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Instrumentation on structural health monitoring systems to real world structures

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Abstract. Instrumentation on structural health monitoring system imposes critical issues for applying the structural monitoring system to real world structures, for which not only on the configuration and geometry, but also aesthetics on the system to be monitored should be considered. To illustrate this point, two real world structural health monitoring systems, the structural health monitoring system of Shenzhen Vanke Center and the structural health monitoring system of Shenzhen Bay Stadium in China, are presented in the paper. The instrumentation on structural health monitoring systems of real world structures is addressed by providing the description of the structure, the purpose of the structural health monitoring system implementation, as well as details of the system integration including the installations on the sensors and acquisition equipment and so on. In addition, an intelligent algorithm on stress identification using measurements from multi-region is presented in the paper. The stress identification method is deployed using the fuzzy pattern recognition and Dempster-Shafer evidence theory, where the measurements of limited strain sensors arranged on structure are the input data of the method. As results, at the critical parts of the structure, the stress distribution evaluated from the measurements has shown close correlation to the numerical simulation results on the steel roof of the Beijing National Aquatics Center in China. The research work in this paper can provide a reference for the design and implementation of both real world structural health monitoring systems and intelligent algorithm to identify stress distribution effectively.

Keywords: structural health monitoring; intelligent systems; information acquisition; stress distribution; fuzzy pattern recognition

1. Introduction

Structural health monitoring system is often related to safety (Farrar 2007). Since the structures in civil engineering are subjected to adverse operational and environmental conditions, their concern on safety then has increased dramatically (Zhu 2010). In this regard, the adaption of structural instrumentation and monitoring in various fields has been mature and extensive, such as the oil industry, large dams and highways (Brownjohn 2007). However, there are still many critical issues in related studies, such as logistically complication, labor-intensiveness, time-consuming, and cost consideration for civil infrastructure applications (Farhey 2006). Meanwhile, the

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structural health monitoring can significantly 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). It has been known that, with the result of destructive effects, the effective durability and life span of the structure is continuously decreasing. Take the bridge as an example, while the official service life of a public facility is expected to attain 75 years with only routine maintenance, many bridges that are only 10-20 years old require extensive and expensive rehabilitation (Farhey 2006). According to the survey in 2003, federal spending in the US for the replacement of structurally obsolete bridges is approximately $10billion per year (Chang 2003).Furthermore, researchers are attempting to find a more comprehensive interdisciplinary method and solution 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). Thus, it is understandable that, 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 defining an intelligent system. An intelligent system can be defined as any system that could receive sensory information and has the ability to process this information with a computationally efficient and effective software, combined with one or more smart or intelligent algorithms for performing functions, such as control, managing resources, diagnostic and decision-making, to achieve multiple or single task (Ng 2003).

Structural health monitoring is a method which can collect the structural responses and estimate the working status of the structure, despite different types of sensors are arranged on the structure. When the number of sensors located in the real world monitored structure is limited, the normal method cannot be used to determine the safety of the structures by monitoring the response of the most favorable components directly (Liu *et al*. 2008). Recently, several 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, 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 sensors on the Wisconsin Rive Bridge in the United States. Abazarsa *et al*. (2013) proposed a method which using a limited number of sensors from recorded free/ambient vibration data to identify the structural modal characteristics. In the structural health monitoring system of the Shenzhen Civic 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 proposed the effective stress identification method by using limited measurements and structural similarity (Teng and Lu 2010).

On this ground, this paper presents the structural health monitoring systems applications to real world steel structures, while the implementations and integrals of intelligent structural health monitoring system are also introduced. Furthermore, the intelligent identification method on stress distribution is introduced and proofed by numerical simulations on real world structures. Considering the intelligent structural health monitoring method, especially the identification on stress distribution, the structure is divided into several regions according to the distribution of plastic hinges using elastic-plastic dynamic analysis (Fu *et al.* 2007).The most critical region is selected to be the key region for stress identification, while different numbers of strain sensors are located on both key region and normal regions. As following, the fuzzy pattern recognition is used to identify the stress distributions based on measurements from different regions. At last, the numerical study on Beijing National Aquatics Center is carried out to validate the reliability of the proposed stress identification method.

2. Instrumentation on SHM of real World Structures

2.1 SHM of Shenzhen Vanke Center

Shenzhen Vanke Center is located at the Shenzhen Dameisha Sea Beach with a total land area 61730 m^2 and total construction area 137116 m^2. The upper four and five floors of the structure are supported by 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.

