the dynamic response of the building was sampled by a TDE-324QI data acquisition instrument through installed accelerometer sensors, including BPS-100 FBV accelerometers, TDV-33S accelerometers, and TDA-33M accelerometers. The sampling frequency of the TDE-324QI varied from 1 to 500 Hz. In the present study, the sampling frequency was set as 100 Hz. The data transmission system mainly consists of switchboards, bridges, and SHD fiber-optics (Fig. 4). The data transmission systems installed in the aforementioned two supervision centers in F90 and F18, were linked together by electronic cables. By introducing a telephone bridge Mikrotik RB2011ii, the observed data in F90, was transferred to F18. Then, all the obtained data was finally transferred to data center by the GPS time-control system. A smart software installed in the computer in the data center was utilized to display, monitor and analyze the observed data, which is convenient for users to evaluate the condition of the building.
3 VALIDATION OF THE FULL-SCALE MONITORING SYSTEM

The power spectra in X and Y directions are obtained according to time-history responses obtained from the monitoring system, as shown in Fig. 5. The damping ratios in X and Y directions identified by a RDT method [27, 28] using the time-history response of SWFC observed from the seismic monitoring system are obtained, as shown in Table 1. It is noteworthy that despite the magnitudes of the spectra in X and Y directions are different, the corresponding frequencies are substantially the same. The fundamental frequencies in the two directions are in close agreement (0.1511 and 0.1526 in X and Y directions, respectively), suggesting that the stiffness in X direction is close to that in Y direction. This is identical to the finding in a previous study [26]. Moreover, the fundamental frequencies obtained from the full-scale monitoring system are almost the same with those obtained from a separate wind monitoring system reported in previous studies [29, 30] (in Fig. 6). The differences of the obtained fundamental frequencies observed from the two separate monitoring events are within 0.3 %. In addition, Table 1 shows that the damping ratios identified in the present study are close to those identified from a separate wind monitoring and close to those obtained in previous studies [15, 31]. The results indicate that the dynamic parameters of SWFC identified from the full-scale monitoring system are accurate and the developed monitoring system is effective and valid. Therefore, the observed seismic data can be utilized for further analysis. The effect of the 7.2 M earthquake in the East China Sea on the building will be analyzed in the following section.
Figure 5: Power spectra of the time-history response in F101 of SWFC: (a) in X (East-West) direction; (b) in Y (North-South) direction

Figure 6: Power spectra of the time-history response of SWFC (F101) under the action of wind: (a) in X (East-West) direction; (b) in Y (North-South) direction

![Power Spectra Diagram](image)

Table 1 Comparisons of dynamic parameters of SWFC

<table>
<thead>
<tr>
<th></th>
<th>Fundamental frequency (Hz)</th>
<th>Damping ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X direction</td>
<td>Y direction</td>
<td>X direction</td>
</tr>
<tr>
<td>In the present study</td>
<td>0.1511</td>
<td>0.1526</td>
</tr>
<tr>
<td>From a separate wind monitoring system</td>
<td>0.1507</td>
<td>0.1526</td>
</tr>
<tr>
<td>In a previous study [15]</td>
<td>0.1554</td>
<td>0.1579</td>
</tr>
<tr>
<td>In a previous study [31]</td>
<td>0.1538</td>
<td>0.1563</td>
</tr>
</tbody>
</table>

4 DYNAMIC CHARACTERISTICS OF SWFC

4.1 Earthquake-induced response

The time-history responses at different floors of SWFC under the action of the 7.2 M earthquake in East China Sea were observed by the full-scale monitoring system. For the purpose of simplicity, the responses in three floors (low level, mid-height, and high level) are selected for analysis and they are presented in Fig. 7. It shows that the magnitudes of the time-history responses increase with the height of SWFC and the responses in different directions are comparable, confirming that the stiffness of SWFC in X direction is close to that in Y direction. Based on the time-history responses, the envelop curves of acceleration and displacement in X and Y directions are obtained, as shown in Fig. 8. It indicates that, along the height of SWFC, both the peak values of acceleration and displacement increase first from F1 to F42 and then decrease from F42 to F80. It is noteworthy that, the peak values at upper levels, are larger than those at lower levels, and the maximum values take place in the top floor (F101). The maximum peak values of acceleration and displacement are 6.57 cm/s² and 0.071 m, respectively, and the maximum dynamic magnification factors (peak values in F101/ peak values in F1) are around 13. The results suggest that the high-rise building is sensitive to dynamic excitations even though the ground motion is small. The upper floors of the building are significantly amplified under the action of earthquake, which should be well considered in the design of high-rise buildings. Fig. 8 also indicates that the envelope curves are smooth without inflexions, suggesting that the earthquake-induced deformation of the building is in an elastic stage. In addition, the trends of acceleration and displacement in different directions are similar.
Figure 7: Time-history responses of SWFC: (a) in X (East-West) direction; (b) in Y (North-South) direction

