Smart Structures and Systems, *Vol. 15, No. 4 (2015) 1019-1039*
DOI: http://dx.doi.org/10.12989/sss.2015.15.4.1019

Development and application of construction monitoring system for Shanghai Tower

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(Received September 1, 2013, Revised February 13, 2014, Accepted March 10, 2014)

Abstract. Shanghai Tower is a composite structure building with a height of 632 m. In order to verify the structural properties and behaviors in construction and operation, a structural health monitoring project was conducted by Tongji University. The monitoring system includes sensor system, data acquisition system and a monitoring software system. Focusing on the health monitoring in construction, this paper introduced the monitoring parameters in construction, the data acquisition strategy and an integration structural health monitoring (SHM) software. The integration software - Structural Monitoring/ Analysis/ Evaluation System (SMAE) is designed based on integration and modular design idea, which includes on-line data acquisition, finite elements and dynamic property analysis functions. With the integration and modular design idea, this SHM system can realize the data exchange and results comparison from on-site monitoring and FEM effectively. The analysis of the monitoring data collected during the process of construction shows that the system works stably, realize data acquirement and analysis effectively, and also provides measured basis for understanding the structural state of the construction. Meanwhile, references are provided for the future automates construction monitoring and implementation of high-rise building structures.

Keywords: high-rise building; construction monitoring; software integration; finite element method (FEM); dynamic property; deformation; strain

1. Introduction

Structural Health Monitoring (SHM) was initially used in the civil engineering infrastructure such as bridges and dams (Aktan *et al*. 1998, Ko and Ni 2005). With the development of high-rise buildings, SHM technical has been gradually applied in large and complex structures. Typical application of SHM in high-rise buildings include John Hancock Tower (USA) (Durgin *et al.* 1990), Burj Khalifa (UAE) (Tracy *et al.*2012, Baker *et al*. 2007),Guangzhou New TV Tower (China) (Ni *et al.* 2009, Xia *et al.* 2011)) and Shanghai World Finance Center(China) (Shi *et al*. 2011). It has reported that more than 150 buildings in California, U.S.A., more than 100 buildings in Japan, and more than 40 buildings in Taiwan have been instrumented with monitoring systems (Huang and Anthony2001, Lin *et al.* 2005, Huang 2006).

However, most structural health monitoring projects focuse on the existing buildings, rarely on

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http://www.techno-press.org/?journal=sss&subpage=8 ISSN: 1738-1584 (Print), 1738-1991 (Online)

their construction process. For the high-rise buildings, health monitoring in construction stage may be much more important. First, structural design generally targeted to completed structures with careful examination through FE analysis and experiments, while the actual structure may go through many construction stages until completion. Second, the structure is a time-varying system throughout the whole construction process with which materials, geometry and boundary conditions are changing along with the construction process (Xia *et al.* 2011). Structural force and deformation are the cumulative effect as results of each construction step. For multi-story buildings, this difference may not impact a lot, while the structural construction process of high-rise buildings is rather complex with strict control requirements. Any construction deviation from the design or structural damage during the construction process would lead to large structural internal force, even destruction of the structure (Zhao *et al.* 2011). Therefore, it is necessary to implement construction health monitoring.

Meanwhile, there are other issues worth concerning. In the field of SHM, there are many researches on sensor and structural damage identification theory and rarely on the integration on SHM system. In traditional SHM system, the monitoring system can only collect data from the sensor network and perform some simple data processing. The work of analyzes and assessment has to be done manually by monitoring personnel with using different independent analysis tools which may generate great inconvenience in analyzes and comparison. When the structural scale became more and more large, traditional SHM cannot satisfy the requirement. In addition, the structure of construction process belongs to a time-varying system. The present monitoring systems cannot carry out finite elements analysis to compare the results of FEM and real-time measurement. All of the above problems are the main causes leading to the situation of inefficiency, resources waste of the monitoring system.

To solve these problems, a comprehensive, integrated SHM system named structural monitoring/analysis/evaluation software (SMAE) was designed jointly by Tongji University, Hong Kong Polytechnic University and Tongji Architectural Design Institute, targeted against health monitoring for the construction process and service period of Shanghai Tower. The structure, as shown in Fig. 1, is located in the Z3-1, Z3-2 district of Pudong new area in Shanghai LuJiazui financial center. It is a high-rise building frame-core structure with a total height of 632 m. The structure mainly contains a high-rise building with a height of 632m, a seven-story annex and a five-story basement. Its main characteristic is embodied in the shape of a revolving rising statue. The high-rise building comprises a main tower (580 m) and a high tower crown (52 m).The main tower is composed of a steel reinforced inner tube (core) and a steel reinforced mega frame structure, and divided into eight zones by eight rotundas and the tower crown. This hyperbolic shape makes the structure vital and attractive in aesthetics while complex in mechanics. Therefore, it is necessary to monitor the real-time health statue of the structure during its construction process and service period. This paper mainly focuses on the technological innovation issues in developing and implementing the in-construction part of SHM system, and presents preliminary comparison results of monitoring and FEM obtained during construction.

2. Designing the in-construction SHM system

The primary goal of the SHM system is to acquire data, covert it into information and deliver that information on-time in regard to better project performance. In construction health monitoring, we focus on construction as the main entities information loop, which includes the on-site structural health monitoring, finite element simulation of construction and construction schedule updating, as shown in Fig. 2. The main objects of designing this system are: (1) to monitor the structural health conditions; (2) to verify design assumptions and parameters and make recommendations for the construction scheme; and (3) to provide information for the plans of inspection and maintenance activities.

For the purpose to obtain a full view of the structural health in construction, static and dynamic monitoring data will be executed in the in-construction SHM system. The Modal properties that constitute the basic parameters for vibration-based damage detection will be identified from ambient vibration responses acquired by the accelerometers. The strain in member is very sensitive and will be obtained directly from the vibration stain gauge. The vertical displacement of the tower reflects the accuracy of the construction plan, and will also be obtained through analyzing the monitoring data from total station. The detail information of the monitoring parameters is presented in a later section of this article.

In structural health monitoring, the monitoring data acquisition and storage method has a significant effect on the SHM system. The data acquisition software is usually offered by the equipment supplier. The methods of outputting process data are different depend on the data acquisition software. Considering the huge data volume, it’s hard to coordinate data storage format from different sensor with the software offered by the equipment supplier. Therefore, the data acquisition software with a standard data port is essential to redesign based on the data characteristics and system requirement to realize the data acquisition from different sensor. In the data management, two databases are equipped. One is original database responsible for the raw data storage. And the other is publication database to realize the data publication. With the arrangement, the data security is guaranteed and benefits follow-up optimization to reduce redundant and improve query efficiency.