Two main purposes of the structural health monitoring on this structure are firstly to guide the construction process, and secondly to evaluate the safety of structure in its working status. In its construction stage, the measurands are the stresses for the main elements and the deformation of the structure. During its usage stage, the measurands are the stresses of main elements and the vibration of the structure. The overview of sensors on structural health monitoring system of Shenzhen Vanke Center is shown in Fig. 1, and the sensor details are listed in Table 1.

There are three kinds of sensors installed in this project, which are those on surface, embedded and non-contact. Monitoring the stresses of the steel beams, columns, the optic fiber strain sensors were installed in the project, which are all located on surface of the elements such as steel beams and steel columns. The installation pictures of the fiber optic strain sensors are shown in Fig. 2. As the environment in field is harsh, the protection method for the sensors and wires, which is shown in Fig. 3, is to install a steel case for the sensors and to weld steel circuit for the wires.

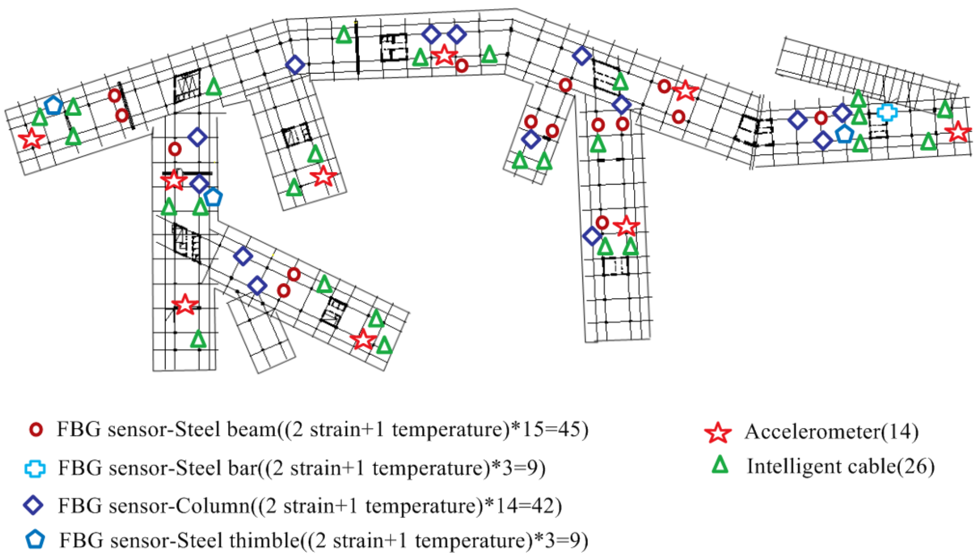

Fig.1 Overview of sensors on SHM of Shenzhen Vanke Center

Table 1 Sensor details for Shenzhen Vanke Center

Monitoring	Type of sensor	Number	Position
Stress	FBG strain sensor	30	Steel beam
Stress	FBG strain sensor	28	Concrete-steel tube column
Stress	FBG strain sensor	6	Steel bar
Stress	FBG strain sensor	6	Steel thimble
Cable force	Intelligent cable	26	Cable
Temperature	FBG temperature sensor	35	Strain sensor
Deformation	Prism and total station	102	The end of long cable
Comfort level	Accelerometer	14	Floor

Fig. 2 The fiber optic strain sensors

Fig. 3 Steel case and protector for wires

To monitor the force of the cables, the intelligent cables were used in the project. The intelligent cables belonged to the fiber optic strain sensors, the intelligent cables should be embedded in the cables when the cables are manufactured in the factory. Fig. 4 shows the cable with the intelligent cable embedded. The intelligent cable with the fiber optic strain sensor was embedded and manufactured with the other steel bars. Further, the wires for transmitting signals were connected with the intelligent cables in the factory. At last, the cables with the intelligent cables were installed on site (Fig. 5) and therefore the forces of the cables can be detected.

To monitor the deformation of the structure floors, the total station and prisms were used. In this project, the deformation monitoring was only explored during the construction period, which can supply the deformation of the structure under different construction loads and guide the construction. The total station and the prisms installed on the surface of the structure are shown in Figs. 6 and 7. In order to monitor the structural vibration, the accelerometers were used as well. The structural vibration considered in this project was the vibration of the floor. So the accelerometers were installed on the second floor, the installation of the accelerometer is shown in Fig. 8.

