The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

Implementation of structural health monitoring to a real large span steel roof and analysis on its stress identification

*Jun Teng[1)], Wei Lu[2)] and Fengqi Wu[3)]

[1), 2) , 3)] *Shenzhen Graduate School, HIT, Shenzhen 518055, China*
[1)] *tengj@hit.edu.cn*

ABSTRACT

The implementation of structural health monitoring to a real large span steel roof is presented, including the instruments and system integration. Furthermore, the stress identification method for this real steel roof is proposed, which can identify the stresses at locations free of measurement devices. Utilizing the real large span steel roof structure and considering the strain sensors located in this structural health monitoring system, the finite element model of the real roof structure is simulated and the stress identification method using the simulated data and the measurements are discussed separately. In order to proof the effectiveness and the robustness of the proposed methods, the influences of different number of measurements, the different locations of sensors, and the different levels of noises are simulated and compared. Besides, the measurements from the real structural health monitoring system are applied in the paper, where the real monitoring data is used to proof the proposed method and the effectiveness and uncertainty to the real monitoring data are also discussed.

1. INTRODUCTION

Structural health monitoring plays an integral role in maintaining the integrity of important civil, mechanical, and aerospace engineering systems (Labuz 2011). As civil structures are continuously subjected to adverse operational and environmental conditions, their safety condition becomes increasingly concerning over-time (Zhu 2010). Meanwhile, the structural health monitoring can improve the safety, reliability, and ownership costs of engineering systems by autonomously monitoring the conditions of structures and detecting damage before it reaches a critical state (Park 2008). Furthermore, the researchers are trying to get a comprehensive interdisciplinary research method in providing understanding, simulation, laboratory testing and development of an intelligent infrastructure system to make cost-effective decisions about infrastructure maintenance, repair, and rehabilitation (Sinha 2004). As we have

[1)] Professor
[2)] Assistant Professor

seen, the structural health monitoring is developed not only on the purpose to deploy the applications, but also to improve the structural health monitoring methods. However, it is still a concerned question on giving a robust system. Usually, a life cycle analysis is dependent on structural assessment and prediction models under uncertainty, and the accuracy associated with them can be considerably improved if the data from structural health monitoring are used efficiently (Peil 2005). Due to the presence of errors and uncertainties, the comprehensive structural health monitoring system explored by involving a combination of advanced structural analyses integrated with field investigation using sensors and performance data acquisition (Modares 2011). The actual performance assurance relies heavily upon sensor data. The sensor data is used to document performance and to improve the technical design of the structures, whereas an interactive graphical user interface supports continuous decision-making. The sensor system serves the needs for both customs and the service providers (Glaser 2008). However, the measurements of strain sensors located on the normal regions should also be installed to obtain the stress distribution identification of the key region, which can provide much more known measurements and reduce the incompleteness of information existing in structural health monitoring system.

Structural health monitoring is a method which can collect the structural responses and give the estimation of the working status of the structure, while different types of sensors are arranged on the structure. Recently, the researchers (Catbas *et al.,* 2008; Chan *et al.,* 2006; Farrar *et al.,* 2001; Barr *et al.,* 2006) put emphasis on realizing objectives and functions of structural health monitoring system using limited measurements of sensors. For example, Ming Liu *et al.* (2009) assessed the reliability of bridge through the long-term monitoring measurements of strain sensors under traffic loads and researched the security limit using the actual traffic conditions and measurements of strain sensor on the Wisconsin Rive Bridge in the United States. In the structural health monitoring system of the Shenzhen Citizen Center in China, the stress fields of brace steel brackets are identified by the limited measurements of strain sensors located on the key points (Wang *et al.,* 2007). Teng and Lu in their 2010 article proposed the effective stress identification method by using limited measurements and structural similarity (Teng & Lu, 2010) and later updated this identification method by using limited measurements in key areas, which was proofed by the simulation on the Water Cube (Teng *et al*., 2012).

