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SHM system design and application to large span structures

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ABSTRACT

Structural health monitoring (SHM) system takes its applications on multiple kinds of structures, while the different factors and considerations are taken account of when the SHM system is designed and applied to real world structures. The paper focuses on the large span structures, while the requirements and monitoring considerations are explained in details for their structural health monitoring in construction phase and usage phase. Two projects are shown in paper as examples to illustrate the SHM system design method and application implements. Furthermore, the sensor system, data acquisition and analysis, intelligent algorithms for decision and system integration are illustrated. At last, the sensor measurements and advantages the SHM system supplied are stated to make a references for the future SHM system design and applications.

1. INTRODUCTION

Recently, a large amount of large span structures were built in China, such as National Stadium, National Aquatic Center and so on. These structures usually transcend the normal limits, sometimes even beyond research. The designer often conducts a large amount of calculations or model test. But they usually can't assure that the precise model of the structure they have taken. This is because that the disadvantage loading condition and structural failure mode is hard to set (Teng 2010). Moreover, structures start to deteriorate when they are built and during long-term service. The structure may deteriorate slowly when suffering from processes such as corrosion, fatigue, overloads or material aging during life spans or to be damaged even collapse when subjected to extreme events, such as some natural disasters like earthquakes (Xu 2007). As a result, the safety and reliability of structures is really important to all of us. The structure itself must meet the requirement of serviceability, safety, durability and sustainability. Above all, both the economy and human life loss

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can be inconceivable when accidents occur in large-span structure (Ou 2010). So it is necessary for us to know the integrity of the structure or its level of safety. Developing structural health monitoring systems for continually monitoring and assessing the health of the structure can achieve this goal (Farrar 2007). And large span structures always have a lot of elements. It is difficult for people to identify each structural element most appropriate and find the most appropriate position of each element. Due to the limit number of sensors, the normal means can't be used to decide the safety of the structure. Therefore, it is urgent for us to find an appropriate structural health monitoring system for the large span structure (Teng 2010).

Successful performances of structural health monitoring systems for bridges have been widely announced. However, the use of structural health monitoring systems to other structures is not as popular as bridges. In 1993, a structural health monitoring program on a 280m 65-story office tower has been done by Brownjohn and his colleagues, which was used to monitor the dynamic responses and to find out whether there are any variations in the structure (Brownjhon 2007). In America, a structural health monitoring program was done by the University of Notre Dame, which was used to monitor the responses of three buildings which were in Chicago and compared them with the expected responses from finite element analysis (Kijewski-Correa 2003 Ni 2009). Indeed, in mainland of China, a lot of SHM systems have been applied in different structures, such as bridges, offshore structures, large-span structures and so on (Ou 2010). Some examples of applications in large span structures recently are the National Stadium of China, the Shenzhen Citizen Center and the Chinese National Aquatic Center (Teng 2012).

The structural health monitoring system is a tool for civil engineering to detect the damage position and ensure the safety of structure during its entire life-span. The functions of structural health monitoring may be concluded as: i) providing information for the safety during construction phases; ii) evaluating integrity and durability of structure during entire life-span; iii) predicting the potential damage of structure under extreme loads and giving early warning; iv) ensuring optimal rehabilitation arrangement for structure; v) help us understand the structural reaction mechanism to the outside environment (Ko 2005).

For an integrated structural health monitoring system, there may be divided into six parts: the sensory system, the data acquisition and transmission system, the data processing and control system, the structural health evaluation system, the structural health data management system, and the inspection and maintenance system (Wong 2007). When design a practical structural health monitoring system, different factors and considerations should be taken such as the number and variety of sensors, the location of measuring points, the system integration method and so on. Generally, it can be summarized as functional requirements and economic efficiency.

In this paper, it shows the details on the different factors and considerations which are taken account of when the SHM system is designed and applied to practical structures. Then the structural health monitoring systems implemented on the Shenzhen Vanke Center and Shenzhen Bay Stadium are introduced as examples to illustrate the SHM design.

2. SYSTEM DESIGN CONSIDERATION

For a practical SHM system design, there are two basic considerations. The first one is integration of functional requirements; the other is the consideration of economic efficiency. The functional requirements focus on whether the design is feasible. The economic efficiency considers the investment and practical application which needs to maximize the effectiveness of data obtained from measuring points and make optimization of the design.