Fig. 4 Intelligent cables in the factory

Fig. 5 Intelligent cables on site

Fig. 6 The prisms installed in the project

Fig. 7 Measuring by total station

Fig. 8 The accelerometer placed on the floor

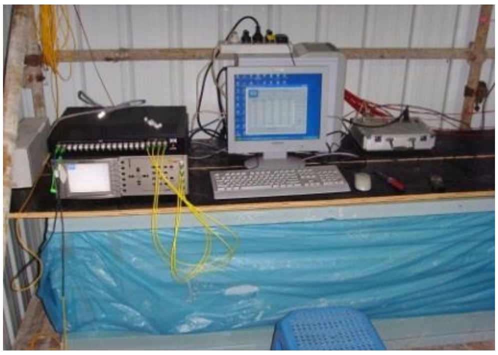

Fig. 9 The temporary monitoring center

2.2 SHM of Shenzhen Bay Stadium

Shenzhen Bay Stadium is open space and bordering along the coastline, which is all located in an intensive typhoon affected area. The main purposes of the structural health monitoring on this structure are firstly to provide the temperatures in different parts of structure, and secondly 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. 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. The overview of sensors on the Shenzhen Bay Stadium is shown in Fig. 10 and the details for the structural health monitoring system of this project are listed in Table 2.

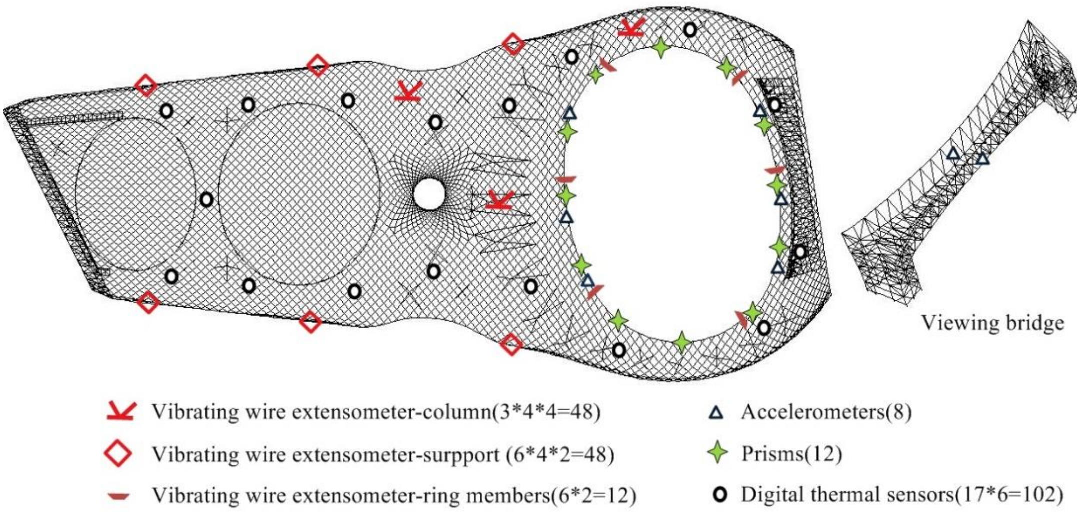

Fig. 10 Overview of sensors on SHM of Shenzhen Bay Stadium

Table 2 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	Accelerometers	8	Steel roof and viewing bridge
Wind speed	Anemometer	2	The open fields of structure

Fig. 11 Installation of sensors

Fig. 12 Sensors implementation

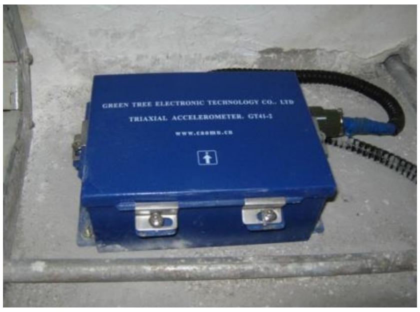

Fig. 13 Accelerometers with steel case

Fig. 14 Temporary acquisition equipment

The installation pictures of the fiber optic strain sensors are shown in Figs. 11 and 12. In the Fig. 11, it shows a technician who was installing the vibrating wire extensometer. The exactly monitoring point was firstly pointed out, and then the vibrating 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. 13. Furthermore, in order to obtain the data from the sensors, the temporary acquisition equipment was placed as that shown in Fig. 14.