Not only the implementation of the structural health monitoring system of a real large span steel roof structure is presented in the paper, but also the stress identification method based on this real large span steel roof structure and the limited strain measurements is proposed and discussed. The core component is the instrumentation and the system integration, in which the types and locations of sensors are listed and the performances of the roof structure with these measurements are shown. By using these data to study stress distribution, as well as to perform a comparison analysis with a finite element model, where the different noise levers are discussed to proof the robustness of the proposed stress identification method. Furthermore, considering the existence of a structural health monitoring system and measurements, this article also discuss the stress identification strategy.

2. STRUCTURAL HEALTH MONITORING SYSTEM OF SHENZHEN BAY STADIUM

2.1 Description of Project

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 Fig. 1. Shenzhen Bay Stadium is open space and bordering the sea, which is in a serious typhoon affected area. Because of its large span spatial structure and irregular complex shape, Shenzhen Bay Stadium is a typical wind-sensitive structure. In addition, the roof structure is composed mainly with the single layer shell and the vertical support system, where the former vibration modes of the structure are formed with the local vibration. Moreover, a large number of elements are designed at their stress ratio larger than 0.9 during its working period. Although the structural capacity calculated satisfied the requirements and codes, the amplitude of structural responses is very large because of its large span shape and low frequency characteristics.

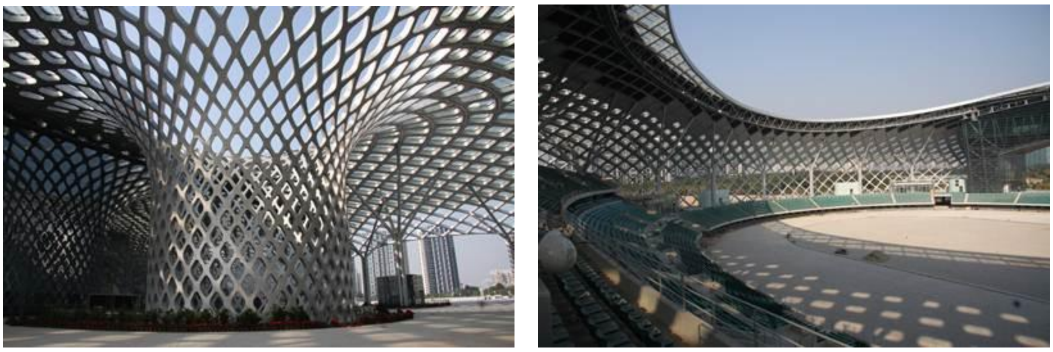

Fig. 1 Corners of Shenzhen Bay Stadium

2.2 Instrumentations and Installations

The first purpose of the structural health monitoring on this structure is to provide the temperature of the different parts of the structure, and second purpose is to choose a properly time to gather up the substructure. 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. Additionally, 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.

For this structural health monitoring system project, the measurement equipment is sensor. 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 Table 1.

Table 1 Sensor details for Shenzhen Bay Stadium

monitoring	type of sensor	Number	position
temperature	digital thermal sensor	102	closing seam
stress	vibrating wire extensometer	12	ring members
stress	vibrating wire extensometer	48	tree-type column
stress	vibrating wire extensometer	48	the support of the roof
deformation	prism and total station	12	the front part of the steel roof
vibration	acceleration sensor	8	steel roof and viewing bridge
wind speed	anemometer	2	the open fields of structure

To monitor the stresses of the important steel members including the front rods of the steel roof, the connecting rods of the steel roof bearings and the tree-type column bars, the vibrating wire extensometers were used in the project. The placements for installing the extensometers are shown from Fig. 2 to Fig. 4. The installation pictures of the fiber optic strain sensors are shown in Fig. 5 and Fig. 6. Fig. 5 shows a worker who was installing the vibrating wire extensometer. Firstly, the exactly monitoring point was pointed out, and then the vibration wire extensometer was wired to the steel element by two steel pieces. Monitoring the vibration of the structure, the accelerometers were used in this project. The installed accelerometers protected with steel case are shown in Fig. 7. Furthermore, in order to obtain the data from the sensors, the temporary acquisition equipment was placed as that shown in Fig. 8.