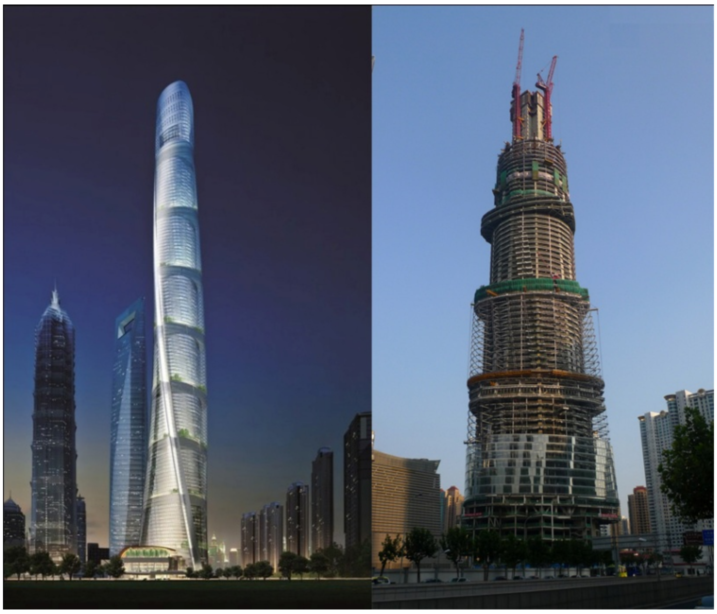


Fig. 1 Structural system of Shanghai Tower

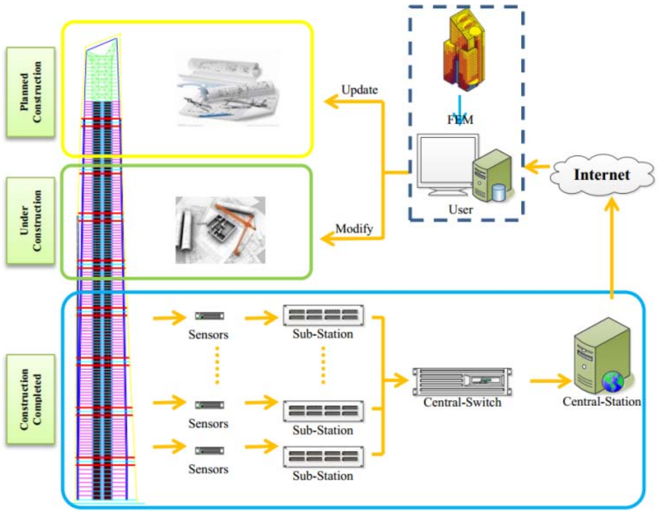


Fig. 2 In-construction monitoring loop

For data query system, the first consideration is easy to use and maintenance. Based on browser/server (B/S) to implementation monitoring data query is one of the best solutions. It has the following advantages: (1) the client-browser is generic and can be used in different working platform; (2) various interactive queries and data display can be realized by the mature development technology of website; (3) complex data-processing operation is running on the server machine with only return the results to client which can reduce the data transfer volume and improve the data access efficiencies; (4) the provide data-port can be used to exchange data with further analysis monitoring software.

All data will be integrated in the SHM system for structural condition assessment. As the integrated monitoring system enables the measurement of acceleration and strain in this project, a more reliable structural health evaluation of Shanghai Tower can be obtained based on multilevel data fusion through combining the global modal properties and the local stain information. At present, most of SHM system doesn't contain the finite element modeling and analysis function. However, as many damage detection methods need a precise finite element model of the structure in healthy state as a baseline. Such a baseline model will be established through model updating by using the measured modal properties and strain in member at various construction stages, and is therefore referred to as a dynamically calibrated baseline model. It's necessary to integrate the finite element modeling module into the in-construction health monitoring system. In the SHM system of Shanghai Tower, a FEM module is integrated to achieve the function of FEM modeling, model calibration and results exchange.

3. Monitoring scheme in construction

The selection of structural parameters to be monitored in construction is the foremost critical issue. This affects the system efficiency and the potential to detect the hazard. Too few parameters may not be enough to represent the behavior of the structure in construction. Too many parameters may cause a high cost and difficulty in data storage. Hence, the parameters of Shanghai Tower monitored were list below with explanation.

3.1 Dynamic property

The structural dynamic property usually reflects the structural property. The structural damages would inevitably lead to changes in the parameters of structural performance, such as stiffness, frequency, damp and weight. At present, structural design is difficult to accurately simulate the loads in construction stage. The real-time monitoring of structure dynamic characteristics can quickly detect whether the construction status is accurate, which should be used for structural damage diagnosis and early warning.

Thirty-six uni-axial accelerometers (Lance LC0132T) were employed for vibration measurement. The frequency range is DC-500 Hz. The amplitude range is ±5 g and the sensitivity 49.67 V/g. The sampling frequency is 20 Hz during construction monitoring and will change into 100Hz on operation, a value that is imposed by filters of the acquisition equipment and which is much higher than that required for this structure, as the most relevant natural frequencies of the structure are below 5 Hz.

Considering the availability of space and access to the data acquisition units, accelerometers are installed on the core-tube at each strengthened story. In the B5 and 7th floor, each monitoring section has two uni-axial accelerometers, on for horizontal vibration along the North direction and the other for the East. At the other 7 monitoring sections, each section has four accelerometers. After completing construction, all of monitoring section will be equipped four uni-axial accelerometers. The arrangement of accelerometers is shown in Fig. 3.

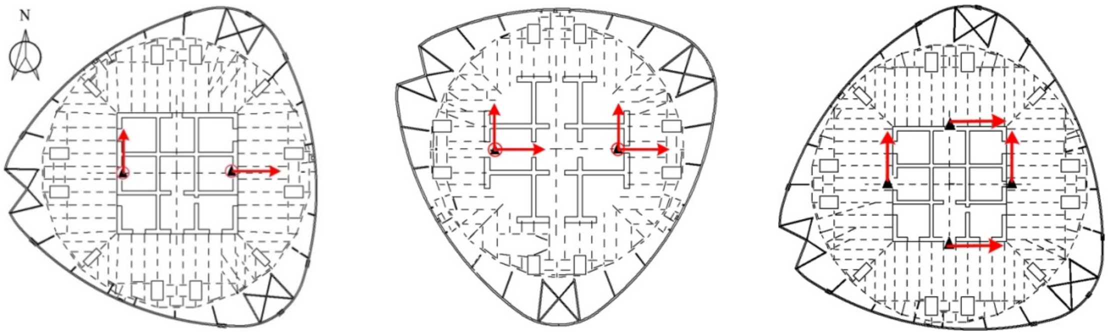
3.2 Strain of the components

Structural design is generally focused on analysis of the overall structure. High-rise structure is constructed layer by layer without considering the impact of the construction process, the vertical loads of each layer is applied to the structural model. In this case, the force situation of structural components differs a lot from once loading. Meanwhile, the concrete creep and shrinkage effect have a great impact on structural force. Especially for the high-rise building structure, creep and shrinkage effect could cause significant redistribution of internal forces. Therefore, the main structural components also require force monitoring during the construction process.

Vibrating wire strain gauge is used to measure the strain. It is made up of a steel wire and two end flanges. The wire is held in tension between two end flanges. When loading of the concrete structure changes the distance between the two flanges, it may result in a change in the tension of the wire. The strain is calculated through measuring the frequency changes of vibration.

Strain wire gauges were installed on strengthened storey and send signals to the substation of each strengthened storey. Fig. 4 shows the positions of the strain gauges in one strengthened storey. Each monitoring point equipped two types of strain gauge to monitoring the strain in steel and concrete, respectively.