2.1 Functional requirements

In order to assess the structure performance at present or in the future, a long span structure health monitoring system at least can accurately monitor the structural parameters which are needed for analysis (Wong 2007). The system may consist of the sensor system, data acquisition and analysis, intelligent algorithms for decision and system integration.

To a SHM system, the appropriate selection and placement of sensors may contribute to a more reliable monitoring data. So the sensors are more likely to be installed at the place which the maximum deformation or strain may occur. Of course, different kinds of sensors should be taken into account (Wong 2007). The selection of sensors should not only consider the property of measurements but also the property of sensors such as the accuracy and durability.

2.2 Economic efficiency

A SHM system usually contains a great number of sensors and acquisition equipments, which cost a lot. It is obviously that the more measurements and sensors, the more comprehensive of information we can obtain, which contributes to the higher cost. Conversely, if we consider the economic efficiency and reduce the sensors, the effectiveness of monitoring data may be reduced as the lack of monitoring information. Therefore, it is necessary to keep balance between the functional requirements and economic efficiency. It needs to make an optimal design which uses few sensors to get the structure information as much as possible.

3. SYSTEM APPLICATION

3.1 Shenzhen Vanke Center

<u>Description of structure</u>   The Shenzhen Vanke Center is located in Dameisha Beach, Shenzhen, China. The total site area is 61,730 m^2, and the building area is137, 116 m^2 which is shown in Fig. 1. The entire superstructure has a ground clearance of 10–15 m, which is supported by some tubes, solid walls, and columns. The spans vary from 50 to 60 m and the lengths of the cantilever spans vary from 15 to 20 m. The horizontal length of the structure is more than 500 m. The upper four or five floors of the structure are supported by some giant tubes, solid web thick walls and columns, by which the large open space for the garden can be provided. The upper main structure is consisted with the mixed architecture framework and cable system. Underlying structure is steel truss girder and the upper flat structure is concrete frame with wide beam system (Fig. 2). The structure is complicated with the irregular surface, large span and the noncontiguous vertical component. In addition, the structure is with project complexity and beyond the

norm.

Fig. 1 The whole structure

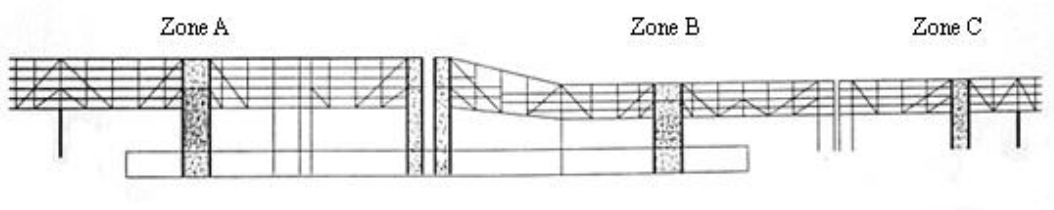

Fig. 2 Main profile of Shenzhen Vanke Center structure

Purpose of SHM system Setting the structural health monitoring systems on this structure is to guide the construction procedure and evaluate the safety of structure during its life span. Due to the complexity, the designers would like to make sure the structure constructed safely and used comfortably during its working period; in addition, the designers wanted to make sure whether the structural behaviors in real world in accordance with the simulation results using finite element model. Based on these requirements, the stresses for the main elements and the deformation of the structure were applied in the structural construction period, as well as the stresses for the main elements and the vibration of the structure were applied in the structural working period.

Sensor system In order to control the safety and the status of the prestressed cables in construction phase, the construction monitoring system mainly includes: the tension of the cable, the stress of critical structure members such as the steel beams and concrete-filled steel tube columns of the second floor, the deformation of floor, the displacement on the top of concrete core and the acceleration of the structure. There are 70 FBG strain sensors, 154 electric resistance strain sensors, 16 intelligence cables, 35 FBG temperature sensors, 14 acceleration sensors, 102 prisms and 1 total station. The sensors for SHM system of Shenzhen Vanke Center are shown in Fig. 3 and Fig. 4.

Examples of outcomes As the cable is the most important force support element in the project, the cable force was monitored in order to guide the procedure of the construction. The cable force was changing during tensioning, re-tensioning and the upper floor construction which is shown in Fig. 5. It created an entire overview of cable force values. It can provide a scientific basis for the safe status of the structure.