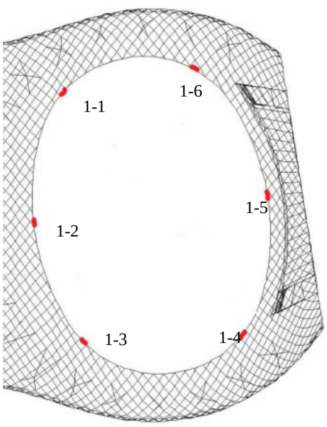

Fig. 2 Front rods of the steel roof

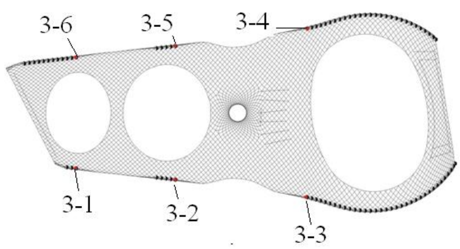

Fig. 3 Connecting rods of steel roof bearings

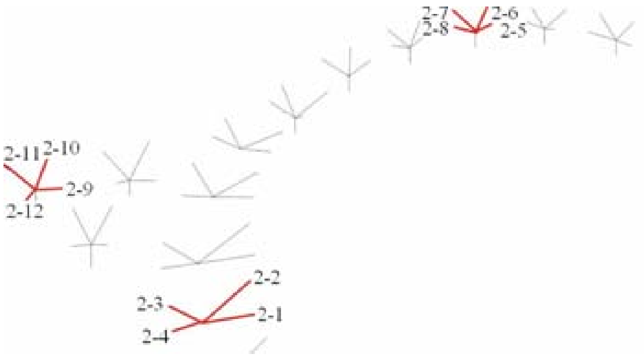

Fig. 4 Tree-type column bars

Fig. 5 Installation of sensors

Fig. 6 Sensors implementation

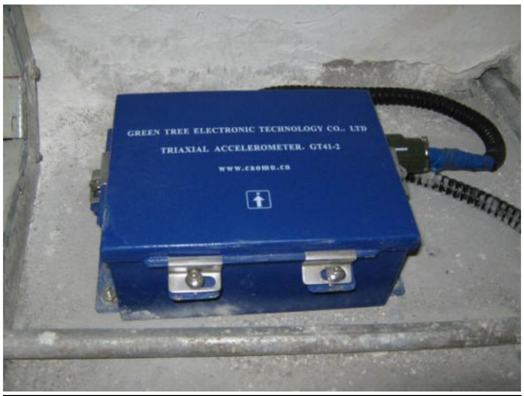

Fig. 7 Accelerometers with steel case

Fig. 8 Acquisition equipment

2.3 Main Functions of System Integration

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. Performances of the three kinds of steel elements were checked and its result verifies that the construction process were safe. In addition, the ability to collect measurements of real loading effects, structural responses and wind load is useful to evaluate design parameters and assumptions. The structural health monitoring system on this project also provides the vibration under its working status, which can give the data to estimate the comfortable range of the viewing bridge.

. ANALYSIS ON STRESS IDENTIFICATION TO FRONT RODS OF STEEL ROOF

The structural stress distribution is a very important part for safety estimation to this large span space steel roof. The vibration wire strain sensors were installed in the steel member and in which there is temperature compensation. The front rods members in Fig. 2 shows the placements with the strain sensors, while the stress variation with time and temperature can be shown for these front rods. However, the stress levels of front rods members free of strain sensors also need to measure and estimate. The stress distribution of the front rods is discussed in the following part.