3. Intelligent structural health monitoring methods on stress identification

The method is divided into early-stage preparation part and real-time monitoring part, which is shown in Fig. 15. In the early-stage preparation part, firstly, the key region identification and the normal region identification are obtained using fuzzy pattern recognition. Secondly, the selected normal region identification results are decided using the D-S evidence theory. Thirdly, the different fusion coefficients for the key region identification and the selected normal identification are assigned using the weighted fusion algorithm. Finally, all the results are saved in the fusion center for obtaining the synthesized stress distribution of the key region in real time. In the real-time monitoring part, firstly, the key region identification and the normal region identification are acquired using fuzzy pattern recognition. Secondly, the synthesized stress distribution of the key region can be obtained with different fusion coefficients.

The detailed algorithm regarding this method can be found in another journal paper (Teng *et al*. 2012). In this paper, the method is proofed by simulating on a real world large steel structure, Beijing National Aquatics Center in China.

4. Stress Identification to Beijing National Aquatics Center using Fuzzy Sets and D-S Theory

4.1 Project description

Beijing National Aquatics Center is known as Water Cube, which is located in the west side of landscape avenue of Beijing Olympic park, covers an area of 6.295 hectares. The accurate size of the outside of structure is 176.5389 m in length, 176.5389 m in width and 29.2789 m in height. Asan extremely important structure, a lot of new technology and new material were adopted for Beijing National Aquatics Center, which was one of the stadiums for the 2008 Olympic Games held in Beijing. Meanwhile, it is significant to install the structural health monitoring system, where the loads, environment and its responses were monitored, as well as the health condition of the structure were evaluated. Because of the large roof span and complex forces, the sensors of the health monitoring system are mainly arranged on the roof (Fu *et al*. 2007).

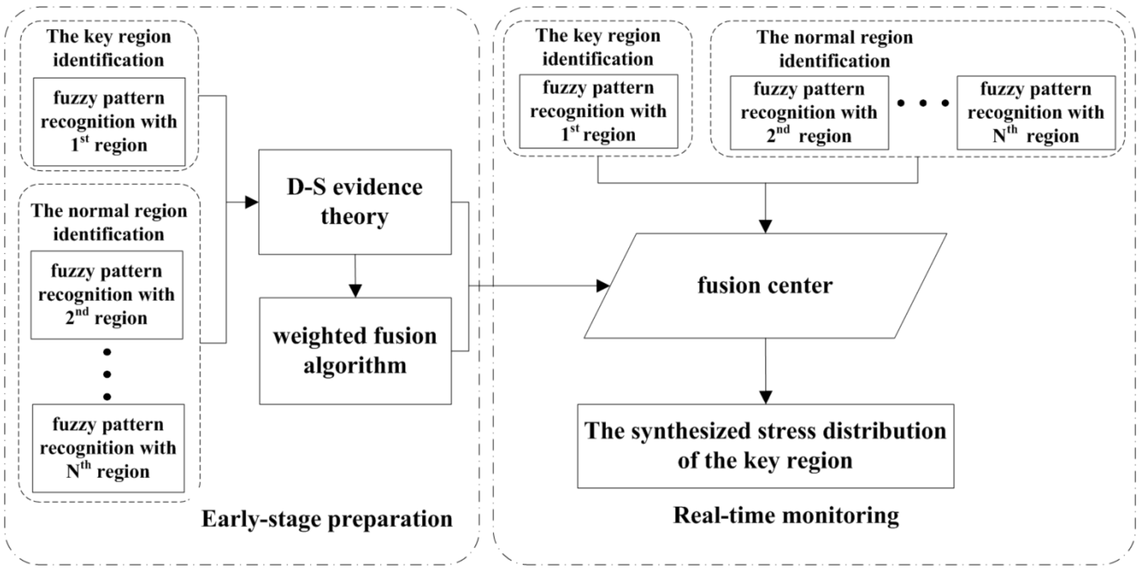

Fig. 15 The framework of the stress identification method

4.2 Finite element model and division on key region and normal regions

4.2.1 Finite element model of Beijing National Aquatics Center

The steel structure of Beijing National Aquatics Center is a new polyhedron space steel structure, which has the simple composition accompanied withhigh repeatability. There are only 4 kinds of length of member bars and 3 kinds of different nodes in the polyhedron structure unit, while each node has four concurrent member bars. The node and support are rigid connection, and the bar is simulated as space beam element. The stress state of components is between the concurrent force system of hinged frame and rigid connection of straight diagonal vierendeel truss, where the bending, shearing, tension (or compression) and twist are existed at the same time (Fu *et al*. 2007). SAP2000 is used to carry out structure finite element analysis in this paper, where the finite element model is shown in Fig. 16.