Figure 8: Envelope curves: (a) acceleration; (b) displacement
4.2 Amplitude spectral ratio

The power spectra of SWFC in different floors are obtained (in Fig. 9) by using a Fast Fourier Transform method based on the earthquake-induced responses. Fig. 9 shows that considerable peaks occur in X and Y directions, and the amplitudes of the peak values tend to increase with the height of the building. From the peaks, the natural frequencies of sway modes in X and Y directions are obtained using a peak-picking method. Comparisons of the natural frequencies obtained using the method and those identified by the frequency domain decomposition (FDD) [32,33] method are presented in Tab. 2. It indicates that the frequencies of different modes in X direction are comparable with those in Y direction. Moreover, the natural frequencies identified by using the FDD method are substantially close to those identified using a peak-picking method, and the maximum differences are within 5%. Using the FDD method, the damping ratios of the first mode are around 0.68% and 0.71%, respectively, which are close to those observed from a RDT method. The results suggest that the FDD method is valid and can be utilized for the identification of dynamic parameters.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1511</td>
<td>3.0%</td>
</tr>
<tr>
<td>2</td>
<td>0.5508</td>
<td>0.3%</td>
</tr>
<tr>
<td>3</td>
<td>0.9827</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

In Fig. 9, the amplitude spectral ratios of the first three modes in X and Y directions are determined by taking the peak values of the corresponding modes in F1 as 1, as given in Fig. 10. It is observed that the amplitude spectral ratios of the fundamental sway modes in X and Y directions increase with the height of the building; However, the ratios of the second and third modes do not always increase along the height of the building. Furthermore, the maximum amplitude spectral ratios of the first three modes both in X and Y directions take place at the top floor (F101) and the values at this floor are much larger than those at other floors. This may be ascribed to the smaller floor area and rigidity of the floor. This confirms that designers should pay much attention to the upper floor in the design of high-rise buildings.
Figure 10: Normalized amplitude spectral ratios along the height of SWFC

4.3 Mode shape

The mode shape of the building can be obtained from the earthquake-induced responses observed in different floors (sensors installed in 15 floors, Fig. 3) of SWFC by using the FDD method. Selecting the first three modes in X and Y directions for analysis, the mode shapes of the first three mode shapes are obtained in Fig. 11.
In Fig. 11, records at the base floor were considered as the reference for the identification of the mode shapes. The mode shapes at the top floor (F101) are normalized as 1 whereas those at the base floor are normalized as 0. It is observed that the first mode shapes in X and Y directions increase with the height of the building and they present notable nonlinear characteristics. This is contrary to a linear assumption for the first sway mode shape adopted in some codes and standards as well as in measurements of aerodynamics force and responses of high-rise structures [34, 35], which may lead to considerable discrepancies in the estimation of the equivalent static wind loads and responses. For the second and third sway mode shapes, they do not always increase with the height of the building, and they present much stronger nonlinearities than the first sway mode shapes. Furthermore, the first three sway mode shapes in X direction are similar with those in Y direction.

5 CONCLUSIONS

The study presents a full-scale monitoring system for the 492 m-height high-rise SWFC. The efficiency of the developed system has been validated based on the full-field data observed from earthquake-induced responses of SWFC. The dynamic characteristics of SWFC have been analyzed. The main findings of the study are summarized as follows.

(i) The dynamic characteristics of SWFC identified from earthquake-induced responses observed from a full-scale monitoring system, i.e. fundamental sway frequencies and damping ratios in both X and Y directions, are in close agreement with those obtained in previous studies, indicating the developed monitoring system is valid and can be utilized for the measurement of the earthquake-induced response of SWFC.

(ii) The FDD method was validated and utilized to estimate the dynamic characteristics of SWFC. Both the identified frequencies and damping ratios of SWFC in X direction are close to those in Y direction, indicating that the stiffnesses in the two directions are close.

(iii) The building is sensitive to earthquake excitations, and the upper floors of the building are significantly amplified under the action of earthquake, which should be well considered in the design of high-rise buildings. Moreover, the envelope curves of accelerations and deformations are smooth without inflections, suggesting the building is in an elastic stage under the action of the earthquake.
The first sway mode shapes in X and Y directions present notable nonlinear characteristics and are contrary to a linear assumption adopted in codes and standards as well as measurements of aerodynamic forces and responses of high-rise buildings. The identified mode shapes can be utilized for analyzing the structural dynamics of the building.

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