3.1 Stress Variation With Time In Front Rods

The labels for the six front rods with vibration wire strain sensors are 1-1, 1-2, 1-3, 1-4, 1-5, 1-6, while the measurements are recording from the beginning of construction to this day. The placements for the vibration wire strain sensors located on the six front rods are shown in Fig. 2. There are two vibration wire strain sensors in each front rod, in which the placements of these two strain sensors in front rod labeled 1-1 are illustrated in Fig. 9, in which the sensors are labeled by 1-1-1 and 1-1-2 with the inside location and outside location, respectively. The other 10 vibration wire strain sensors located on the other five front rods are labeled as 1-2-1, 1-2-2, 1-3-1, 1-3-2, 1-4-1, 1-4-2, 1-5-1, 1-5-2, 1-6-1 and 1-6-2, respectively. The stress variation in 16 months from 2011 to 2013 is shown in Fig. 10, the stresses for these three front rods were all collected at 11:00 and it shows that the stress values along these three years are almost the same and stable. The stress variation in three continuous days with sampling frequency 1/120 Hz from 15:09 on May 24, 2013 to 10:17 on May 28, 2013 is shown in Fig. 11, it can be seen that the stresses are changing in the value of 5Mpa approximately in three days.

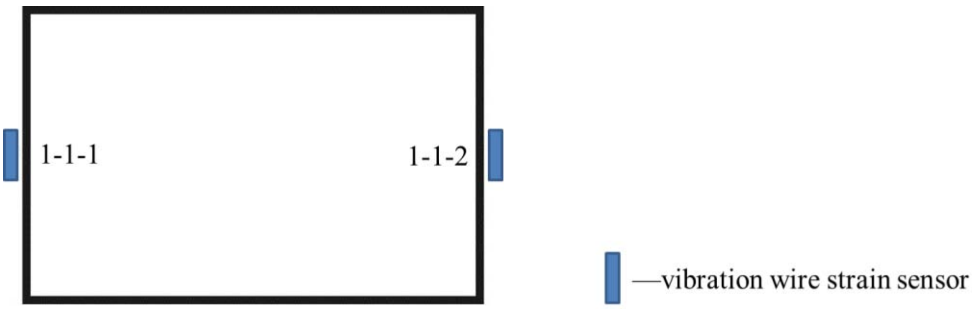

Fig. 9 Vibration wire strain sensors in front rod

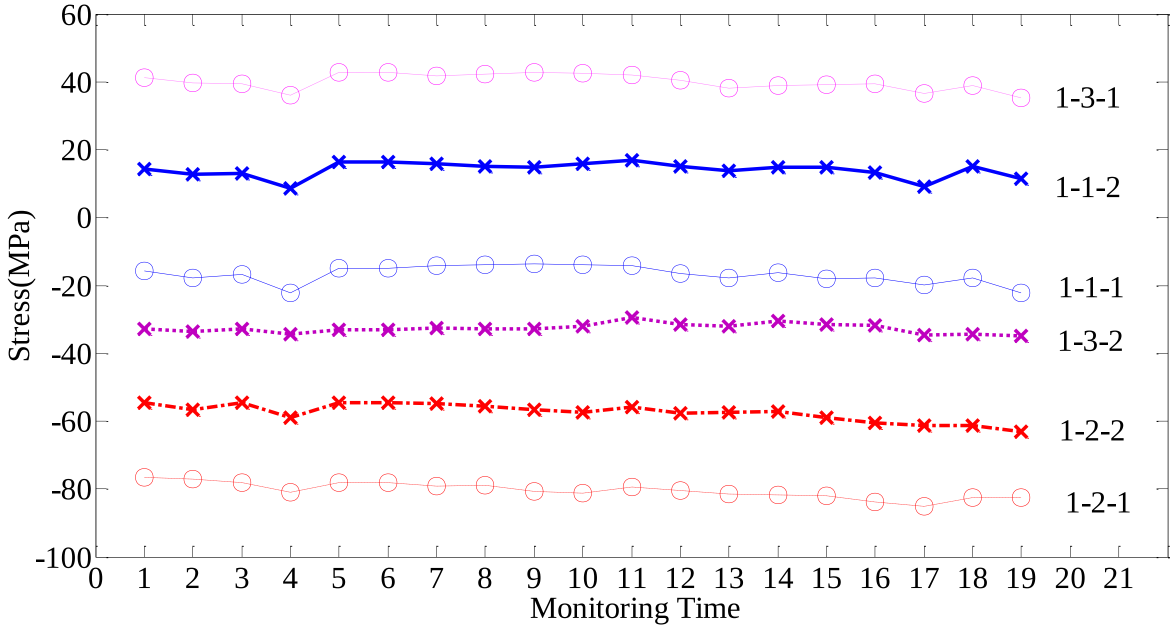

Fig. 10 Stress variation curves of three front rods in three years

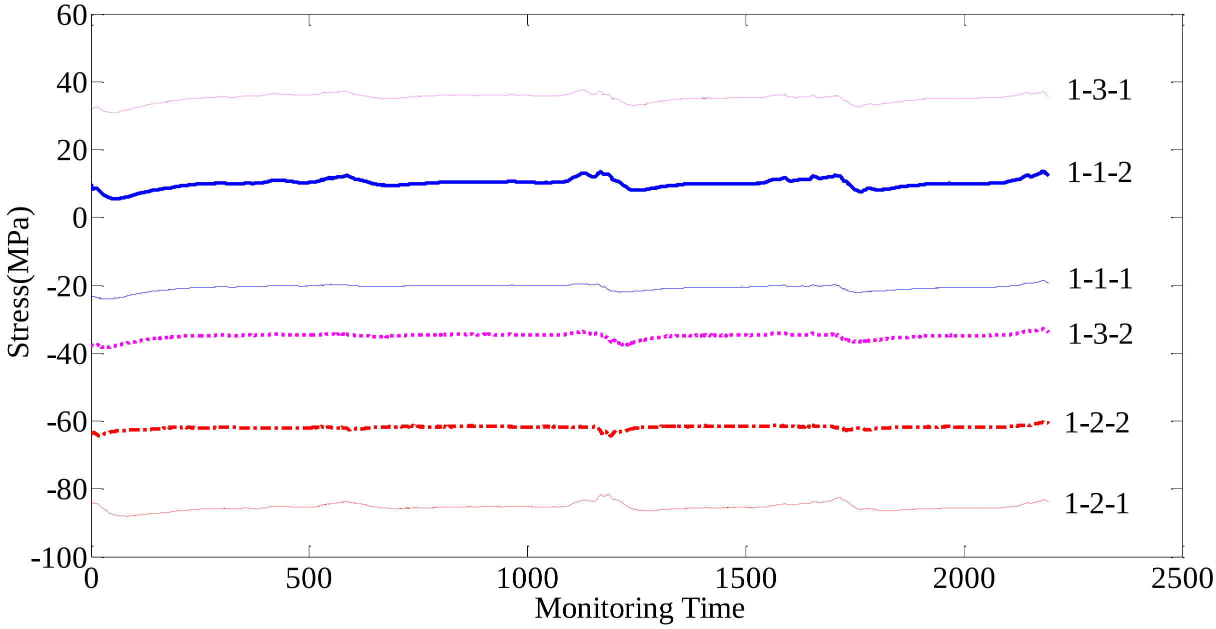

Fig. 11 Stress variation curves of three front rods in continuous time

3.2 Pattern Recognition Based Stress Identification Using Measured Data

Patterns set. The patterns set are built from the simulated data in finite element model analysis; the finite element model commercial FE code Midas® is shown in Fig. 12. The transient analysis was used to analyze the stress distribution of the roof structure, in which the load for the roof structure was the earth pulsation in the form of acceleration series in the time domain and simulated by the white noise in three directions. The peak values of such an earth pulsation were 0.1g, 0.1g and 0.15 g in X, Y and Z directions, respectively; the frequencies were from 0.5 to 20 Hz; and the time duration was 600s in total with a step of 0.02s. The stress values in monitoring locations 1-1-1, 1-2-1, 1-3-1, 1-4-1, 1-5-1 and 1-6-1 are extracted firstly. 15000 scenarios are used to be the patterns set, where the scenarios are from the first step, third step, …, and the 29999th step.