Strain monitoring of the steel applies the BGK-4200 surface-type, which is welded on the surface of steel and covered with steel cap to avoid the influence of the concrete (Fig. 5(a)). The BGK-4200 embedded strain gauge is applied to concrete. To ensure the strain gauge forced together with the concrete, the strain gauges are embedded in the concrete precast blocks in advance, then pouring the precast blocks into the concrete structure (Fig. 5(b)). The embedded gauges were attached to rebar by wire to avoid movement although concrete was poured. The initial strain of the concrete was taken after 1 week to make sure the temperature and strain reading stable. Although all the gauges were inspected and tested using portable readout box, 10% sensors don't work due to the construction activities effect.



during congstruction	during congstruction	after structure compeltion
(a) B5 and 7th floor	(b) 21th, 37th, 51th, 67 th, 84th, 100th and 117th floor	(c) All monitoring section

Fig. 3 Arrangement of acclerometers in construction

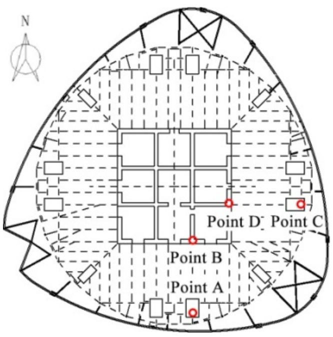
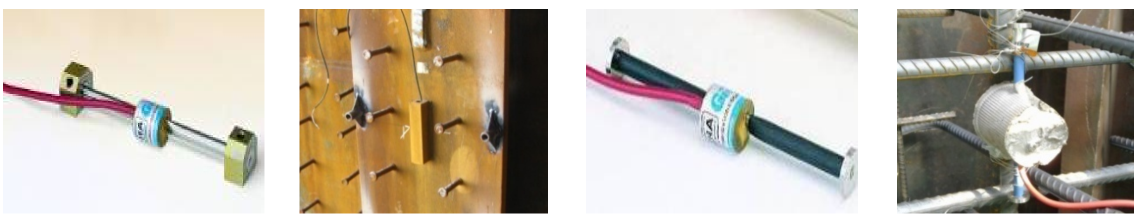


Fig. 4 Arrangement of strain monitoring point



(a) vibration strain gauss on steel (b) vibration strain gauss in concrete

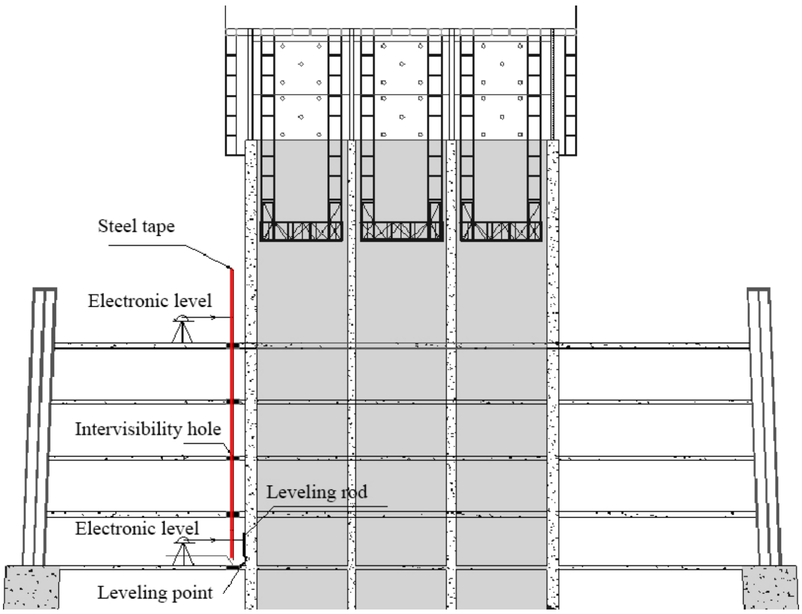
Fig. 5 vibration strain gauss

3.3 Vertical deformation of the floor

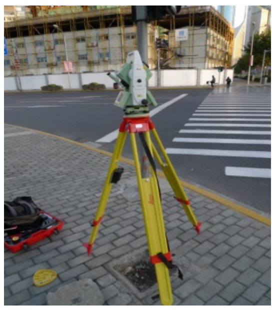
In high-rise buildings, the vertical loads are very huge and may lead to large vertical deformation in the structure. Shanghai Tower is one of the world's tallest buildings and has a long construction period. In the previous study, the author's team found the vertical deformation of Shanghai tower is significant effect by the time-varying effect of concrete (Lu *et al.* 2013). Therefore, it is necessary to trace and simulate the construction process and monitor the vertical deformation in construction.

Leveling control points (+0.500 m) were used as the starting point of elevation transmission in the vertical deformation measurement of Shanghai Tower. The 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. Deformation observation points of the main building were arranged in the super columns and core-tube walls of the monitoring section. When the building construction comes to a certain height, full use of the hanging steel tapes for elevation transmission might bring about inevitable errors. At this point, the total station instrument should be used for transmitting the elevation from the ground to the control points of certain floors (joint measurement points). The distance from the total station to observation point should be less than 400 m, vertical observation angle should be less than 15 degree.

The measuring method is showed in Fig. 6. Elevation measurements should be initiated when the slabs of monitoring section inside and outside the core-tube get completed, and then save the measurement data to database for further analysis.



(a) The position of elevation measure points



(b) Total station

(c) Reflective prism

Fig. 6 Vertical deformation measurement method and equipment

4. Data acquisition system

In terms of data acquisition frequency, the SHM system has three different types: dynamic real-times, static real-times and condition trigged. For accelerator and wind filed monitoring, the dynamic real-time monitoring will be used. For structural vertical displacement and vertical inclination which are less time-sensitive, static real-time monitoring should be adopted. When earthquake and typhoon are encountered, data acquisition process is triggered only if earthquake and wind vibration is strong enough. This strategy of data acquisition method is used in the data acquiring system.

Targeting to the special requirements of the data acquisition, the following third components of data acquisition system are specially designed. (1) Three-layer distributed system was used in the data acquisition system. The entire system is configured as Sensors/Substation/Server. Sensors are connected to the data acquisition device directly. The data acquisition devices are connected to the central server with Ethernet cable, as shown in Fig. 7. (2) For real-time data acquisition in distributed system, the clock synchronization is a key issue in data acquisition control system. The crystal oscillator is built-in collecting unit to solve this problem. By sending broadcast in the system, the time can be calibrated to eliminate the time difference. Using this method, the time error can be reduce at the level of milliseconds. (3) Due to the number of sensors, the server became too burdened with tasks in receiving, processing and saving data from multiple channels.

Thus, data transmission should balance the transmission rate and transfer bandwidth. The data acquisition device has 128Kb data storage space. It can story the real-time data package into the acquisition device first. Then, the control system uses the time-division multiplexing (TDM) technique to write the data package into service. In this method, the burdened of server and system overhead are reduced.

