The 6th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
Hong Kong | 9-11 December 2013

APPLICATIONS TO SHM SYSTEMS OF REAL STRUCTURES USING INTELLIGENT METHODS

J. Teng and W. Lu
Department of Civil and Environmental Engineering, Harbin Institute of Technology Shenzhen Graduate School, Shenzhen, China. Email: tengj@hit.edu.cn, lu.wei@hit.edu.cn

ABSTRACT

As the development on structural health monitoring systems and the applications on real structures, the intelligent structural health monitoring methods has been becoming the significant research contents. The implementation of structural health monitoring systems of the real large span steel roof is presented, including instruments and system integrations. Based on these structural health monitoring system applications on real projects, the intelligent algorithms are proposed to obtain more information on structural safety. The intelligent structural health monitoring methods are explored by the limited number of sensors and the various types of sensors. Extensive research focus on the information acquisition by similarity in substructure and using limited sensors, which is proofed by the simulation on a steel roof structure of Shenzhen Transportation Centre. As following, the information acquisition methods based D-S evidence theory and fuzzy sets are introduced, which is used to obtain the stress distribution on an important part of the structure and proofed by the numerical simulation on the steel roof of the National Aquatic Centre in China. Furthermore, the acquisition on stress distribution based on uncertainty is given and the measurements from the real structural health monitoring system of Shenzhen Bay Stadium are used and discussed. The research work in this paper can provide a reference for the designation and implementation of a real structural health monitoring systems and apply the identification on stress distributions effectively.

KEYWORDS

Structural health monitoring, intelligent systems, information acquisition, stress distribution.

INTRODUCTION

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 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 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 or goal (Ng 2003).

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. When the number of sensors located in the real monitored structure, the normal method cannot be used to determine the safety of the structures by direct monitoring the response of the most favorable components (Qu *et al.*, 2006). 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 and 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).

The structural health monitoring systems applications to real steel structures are presented in the paper, while the implementations and integrals of intelligent structural health monitoring system are introduced. Furthermore, the intelligent identification methods on stress distribution are proposed and proofed by numerical simulations on real structures or the measurements from the real structural health monitoring system of real structure. 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 developing on intelligent structural health monitoring method, the intelligent sensor systems are also discussed.

APPLICATIONS TO SHM OF REAL STRUCTURES

SHM of Shenzhen Vanke Center

Shenzhen Vanke Center is located at the Shenzhen Dameisha Sea Beach with a total land area of 61730m^2 and total construction area of 137116m^2. 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 (Figure 1). The reasons for taking a structural health monitoring system on this structure are from the architecture to the calculations on the structure. First of all, the structure is complicated with the irregular surface, the irregular reversing, large span and cantilever the noncontiguous vertical component; meanwhile, the structure is defined as project complexity and over-code-limit situation. Furthermore, the upper structure of the main work is hanged and the key construction process is the shape and deformation control. At last, the front four modes of the structure are sensitive to the dynamic loads, because of the long span and lower vertical frequency. It is close to the pedestrian running and jumping frequency, therefore the comfortable analysis is needed.

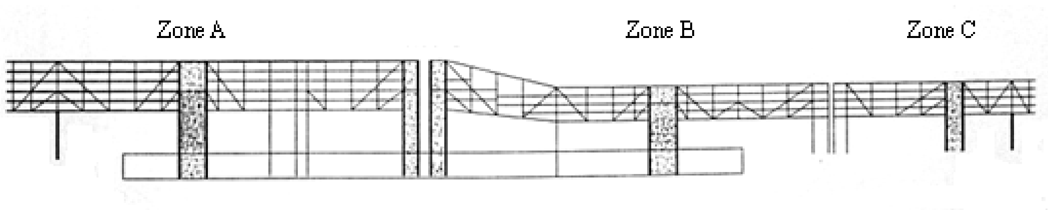

Figure 1. Main profile of Shenzhen Vanke Center structure

The 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. For this structural health monitoring system project, the stresses for the main elements and the deformation of the structure were applied in the structural construction period, and the stresses for the main elements and the vibration of the structure were applied in the structural working period. For various kinds of measurements, the strain sensors, accelerometers and total station all were used in the project as the sensor details are shown in Table 1.