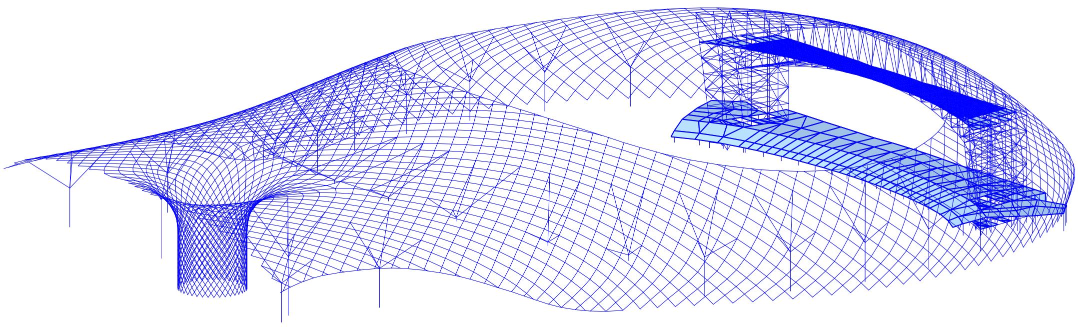

Fig. 12 Finite element model in Midas

Measurements set. The measurements set is built by the stress values in monitoring locations 1-1-1, 1-2-1, 1-4-1, 1-5-1 and 1-6-1. 19 scenarios are used here, which is shown in Fig. 10, in which the monitoring time is illustrated in Table 1.

Table 1 The corresponding date to monitoring time

Monitoring Time	Date	Monitoring Time	Date	Monitoring Time	Date
1	Jul. 2, 2011	8	Nov. 16, 2011	15	Sep. 7, 2012
2	Jul. 8, 2011	9	Dec. 19, 2011	16	Oct. 19, 2012
3	Aug. 10, 2011	10	Mar. 19, 2012	17	Dec. 19, 2012
4	Aug. 14, 2011	11	Apr, 23, 2012	18	Jan. 23, 2013
5	Aug. 26, 2011	12	May. 30, 2012	19	Mar. 10, 2013
6	Sep. 12, 2011	13	Jun. 19, 2012		
7	Oct. 18, 2011	14	Jul. 26, 2012		

Identified variations set. The identified variation set is built by the stress values in monitoring location 1-3-1. The stress values in monitoring location 1-3-1 is monitoring, the reason that it is used as identified variation is to proof the effectiveness of the proposed method.

Identified results analysis. The identified results are shown in Table 2, it can be seen that most of the identified results takes the error values of larger than 25%. So the following simulated data is used to discuss the reasons on errors.

Table 2 The errors using measured data

Time	Measured data	Identified Data	Error(%)	Time	Measured data	Identified Data	Error(%)
1	41.3	79.03	91.36	11	42	59.10	40.71
2	39.8	48.74	22.46	12	40.5	18.11	55.28
3	39.3	89.22	127.02	13	38.2	83.37	118.25
4	36.1	13.36	62.99	14	39	20.39	47.72
5	42.8	63.18	47.62	15	39.1	30.01	23.25
6	42.8	33.87	20.86	16	39.5	50.94	28.96
7	41.8	102.61	145.48	17	36.6	21.79	40.46
8	42.3	62.59	47.97	18	38.9	26.80	31.11
9	42.9	31.42	26.76	19	35.2	62.12	76.48
10	42.4	38.92	8.21				

3.3 Pattern Recognition Based Stress Identification Using Simulated Data

Patterns set. The patterns set is the same as that in part 3.2.

Measurements set. The measurements set is built by the stress values in monitoring locations 1-1-1, 1-2-1, 1-4-1, 1-5-1, 1-6-1. The data in measurements set is extracted from the simulation results by finite element model, and 500 scenarios are used to build the measurements set, where the scenarios are from the sixth step, sixty-six step, and so on to the 29946th step.

Identified variations set. The identified variation set is built by the stress values in monitoring locations 1-3-1. The data in identified variation set is extracted from the simulation results by finite element model, and 500 scenarios are used to build the identified variation set, where the scenarios are from the sixth step, sixty-six step, and so on to the 29946th step.