4.2.2 Division on key region and normal regions

The division on key region and normal regions is based on the distribution of plastic hinges on the super steel roof structure, while an elastic-plastic dynamic analysis was carried out using MIDAS/Gen software by Fu *et al.* (2007). The steel structural members were simulated as nonlinear beam-column elements, while a bilinear stress-strain relationship was used for the steel material, where the second stage elastic modulus was taken as 3% of initial elastic modulus. The elastic-plastic characteristics of the beam-column element were simulated by concentrated non-elastic hinges. It was assumed that the non-elastic hinges only occurred at the member ends while the part of the member between two hinges always stayed in an elastic stage (Fu *et al.* 2007). The distribution of plastic hinges at the termination of the elastic-plastic dynamic time history analysis of the structure subjected to three direction site time histories is shown in Fig. 17 (Fu *et al*. 2007), where the larger dots represent the position of plastic hinges. It can be seen from Fig. 17 that there are more plastic hinges in placement R3 of the roof. The discussion of the stress identification using the proposed algorithm is given around the placement R3 of the roof.

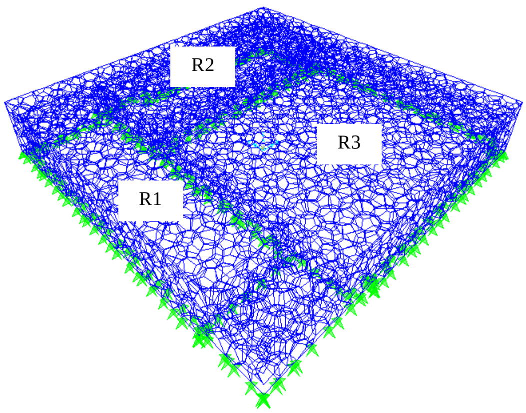

Fig. 16 FEM of Beijing National Aquatics Center

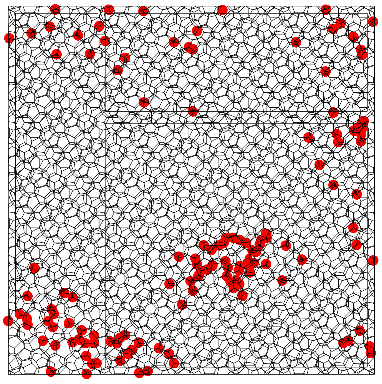

Fig. 17 Plastic hinge distribution of the roof

According to structural similarity and the structural unit, the upper chord members in five regions are selected and shown in Fig. 18. Region 1 is considered as key region, and the other four regions are considered as normal regions. Regarding the placements selection for the strain sensors, two reasons are considered. One is the stress value when the structure is subjected to live load, which leads to that the member with the maximum stress value is recommended to place the sensor. The other one is the influence of the stress value of a member, which leads to that the member influencing the variations on stress values of surrounding members is recommended to place the sensor. There are 210 strain sensors placed on the steel structure of Beijing National Aquatics Center, where 65 strain sensors are placed on the upper chord members (shown in Fig. 18). As the sensors shown in Fig. 18, there are 13 strain sensors in the key region and 8 strain sensors in the other 4 normal regions respectively.

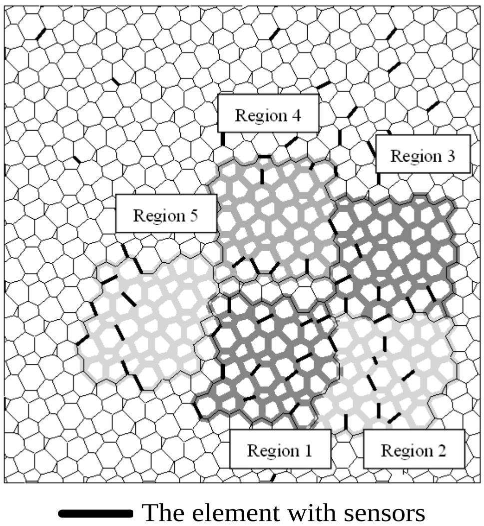

Fig. 18 The division of the identification region

Table 3 Establish the standard pattern library and training pattern library

Library	Extracted stress response	Number of stress patterns
Standard pattern	Stresses at 0.02s, 0.04s, … , 600s	15000
Training pattern	Stresses at 0.12s, 0.36s, … , 599.88s	2500

4.3 Data preparation

4.3.1 The establishment of the sample library

4.3.1.1 The establishment of the standard pattern library and training pattern library

The stress values from the sensors located on the members in key region and the members in other four normal regions are extracted from the transient time history analysis, where the structure is subjected to ground pulsation. The ground pulsation is simulated by white noise in three directions, in which the amplitude of white noise are 0.15 g, 0.12 g, and 0.9 g in direction x,y,z, respectively, and frequency is ranging from 0.5 Hz to 20 Hz, time duration is 10min, time interval is 0.02s. The standard pattern library and the training pattern library are selected and shown in Table 3.