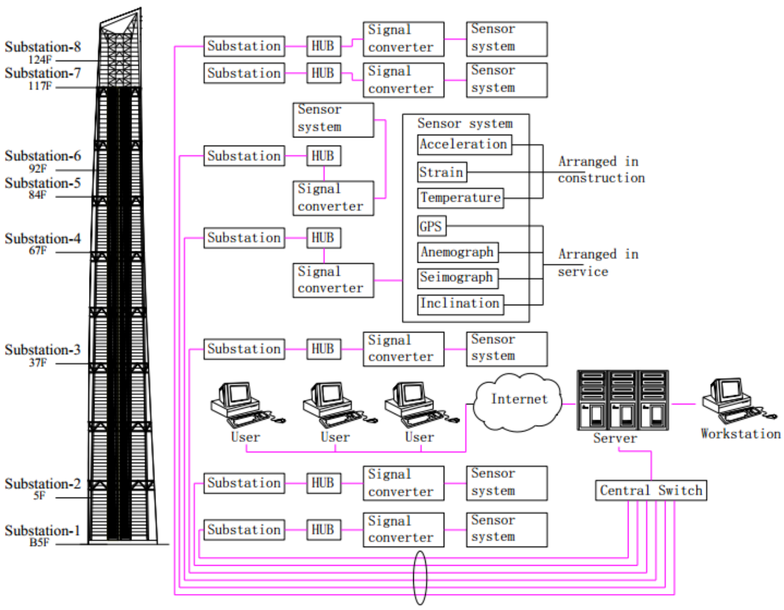


Fig. 7 Data acquisition system architecture

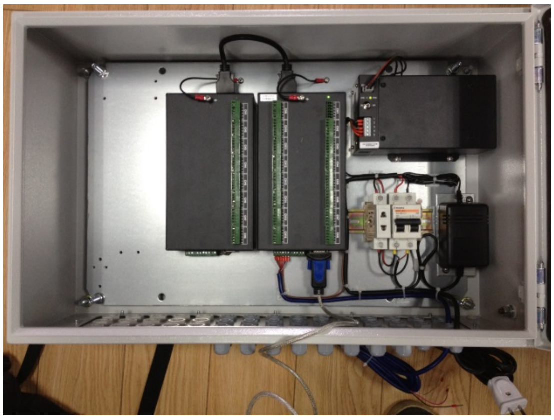


Fig. 8 Substation

5. Monitoring software system

An innovative integration SHM software system named structural analysis/monitor evaluation system (SMAE) was proposed and applied on this building. This software consists of three main components. Each of them can be used as a stand-alone system, but the combination significantly raises the reliability of the system as a whole, as shown in Fig. 9. With the combination of sensory system, the dataflow and functions of this integration SHM system can be illustrated as shown in Fig. 10. The detail information of the system components will be described in the following section.

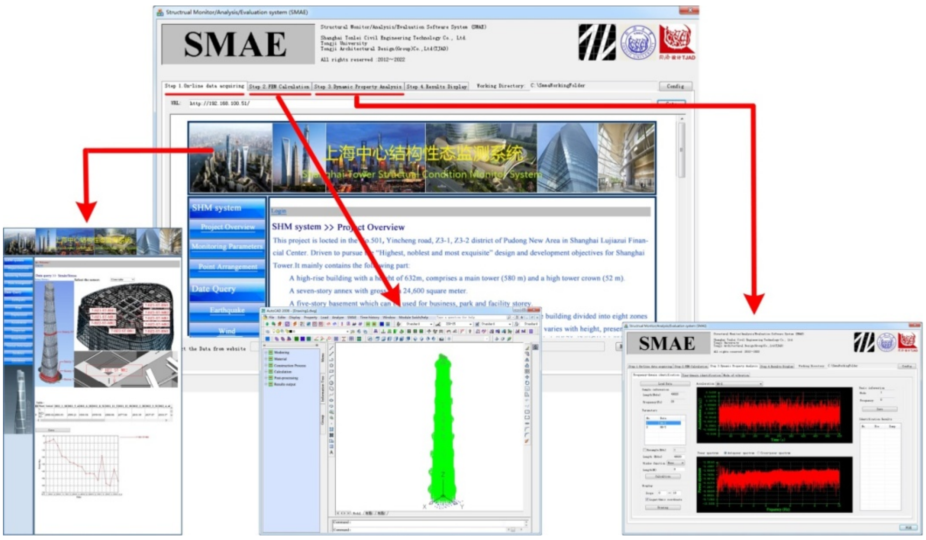


Fig. 9 The software of SMAE

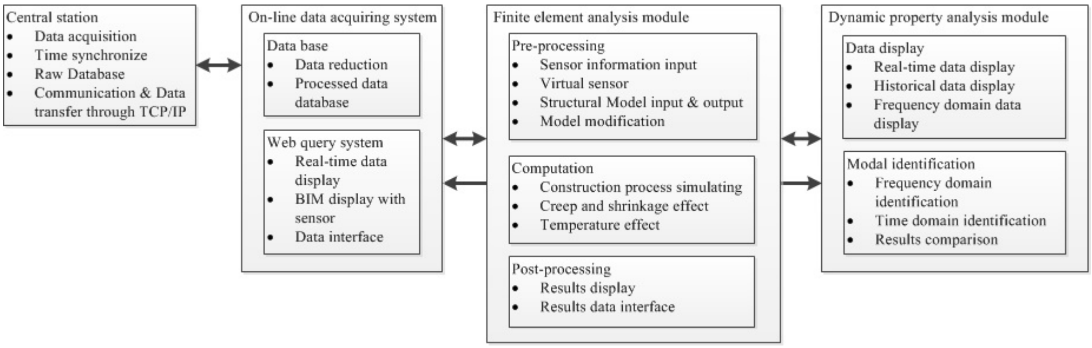
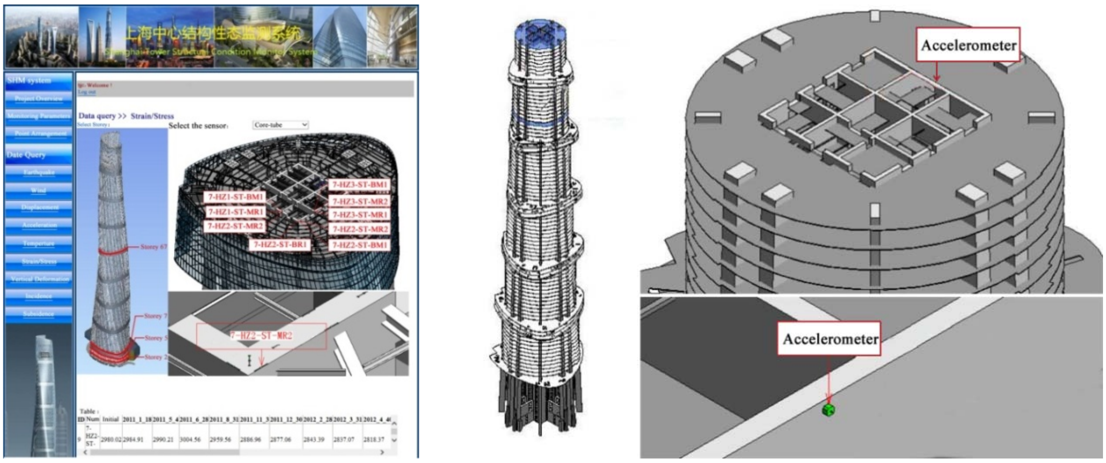


Fig. 10 The workflow and funtion of SMAE



(a) Cilent (b) BIM tool

Fig. 11 Cilent and BIM tool

5.1 Data management system

5.1.1 Remote data publication system

Database is responsible for the remaining data processing and management. It is created and managed by Microsoft SQL server 2005, a large-scale relation database system. The database consists of an original database and a publication database. The former stores all data directly from the substation without optimization. Due to the continuous flow of incoming raw data, the data volume is rather huge. In order to reduce the redundant data, the publication database adopts a series of optimizing technique to save the data. The raw database only stories the lasted three months data and will be cleared in period.

5.1.2 Client and BIM tool

Client is a website which can be visited via internet connection. All of the monitoring data can get through it. The website works as the control center, which can query and display data. Fig. 9 shows the interface of the website. As the technique of active server pages (ASP) was used in it, the website contains the building information model (BIM) and can display the sensor in it according the user's requirement, as showed in Fig. 11.