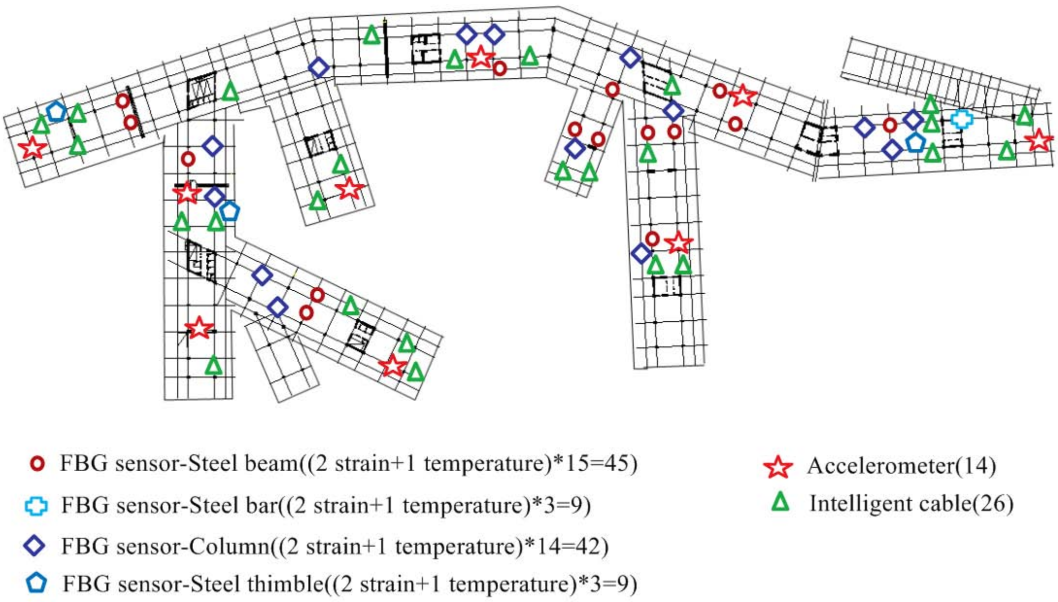

Fig. 3 Layout of FBG strain sensors and temperature sensors

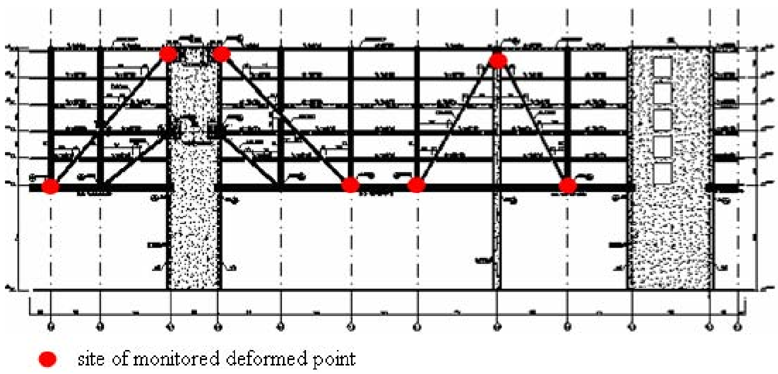

Fig. 4 Layout of deformation sensors

<u>Benefits of using SHM technologies in the project</u> The monitoring results show that the monitoring system developed with various sensors that can monitor different structure parameters during the structural construction such as stress, stain, displacement, acceleration, temperature and so on. The result verifies that the construction process were safe. In addition, Fiber Bragg grating intelligent cable can monitor the cable force effectively and it can guide the cable tensioning construction

process effectively. The monitoring data and analysis are useful to prove that the special structure frame like Shenzhen Vanke Center with cables that used to support such large span structures. Moreover, it can significantly reduce safety accidents during the construction phase, and directly accelerate the schedule and progress of construction and it also can preferably control the quality supervision at construction sites. Structural health monitoring systems also provide the information for latter analysis of the building.