Identified results analysis. The identified results are shown in Table 3, in which the first line represents the errors and the second line represents the number of scenarios within the corresponding errors. It can be seen that the errors of 100 scenarios in 500 scenarios are less than 5%, the high qualify identified scenarios are in small quantity. The result is similar to the identified variation set built by measured data.

Table 3 The errors using simulated data

<5%	5%~10%	10%~15%	15%~20%	20%~25%	>25%
100	94	102	57	75	77

3.4 Analysis On Stress Identification Using Simulated Data

Patterns set. The patterns set is the same as that in part 3.2.

Measurements set. The measurements set is built by the stress values in monitoring locations 1-1-1, 1-2-1, 1-4-1, 1-5-1, 1-6-1 and additional 1-7-1, 1-8-1, 1-9-1, 1-10-1, 1-11-1, 1-12-1, where the locations of the additional simulated strain sensors are shown in Fig. 13. Beside the scenarios discussed in part 3.3, three other scenarios are discussed in this part, (1) the measurements set is built by the stress values in monitoring locations 1-1-1, 1-2-1, 1-4-1, 1-5-1, 1-6-1, 1-7-1, 1-8-1; (2) the measurements set is built by the stress values in monitoring locations 1-1-1, 1-2-1, 1-4-1, 1-5-1, 1-6-1, 1-7-1, 1-8-1, 1-9-1, 1-10-1; (3) the measurements set is built by the stress values in monitoring locations 1-1-1, 1-2-1, 1-4-1, 1-5-1, 1-6-1, 1-7-1, 1-8-1, 1-9-1, 1-10-1, 1-11-1, 1-12-1; The data in measurements set are all extracted from the simulation results by finite element model, and 500 scenarios are used to build the measurements set, where the scenarios are from the sixth step, sixty-six step, …, and the 29946th step.

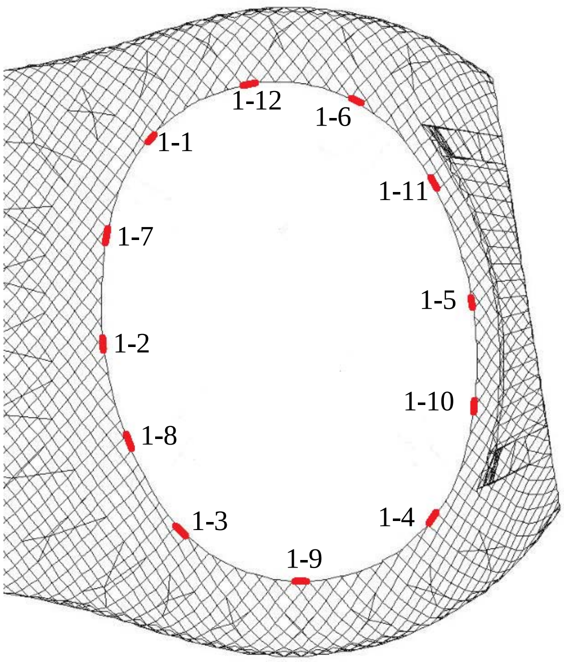

Fig. 13 Locations of additional simulated strain sensors

Identified variations set. The identified variations set is the same as that in part 3.3.

Identified results analysis. The identified results are shown in Table 4, in which the first line represents the errors and the following lines represent the number of scenarios within the corresponding errors. The four kinds of measurements sets are compared, it can be seen that the number of the scenarios with error less than 5% is becoming larger with the increasing on the number of the strain sensors. In the other word, the number of the strain sensors is one of the important parameter for improving the identified results.

Table 4 The errors using simulated data in different number of strain sensors

Number of sensors	<5%	5%~10%	10%~15%	15%~20%	20%~25%	>25%
5	100	94	102	57	75	77
7	110	101	98	74	67	50
9	163	129	74	40	37	57
11	224	141	82	17	18	18

4. CONCLUSIONS

The implementation and the instrumentations of the Shenzhen Bay Stadium are presented in the paper, while the stress identification and stress analysis are given and discussed. The conclusions are as follows:

(1) The stress, the temperature, the vibration, the deformation and the wind load are monitored in the structural health monitoring system of Shenzhen Bay Stadium.