BIM tool provides a better experience for users to retrieve the sensor directly instead of its ID. All of sensors were performed in the 3D model. The main motivation for developing the BIM tool was to obtain full controlling over the data structure in the 3D model. The most important feature of the BIM tool is the 3D model, which presents the 3D model at a defined time point during the building process.

5.2 FEM system

The finite element analysis module was designed based on the development platform of AutoCAD with the utilization of Object ARX and Visual C++. Fig. 12 shows the main interface of the software. The following issues were considered in implementing this subsystem. First, the time-varying effect in material and structure is considered. Time-varying effect in concrete is significant, especially in concrete and composite structural systems (Chowdhary and Sharma 2011). And that the structure is a time-varying system related to the processing of construction. In order to verify the accuracy of construction plan, the finite element model has been developed with considering the concrete time-varying effect model and construction processing simulation. Second, due to the huge number of sensors were installed on the project, it is difficult to swiftly and precisely position the location of sensor in finite element model and then correctly get the results. For that case, we introduced the BIM technique into the FEM subsystem. The detail information will be described in the following section.

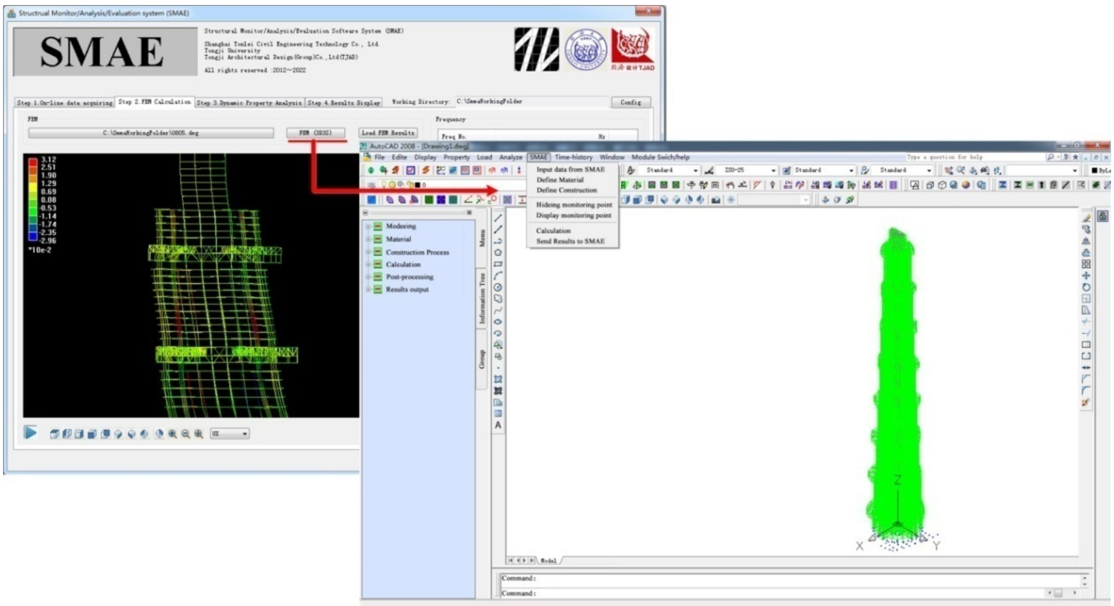
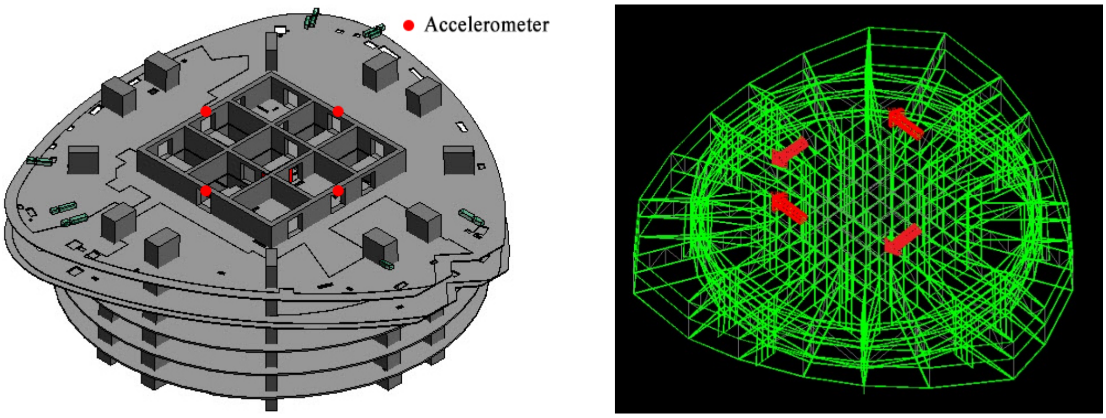


Fig. 12 The interface of FEM module

5.2.1 Virtual sensor

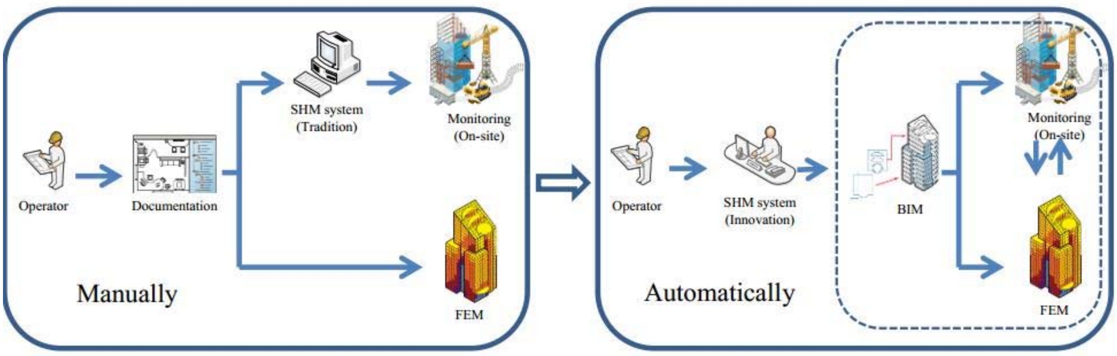
It’s difficult to identify the abnormal of structure only by analyzing the sensor’s signal without comparing to the results of finite element model. A more reliable structural health evaluation is based on multilevel data fusion through combining the sensor’s data and the finite element results. As the integration monitoring system enables the FEM modeling, it is possible for the operator to assess the condition of structure in construction in real-time.

Traditionally, if a particular sensor’s data needs to be checked, the following steps should be followed. First, index the sensor’s ID from documentation, and then input it in SHM system to get the monitoring data. Then, find the FEM results corresponding to the sensor’s through the sensor’s monitoring parameter and location information (Fig. 14(a)). These steps are verbose and inconvenient for the operator to evaluate the condition of structure in time.



(a) Accelerometer in BIM (b) Accelerometer in FEM

Fig. 13 Virtual Sensor



(a) Traditional SHM system (b) Innovational SHM system

Fig. 14 Comparison of tradition and innovation SHM system

For the purpose of simplifying these steps, we introduce the virtual sensor into the FEM module which combines the BIM and FEM technical. With the virtual sensor's help, we can directly get the sensor's monitoring data and can compare it with the FEM results conveniently. Virtual sensors are integrated in the structural finite element model with no need to model it in FEM modeling, as shown in Fig. 13. All of the sensors are automaticly modeled in the FEM module by importing the sensor's information from the BIM model. Once a particular sensor's data is needed to index, the SHM system will automatically index the FEM results corresponding to sensor, then display the comparison of monitoring data and the FEM results (Fig. 14(b)).