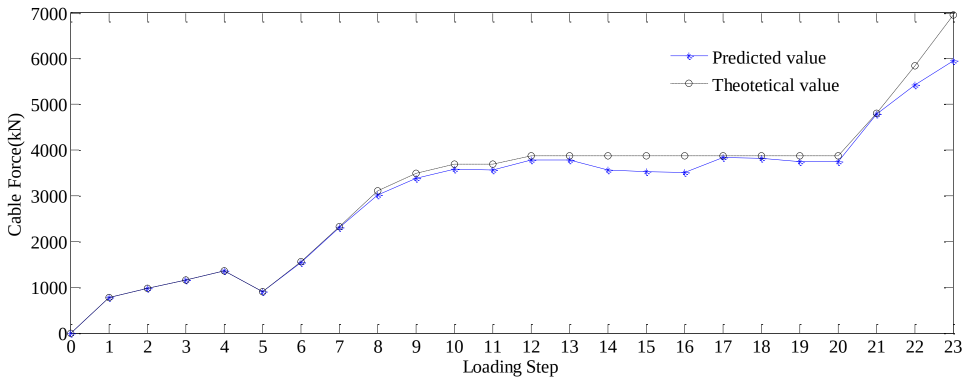

Fig. 5 The contrast of the predicted and the theoretical values in different stages

3.2 Shenzhen Bay Stadium

<u>Description of structure</u> The Shenzhen Bay Stadium is located at the Shenzhen Bay coastal recreation zone, the area is about 307700m^2. The flat shape of the structure is approximating rectangular, that the most length from east to west is about 730m and the north-south length is about 480m. The steel roof of the Shenzhen Bay Stadium is composed with a single shell, double rack (gymnasium, swimming pool) and the vertical support system. The structure plane size is about 500m*240m, which is a large-span spatial structure. The picture of the structure is shown in Figure. 6. Shenzhen Bay Stadium is bordering the sea which it is a serious typhoon affected area. The location of Shenzhen Bay Stadium and its large span spatial and irregular complex shape contribute itself to be a typical wind-sensitive structure. In addition, the complex components of the single layer shell may cause local vibration of the structure.

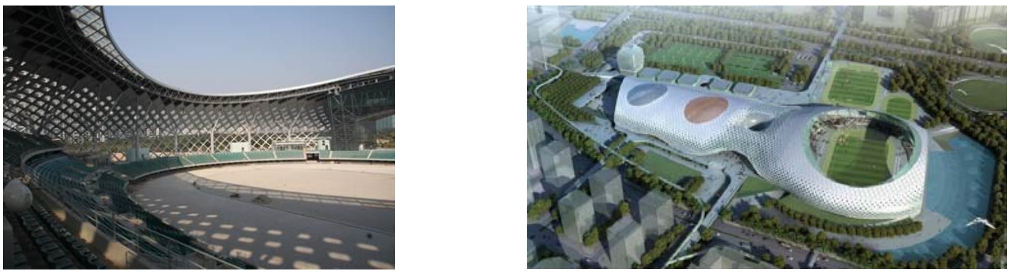

Fig. 6 General view of the Shenzhen Bay Stadium

Purpose of SHM system As a large-span steel structure, the temperature effect needs to be concerned when the structure is during construction. Due to its structural complexity and wind sensitive characteristic, the vibration of the structure induced by wind load was concerned in this structural health monitoring system. In addition, the stress of the important elements and the deformation of the important structural part should be concerned in order to give the estimation on the safety of the structure and guide the construction.

Sensor system For various kinds of measurements, the strain sensors, temperature sensors, anemometer, accelerometers and total station were used in the project and the sensor details is shown in Fig. 7.