(2) The monitoring stress data in front rods from the recently three years are stable.

(3) The monitoring stress data in front rods are changing within value of 5MPa in three days.

(4) The proposed stress identification method can be used for the real large span space steel roof and the measured data, while the number of the located strain sensors is one of the most important parameter.

(5) As the increasing number of the located strain sensors, the errors of the identified stress values are smaller.

REFERENCES

Barr, P. J, Woodward, C. B., Najera, B. and Amin, M. N. (2006), “Long-term Structural Health Monitoring of the San Ysidro Bridge.” *J. Perform. Constr. Facil,* **20**(1), 14-20.

Catbas, F. N, Susoy, M. and Frangopol, D. M. (2008), “Structural Health Monitoring and Reliability Estimation: Long Span Truss Bridge Application with Environmental Monitoring Data,” *Eng. Struct.,* (30), 2347-2359.

Chan, T. H. T, Yu, L., Tam, H. Y., Ni, Y. Q., Liu, S. Y., Chung, W. H. and Cheng, L. K. (2006), “ Fiber Bragg Grating Sensors for Structural Health Monitoring of Tsing Ma Bridge: Background and Experimental Observation.” *Eng. Struct.,* (28), 648-659.

Farrar, C. R, Sohn, H., Fugate, M. L. and Czarnecki, J. J. (2001), Integrated Structural Health Monitoring, Advanced Nondestructive Evaluation for Structural and Biological Health Monitoring, *Proceedings of SPIE,* Vol.4335.

Glaser, S.D. and Tolman, A. (2008), “Sense of sensing: from data to informed decisions for the

built environment.” *J. Infrastruct. Syst.,* **14**:4-14.
Teng, J., Zhang, T. and Lu, W. (2012), “Structural Stress Identification Using Fuzzy Pattern Recognition and Information Fusion Technique.” *J. Civ. Eng. Archit.,* **6**(4): 479-488.
Labuz, E.L., Pakzad, S.N. and Cheng, L. (2011), “Damage detection and localization in structures: a statistics based algorithm using a densely clustered sensor network.” *Proceedings of '11 Structures Congress,* Vegas.
Liu, M, Frangopol, D. M. and Kim, S. Y. (2009), “Bridge System Performance Assessment from Structural Health Monitoring: A Case Study,” *J. Struct. Eng.,* **35**(6), 733-742.
Modares, M. and Mohammadi, J. (2011), “Asset management of structures using hybrid structural health monitoring and structural uncertainty analysis procedure.” *Proceedings of 11’ International conference on vulnerability and risk analysis and management,* .
Park, G., Rosing, T., Todd, M.D., Farrar, C.R. and Hodgkiss, W. (2008), “Energy harvesting for structural health monitoring sensor networks.” *J. Infrastruct. Syst.,* **14**: 64-79.
Peil, U. (2005), “Assessment of bridges via monitoring.” *Struct. Infrastruct. Eng.,* **1**(2):101-117.
Sinha, S.K. (2004), “A multi-sensory approach to structural health monitoring of buried sewer pipelines infrastructures system.” *Proceedings of '04 Pipelines,* San Diego.
Teng, J. and Lu, W. (2010), “Efficient structural health monitoring by limited strain measurements.” *Proceedings of '10 Earth and Space Conference,* Honolulu.
Wang, J., Qu W.L., Zhen, J.and Liu, H. (2007), “Fuzzy Pattern Identification and Experimental Verification of Stress Field of Space Steel Structure.” *Proceedings of 07’ International Conference on Health Monitoring of Structure, Material and Environment,* Nanjing.
Zhu, D.P., Yi, X.H., Wang, Y., Guo, J.J. and Lee, K.M. (2010), “Mobile sensor networks: a new approach for structural health monitoring.” *Proceedings of '10 Structures Congress,* Orlando.