5.2.2 Time-varying effect

In order to verify the validity of construction process, an accuracy FEM model is necessary. The construction process of high-rise building belongs to the area of slow time-varying structural mechanics, which requires two points to be concerned. First, the redistribution of internal force is significant along with the construction process owe to shrinkage and creep effect (Zhao *et al*. 2011); Second, structural changes in shape with the construction process. In order to accurately simulate the construction process of Shanghai Tower, the numerical simulation has been developed with considering the concrete time-varying effect and construction process.

(1) Creep and shrinkage of concrete

Time varying effect in concrete is closely related with loading age, ambient relative humidity, scantlings, reinforced constraint effects and other factors. To make an analysis of long-term effect of steel-reinforced concrete structures, the author's research team has adopted the method of using master-slave constraint to deduce substructure element model of composite member in the FEM sub-system (Lu *et al*. 2013). The method effectively solves the problem of the concrete shrinkage and creep of the composite members.

(2) Construction Process

The construction process can be considered as a project of slow time-varying structural mechanics. Therefore, the process can be divided into a series of construction phases, each phase treated with a finite element solution to get the structural deformation conditions of various phases. According to the construction plan, the whole construction process should be divided into 50 construction stage. The duration of each construction phase refers to the Construction Schedule of Shanghai Tower. All members in the basement shall be constructed simultaneously, whereas the ground portion starts in the sequence of core tube, outer frame to tube floor. With the progress of construction, the construction of mega-frame is left behind core-tube 9/15 floors and floor left behind column 4/7 floors. The installation of curtain wall begins when the structure constructs to 1/3 height. The curtain wall is considered as an external load applied on the frame. Meanwhile, in order to consider the effect of construction load, the construction is applied on the structural as live load (1kN/m^2) until the roof atop is sealed.

According to the construction schedule mentioned above, the steps of finite element simulation are as follows: 1) Establish the finite element model of overall structure once based on the design information; 2) define the construction loads of various phases, and also define the material parameters according to the material time-varying model; 3) based on the actual construction progress, activate the unit, load and boundary conditions of corresponding phases subsequently, then achieve the phase construction model and solve it.

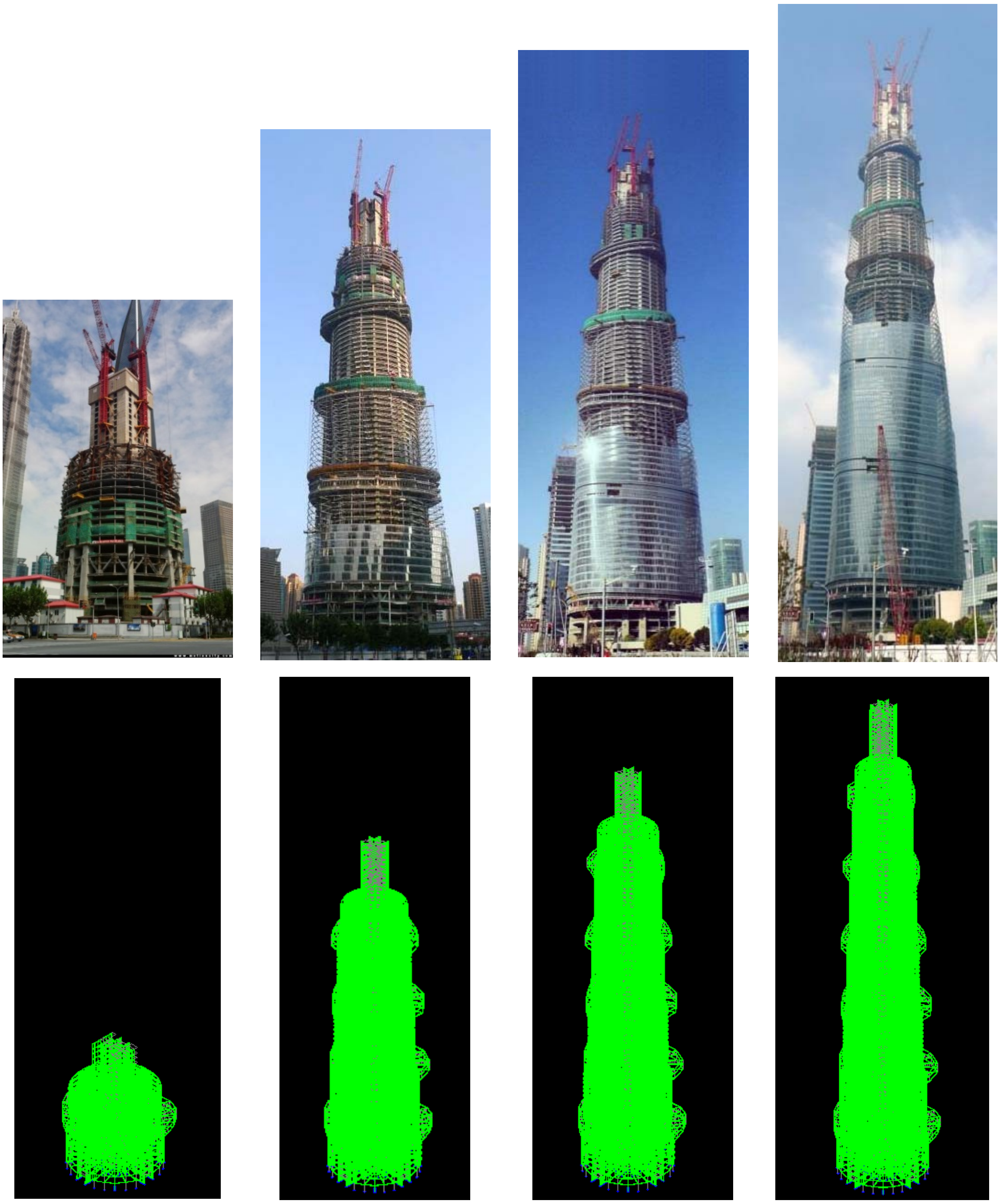


Fig. 15 Photos of the tower and the corresponding FE models

(a) Acceleration query in SAME (b) Identification of natural frequency

Fig. 16 Interface of dynamic property analysis module

5.3 Dynamic property analysis module

Currently, researchers have proposed a variety of model parameter identification methods with their respective advantages and disadvantages based on output response. To ensure the accuracy of identification, the dynamic characteristics identification and analysis module have applied two identification methods, i.e., the Peak-pick method (PPK) (Bendat and Piersol 1993) based on frequency domain and the stochastic subspace method (SSI) (Overschee and De Moor, 1993) based on time domain. The dynamic property identification module has been developed based on the above identification methods.

The process of modal parameters identification is as follows. First, login the remote monitoring website via SMAE and query the acceleration, as shown in Fig. 16(a), and then download the acceleration data to the local computer. After download, the information of the data will be automatically read from the data file, such as sample frequency, sampling length and sensor information. Then, turning to the dynamic analysis module's page and make the modal parameters identification. For guarantee the identification results, two identification methods mentioned above will be used. The SMAE provide an interactive graphical interface, the identification results can be selected by selecting the results agree well from the comparison between PPK and SSI, as show in Fig. 16(b).