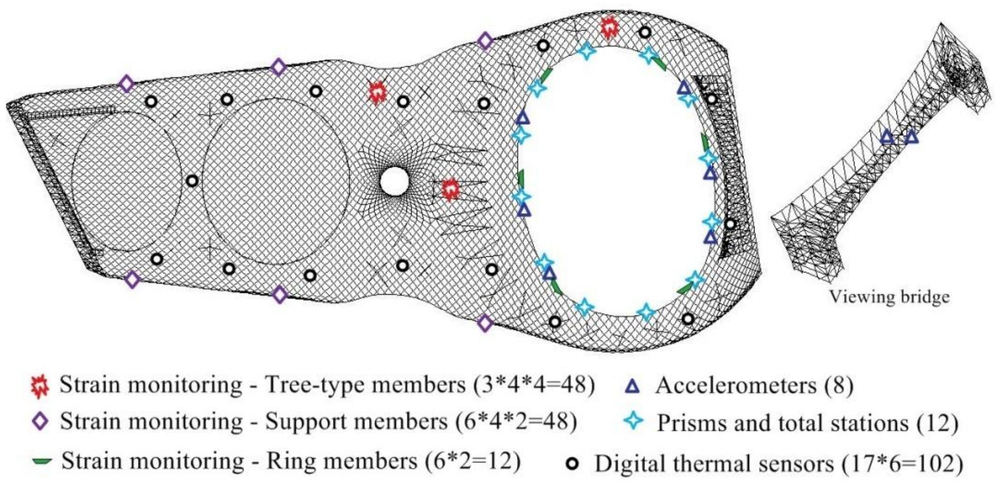

Fig. 7 Locations of sensors

Examples of outcomes The temperature monitoring results during construction phase are shown in this part. The structure was under unloading construction from April 10, 2010 to May 25, 2010. As the steel structure construction schedule was greatly influenced by temperature, the temperature monitoring system was applied during the whole construction phase. The locations of temperature sensors are shown in Fig. 8. The temperature measurements on April 20, 2010, the weather of which was cloudy and shower, the minimum temperature was 23℃ and maximum temperature was 29℃, are shown in Fig. 9 to Fig. 11. The temperature shown was acquired from measured points 4, 11 and 16 every half an hour from 9 am to 4 pm, respectively. From the overall temperature measurements during the construction phase, the temperature of steel structure was normal.

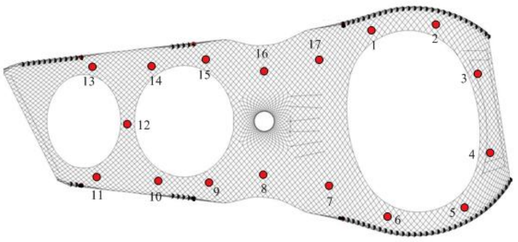

Fig. 8 The locations of sensors

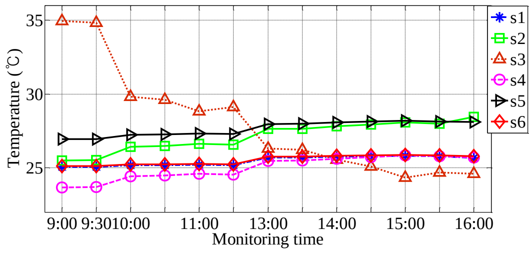

Fig. 9 Temperature data in point 4

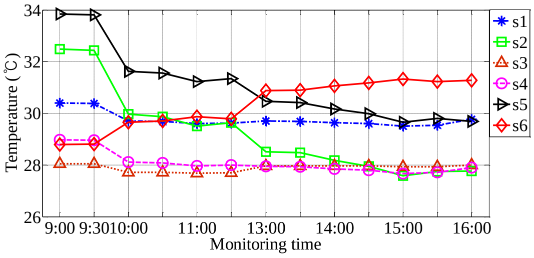

Fig. 10 Temperature data in point 11

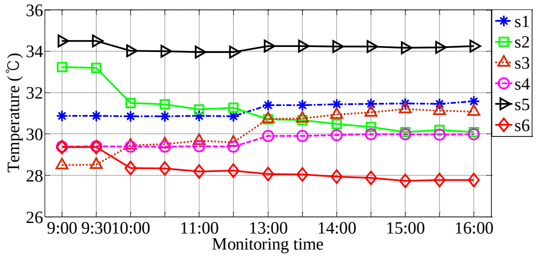

Fig. 11 Temperature data in point 16

<u>Benefits of using SHM technologies in the project</u> Monitoring temperature data during the steel structure closing process in construction and unloading process provides the perfect closing time for the structure and supplies the technical parameters for the construction. The entire monitoring system which includes the stress, deformation and vibration is used to determine the safety of the structure during usage phase. The reaction properties of structure presented by the structural health monitoring system can reduce safety accidents by early warning.

4. CONCLUSIONS

The different factors and considerations of designing a practical structural health monitoring system were introduced in this paper. It is concluded that a structural health monitoring system should at least be able to monitor the structural real-time parameters so that the safety assessment can be evaluated in time. Two practical projects were introduced to illustrate the SHM system design method and application implementations. Moreover, the monitoring results showed that the application implements are available.

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