Table 1. Sensor details for Shenzhen Vanke Center

monitoring	type of sensor	number	positon
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
stress	electric resistance strain gage	72	load bearing plate
stress	electric resistance strain gage	10	concrete- steel tube column
stress	electric resistance strain gage	72	welding
cable force	intelligence cable	16	cable
temperature	FBG temperature sensor	35	strain sensor
deformation	prism and total station	102	the end of long cable
comfort level	acceleration sensor	14	floor

Monitoring the stresses of the steel beams, columns, the optic fiber strain sensors were installed in the project. The installation pictures of the fiber optic strain sensors are shown in Figure 2. The protection method for the sensors and wires, which is shown in Figure 3, is to install a steel case for the sensors and to weld steel circuit for the wires. In this project, the steel cases were installed for all the optic strain sensors.

Figure 2. The fiber optic strain sensors

Figure 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, but the differences from the fiber optic strain sensors used for monitoring the steel beams and columns are their shapes and sizes. The intelligent cables should be embedded in the cables when the cables are manufactured in the factory. Figure 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, and 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 (Figure 5) and therefore the forces of the cables can be detected.

Figure 4. Intelligent cables in the factory

Figure 5. Intelligent cables on site

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 Figure 6 and Figure 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 Figure 8.

Figure 6. The prisms installed in the project

Figure 7. Measuring by total station

Figure 8. The accelerometer

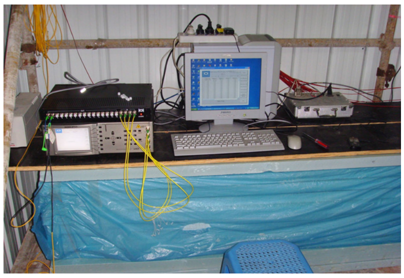

Figure 9. The temporary monitoring room

Only a standard substructure is selected to show the monitoring outcomes. The standard substructure is consist with two concrete tubes, steel beams and columns, steel girders and cables. The standard substructure model is shown in Figure 10. In this substructure, two intelligent cables were embedded in cables numbered LS54 and LS55. Here, in order to show the outcomes, the monitoring results from one cable numbered LS55, one steel beam, one steel column and deformation of one point are given and compared. The comparison on the measured cable force and designed cable force is presented in Table 2. It can be seen from Table 2 that during the 12 steps of loading, reloading and unloading process, the errors between measured cable force and designed cable force are less than ±6% except the second step. For the second step, the cable force is so small that the error calculated is larger than the other steps.

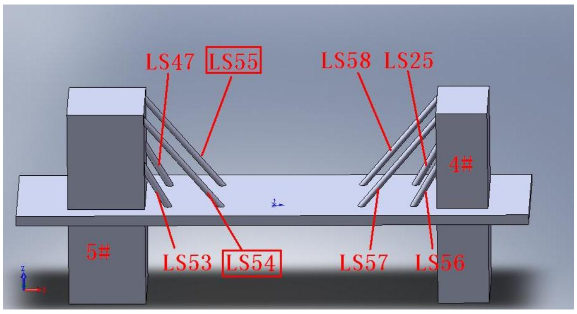

Figure 10. The standard substructure model

Table 2. Comparison on measured cable force and designed cable force

step	measured force	designed force	errors	description of tensioning step
1	0.0	0.0	0.00%	no loading
2	668.6	775.6	-13.8%	loading 20% of designed force
3	1163.4	1163.4	0.00%	loading 30% of designed force
4	1551.2	1551.2	0.00%	loading 40% of designed force
5	1595.8	1551.2	2.88%	reloading 40% of designed force
6	2266.8	2326.8	-2.58%	loading 60% of designed force
7	3040.9	3102.4	-1.98%	loading 80% of designed force
8	3444.0	3490.2	-1.32%	loading 90% of designed force
9	3719.5	3684.1	0.96%	loading 95% of designed force
10	3856.5	3878.0	-0.56%	loading 100% of designed force
11	3719.5	3878.0	-4.09%	unloading 80% of designed force
12	3656.4	3878.0	-5.71%	unloading 100% of designed force

In addition, the monitoring outcomes of the cable force, strains in steel beam and column, the deformation changes of the points are shown in Figure 11 to Figure 15. The monitoring deformation of each point in three directions explained the structural behavior, and guided the contractor and designer to make a decision on whether the construction was safe or not. The cable forces, stress of beam, stress and bending moment of columns, the deformations were monitored, while the structural behaviors of this standard substructure during the cables tensioning process were clear for the designer and the construction contractor with the monitoring measurements and analysis for each elements.