4.3.1.2 The establishment of the testing pattern library

The stress values from the sensors located on the members in key region and the members in other four normal regions are extracted from the transient time history analysis, where the structure is subjected to seismic force. The testing pattern library is established by the stresses at 0.04s, 1.24s, … ,598.84s . The number of stress patterns in the testing pattern library is 500.

The El Centro wave is selected to carry out the transient time history analysis by finite element analysis software SAP2000, and the elastic-plastic model of material is bilinear. The acceleration time histories in three directions are shown in Figs. 19-21, where the time durations are all 10s, time interval is 0.02s.

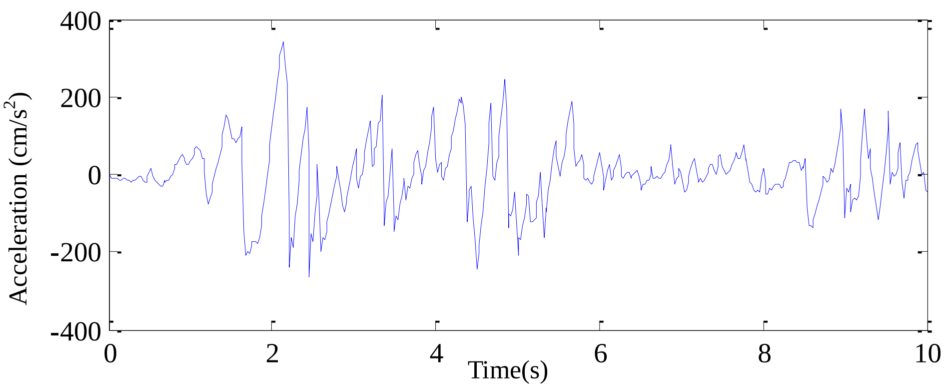

Fig. 19 The acceleration time history in X-direction

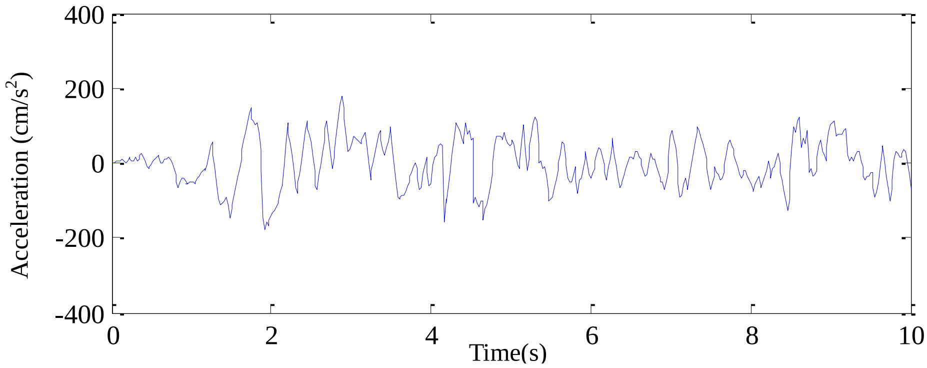

Fig. 20 The acceleration time history in Y-direction

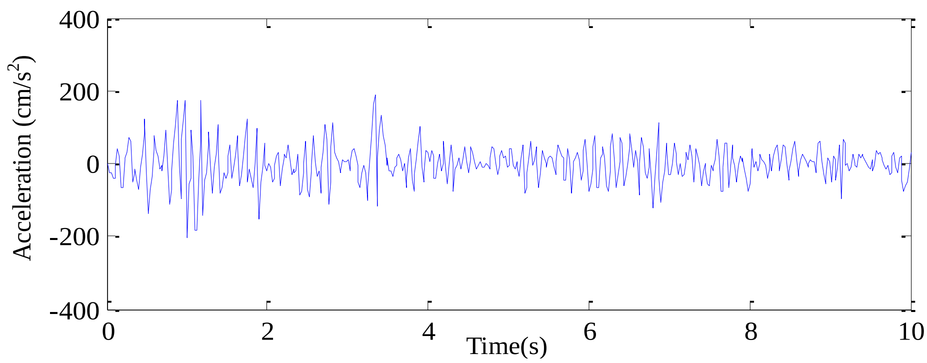

Fig. 21 The acceleration time history of Z-direction

4.4 Stress identification using fuzzy pattern recognition

The modified fuzzy pattern recognition method was proposed (Teng *et al*. 2012), in which the number of the pattern is not only one pattern when the stress identification is processed. There are 77000 patterns which are used to evaluate the proposed method, because there are 500 patterns in testing pattern library and the number of members in key region is 154. In order to verify the validity of proposed stress identification using modified fuzzy pattern recognition, the errors on these 77000 patterns are compared and discussed.

The noises are added to the simulated stress time histories in order to compare the stress identification errors produced by two different methods, the one uses non-improved fuzzy pattern recognition method which is based on one best pattern and the other uses improved fuzzy pattern recognition method which is based on multi patterns. In addition, the stress identification is only given in key region, in other words, the identified stresses and the known stresses are both from the stress of the members in key region.

The noise levels were 0.05, 0.10, 0.15, and 0.20, which are defined as the ratio of the root mean square (RMS) of the noise to the RMS of the stress time series (Chen *et al*. 2008).

Table 4Theproportion of the number of scenarios in identified stresses with less than 10% error

Noise level	Non-improved fuzzy pattern recognition method	Improved fuzzy pattern recognition method
0	100.000%	100.000%
5%	99.330%	99.551%
10%	95.386%	95.595%
15%	83.070%	85.071%
20%	68.325%	66.757%

$$\text{Noise level}=\frac{\text{RMS(noise)}}{\text{RMS(time series)}}\times 100\% \tag{1}$$