6. Evaluation of the SHM system

Since its installation, the SMAE has been collecting, processing and sending data continuously. Studies are carried out on the data measured on May2013. In this situation, the concrete pouredfloor 112 in core-tube and floor 89 in out-frame. The results show that all structural behaviors are within the design limit. Only some errors were generated due to measured error and the difference between FE model and real structure. This is understandable because the assumption of loading in FEM is quite different with the current construction, which cannot be estimated accurately. Therefore, the measure data can be used to update the FE model and the system can be concluded works reliably. Following are the results of the analysis on the dynamic property, strain and vertical deformation according to the monitored data.

6.1 Dynamic property

Fig. 17 shows an original acceleration time history data on 84th floor. The maximum amplitude is 0.4 cm/s^2 in east and 0.3 cm/s^2 in north. Fig. 18 shows the acceleration time history data in 60s in east direction. It can be found that the acceleration time history presents a certain waveform, but with some mutations. The Butterworth low-pass filter was used to smooth the signal with pass frequency 5 Hz and stop frequency 7 Hz. After smoothing filters the data, it can by seen clearly that the maximum oscillation period is approximately 6s (0.16 Hz).

By using the two modal identification methods of SSI and PPK, the measured data with output responses of each construction stage has been undertake with modal analysis, as seen in Fig. 19. On the variation tendency of frequency, the modal identification results are in good agreement with finite element results during the construction process. But as the finite element model can't completely simulate the actual situation of structure in the construction process, the identification result is lower than finite element result. With the processing of construction, the difference between first-order bending identification results and FEM has little variation. It’s also discovered that the tendencies of frequency on two axes are basically the same. But the torsional modal frequency differs a lot. It is showed that the finite element model needs further modify to make the FEM result consistent with identification results.

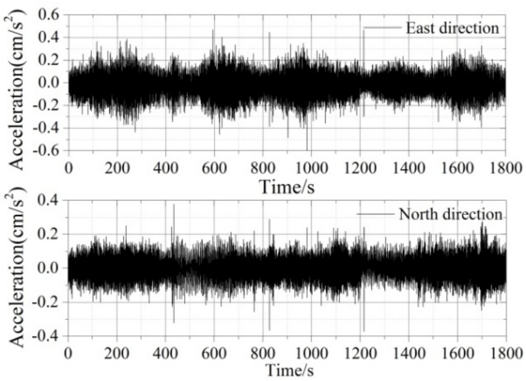


Fig. 17 Acceleration response in 30 minutes

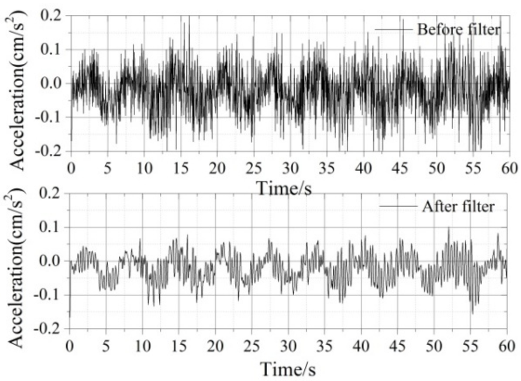


Fig. 18 Acceleration response in 60s

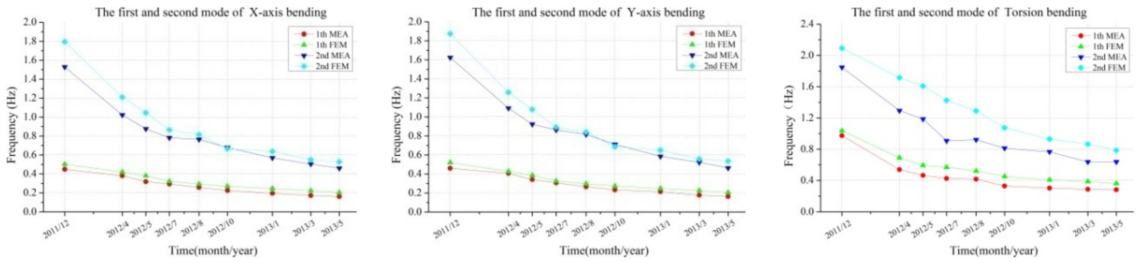
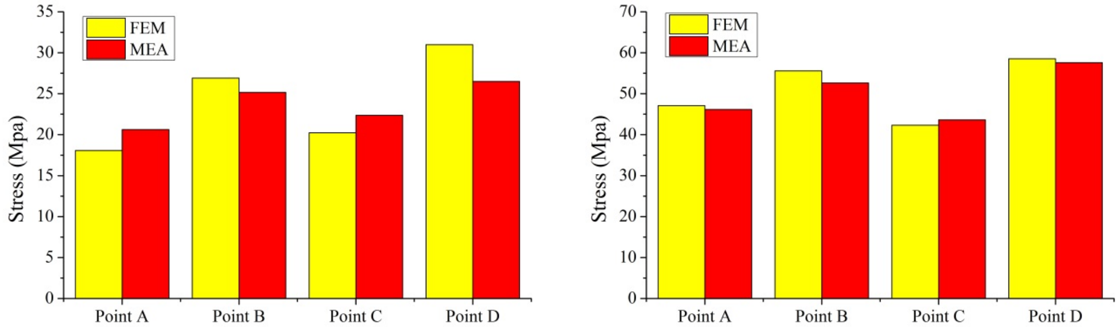


Fig. 19 The evolution of frequencies at different construcion stage*
*MEA: monitoring results; FEA: finite element results, similarly hereinafter



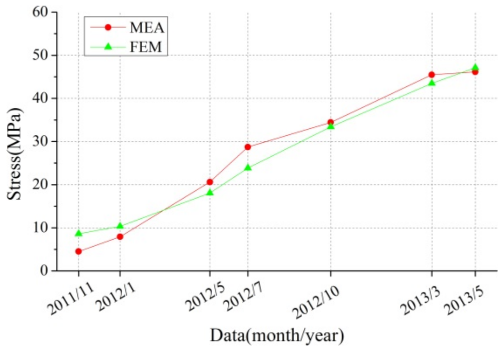
(a) May 2012 (b) May 2013

Fig. 20 Stresses distribution at monitoring point

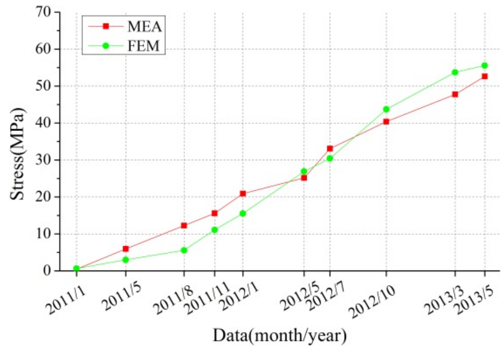
6.2 Stress in member

At different stages, the stresses of the structure are obtained via linear analysis and compared with the measurements. Fig. 20 compares the calculated stresses of 7th floor at different point in May 2012 and May 2013.The comparison shows the results in FEM and measurement are in good agreement. It also can be seen that the discrepancy of stresses between core-tube (point A and C)and frame (point B and D) are smaller in early stage (average discrepancy 5Mpa) and increased in large stage (average discrepancy 11Mpa). The discrepancy may be due to the construction scheme, the construction of mega-frame is left behind core-tube 9thfloor in lower section and will increased to 15th floor in upper section.