The noise is simulated by white noise with mean one, which standard deviation is calculated by given noise level and the root mean square of stress time series. The noise levels are from 0 to 20%, the comparison is proportion, which is the division between the number of scenarios in the identified stresses with less than 10% error and the number of scenarios in all the identified stresses. The error comparison between non-improved fuzzy pattern recognition method and improved fuzzy pattern recognition method is shown in Table 4. It can be seen from Table 4 that the recognition errors using improved fuzzy pattern recognition method is only better than the recognition errors using non-improved fuzzy pattern recognition method in a small range, especially when the noise level is 15%. That is to say, in the case of the low level of noise, using improved fuzzy pattern recognition method can effectively identify the stress in key region, but when the level of noise is high, the reliability of identification result can withstand certain questioning.

4.5 Stress identification using D-S evidence Theory

The identification result using measurements from key region is very ideal under the case with no noise from the above analysis, however, the reliability of the identification results reduced rapidly by increasing in the noise level. Though the errors are decreased when the improved fuzzy pattern recognition method is used, the errors of the identification results with high noise level are still not ideal. The D-S evidence theory is used to improve the reliability of recognition results under high noise level.

4.5.1 Discussion on the identification results influenced by noise

The noises are added to the simulated stress time histories in order to compare the stress identification errors using strain measurements from key region and the stress identification errors using strain measurements from not only key region but also other four normal regions. In addition, the stress identification in key region is still the error comparison content. The noise levels are from 0 to 20%, the comparison is proportion, which is the division between the number of scenarios in the identified stresses with less than 10% error and the number of scenarios in all the identified stresses. The error comparison between those from the key region and the others from key and normal regions is shown in Table 5.

It can be seen from Table 5 that the identification result with fusion is better than that with no fusion. The identification result is much better with increasing in noise level. When the noise level is 15%, the proportion of the result which the identification error is less than 10% using the method with fusion is 94.14%.Itis explainable that the reliability of identification result can still meet the requirement of the engineering practice under the high noise level when adopting the method of information fusion.

4.5.2 Discussion on the identification results influenced by sensor in fault

Considering the instrumentation of the structural health monitoring system and installation of sensors, the identification results influenced by sensor in fault are discussed here. In the real project application, where the sensor in fault may occur, the robustness of the proposed method should be known clearly, while the practicability of the proposed method can be proofed.

Table 5 The proportion of the number of scenarios in identified stresses with less than 10% error

Noise level	Identification result with no fusion	Identification result with fusion
0	100.000%	100.000%
5%	99.551%	99.699%
10%	95.595%	98.208%
15%	85.071%	94.139%
20%	66.757%	84.177%

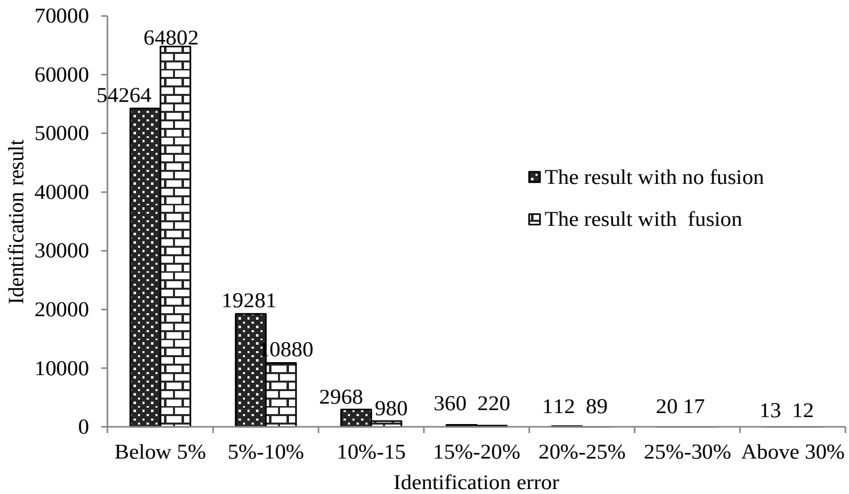

Fig. 22 The distribution of identification error with only one sensor out of work

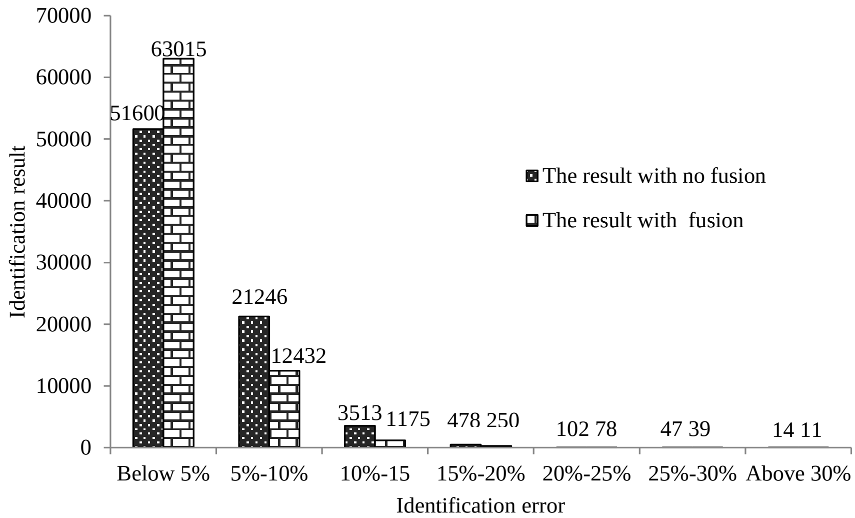

Fig. 23 The distribution of identification error with three sensors out of work

The error distribution of identification result, which is shown in Fig. 22, is under the condition that only one sensor is out of work in key region and the other sensors are disturbed by noise in 10% noise level. The error distribution of identification result, which is shown in Fig. 23, is under the condition that three sensors are out of work in key region and the other sensors are disturbed by noise in 10% noise level.

It can be seen from these two figures, when there is sensor in fault, the proportion of the result, which the identification error is less than 5%, using the method with fusion is greater than that using the method with no fusion. To sum up, when the sensor cannot measure because of its fault, the reliability of identification can be improved by adopting the method with information fusion. The advantage of information fusion method is gradually obvious in increasing number of the fault sensors.

5. Conclusions

This paper has presented the applications to two real world large space structures, such as the structural health monitoring system of Shenzhen Vanke Center and the structural health monitoring system of Shenzhen Bay Stadium. For each structural health monitoring system application, the descriptions of the structure, the purpose of structural health monitoring system, the measurement equipment and the benefits of using structural health monitoring system technologies in the project are listed and discussed in details. The presented real world structural health monitoring systems can offer the references to design structural health monitoring system for a project. As following, one intelligent structural health monitoring method is presented, including the intelligent methods to stress identification on the locations free of strain sensors. With the simulation on Beijing National Aquatics Center in China, the feasibility of the method when applying to complex large-span space structure is proofed.

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