Fig. 21 illustrates the evolution of stress on the point A and point B in 7th floor as construction activity progressed. The measurement results of are in good agreement with FEM results although the average discrepancy is about 10% to 20%.The discrepancy may be due to the uncertain of the measurement and the difference between the FE model and the actual structure. Non uniform temperature distribution throughout the structure also causes non uniform thermal stresses at components, which is difficult to simulate in FEM. Considering these reasons, the discrepancy is acceptable and indicating that the structure is under a normal construction condition.

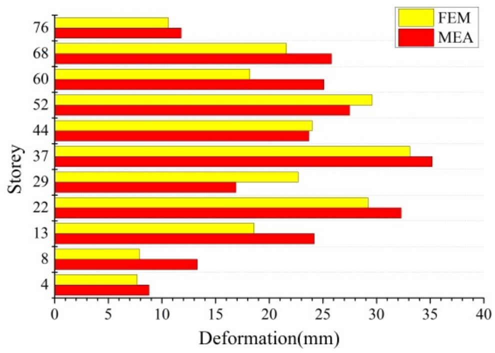


(a) Pont A

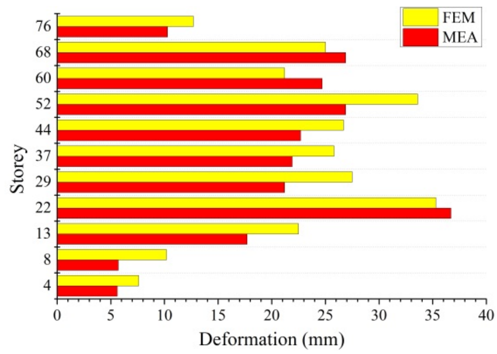


(d) Point B

Fig. 21 Stresses evolution at different stages of constructions (7th floor)



(a) Core-tube



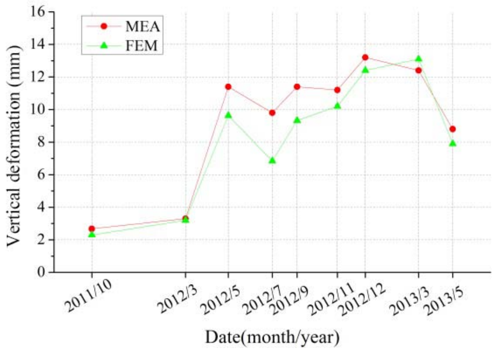
(b) Frame

Fig. 22 Variation in different floors on May 2013

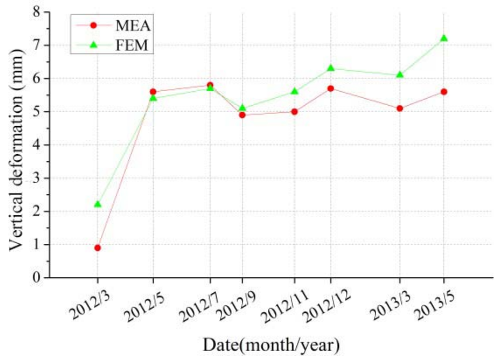
6.3 Vertical deformation

Fig. 22 shows the vertical deformation results in May 2013. As can be seen from the figure, the vertical deformation of each floor presents a shape like fish belly. The maximum vertical deformation of the core-tube is on the 22th floor and 37th floor, whereas the frame is for the 22th floor. Apart from the difference of measurements and finite element results on the 29th floor, the measurement results of remaining floors are in good agreement with finite element results although with average discrepancy about 15% to 20% caused by the accuracy in simulation.

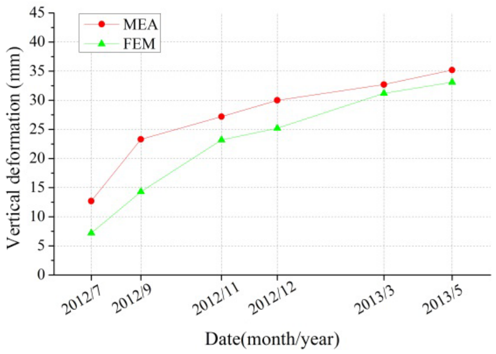
Fig. 23 shows the vertical deformation results of the 4th and 37 th floor. The measure result of maximum deformation of 4th floor is -13.2 mm in core-tube and -5.8 mm in frame. The measure result of maximum deformation of 37th floor is -39.2 mm in core-tube and -21.9 mm in the frame. The measure results are in good agreement with the FEM results. Meanwhile, it can be found that the vertical deformation in 4th floor is irregular compare to the 37th floor. This irregular of deformation is caused by the temperature due to thermal expansion and contracting. It can be concluded that the temperature has a significant effect on the lower storey.



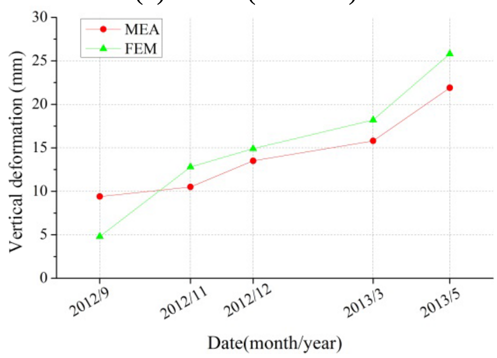
(a) Core-tube (4th floor)



(b) Frame (4th floor)



(c) Core-tube (37th floor)



(d) Frame (37th floor)

Fig. 23 Vertical deformation on 4th floor at different stage of construction

7. Conclusions

This paper focuses on the study of in-construction health monitoring system of Shanghai Tower, describes the system architecture and monitoring scheme, and develops an integrated monitoring and analysis software (SMAE). Then, the system effects have been embodied in the practical application process of Shanghai Tower. The following conclusions can be drawn:

- Propose an innovation monitoring and analysis software integration framework constituted by On-line data acquiring, FEM analysis and dynamic characteristics identification. Based on this framework, the integrated monitoring and analysis software, referred to as SMAE, has been developed to achieve the functions of online monitoring data collection, FEM analysis, dynamic characteristics identification, and so on.
- As a difference to the existing sensor query approach, the structural BIM is applied in the data acquiring system to get a good visual effect of sensor arrangement, while the data download function provides data interfaces for the further analysis.
- By considering the time-varying effect in construction, the FEM analysis software could accurately simulate the development state of structure in construction process. The comparison results between monitoring and FEM indicate the software has a good accuracy.
- The dynamic characteristics analysis module can accurately identify the structural

dynamic characteristics changes in the construction process, but how to reduce the interference of construction activities on the recognition results needs to be further studied.

- With the SMAE software, the construction unit and design unit could get a basic understanding of the development status of stress, strain, and frequency in each construction phase. Compared to the health monitoring of existing structure, this software is able to obtain the exact stress-strain development law of structure. Meanwhile, the integrated system has established an automatic integration platform from the monitoring data collection, storage, publishing to analysis, whose design method provides a good reference value for the SMAE health monitoring system.

Acknowledgments

The research described in this paper was financially supported by the National 863 Projects (No. 2009AA04Z420), Shanghai Science and Technology Research Funds (No. 09DZ1207704) and Shanghai Science and Technology Development Funds (No. 11XD1404900).

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