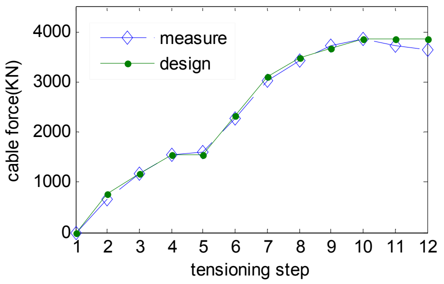

Figure 11. Monitoring cable force

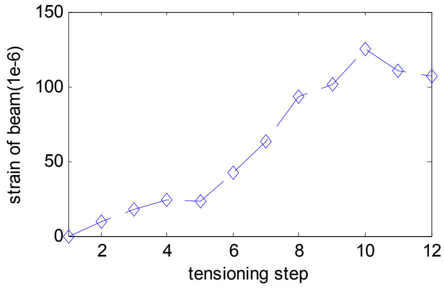

Figure 12. Monitoring strain of beam

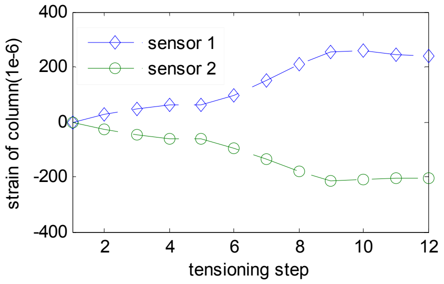

Figure 13. Monitoring strain of column

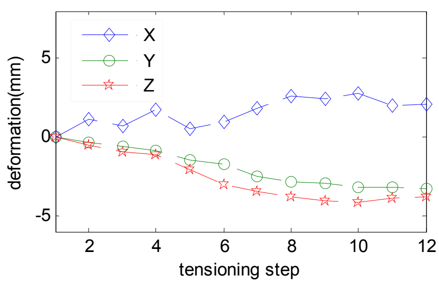

Figure 14. Monitoring deformation

The performances of the cables, steel beams, steel columns and floors are checked and the result verifies that the construction process were safe. In addition, the ability to collect measurements of real loading effects and structural responses is helpful to evaluate the designed parameters and assumptions. The monitoring measurements and analysis are useful to prove that the novel structure frame like Shenzhen Vanke Center with cables can be used to support such big and long space structure. 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 of the structure.

SHM of Shenzhen Bay Stadium

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. The picture of the structure is shown in Figure 15.

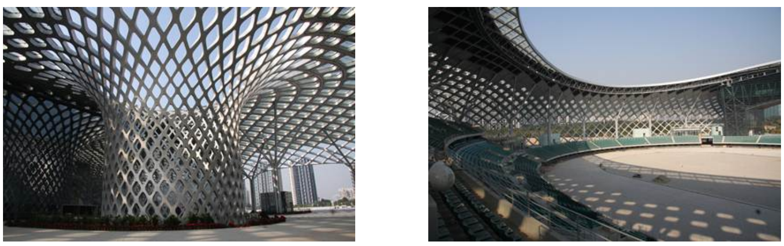

Figure 15. Corners of Shenzhen Bay Stadium

The main purposes of the structural health monitoring on this structure are firstly to provide the temperature of the different parts of the 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. 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 2.

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	acceleration sensor	8	steel roof and viewing bridge
wind speed	anemometer	2	the open fields of structure

The installation pictures of the fiber optic strain sensors are shown in Figure 16 and Figure 17. Figure 16 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 Figure 18. Furthermore, in order to obtain the data from the sensors, the temporary acquisition equipment was placed as that shown in Figure 19.

Figure 16 Installation of sensors

Figure 17 Sensors implementation

Figure 18 Accelerometers with steel case

Figure 19 Temporary acquisition equipment

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.

INTELLIGENT STRUCTUREAL HEALTH MONITORING SYSTEMS AND METHODS

The intelligent structural health monitoring systems are not only based on the intelligent sensors but also the intelligent methods.

Intelligent Sensors and Sensor Systems

Based on the developments and applications of the structural health monitoring systems on various structures, different kinds of the sensors are needed for different monitoring problems and monitoring environments. Furthermore, the functions of the sensors have been attracted more studied and attention.

Intelligent sensor technology (Teng *et al.* 2007) is a booming modern sensor technology. It is a comprehensive multi-disciplinary technology related to micro-mechanical and micro-electronics technologies, computer technology, signal processing, circuits and systems, sensor technology, neural network technology and fuzzy theory, and so on. The intelligent sensor systems are the sensors combined with microprocessor supplying the functions of examination and message treatment and have the properties of perception, study, reasoning, communication and administration. It is important for the intelligent sensor systems to obtain the intellect by intelligent combination of the sensors and microprocessor or microcomputer by means of the message transforming electric circuits. The primary intelligent characteristics of the intelligent sensors are self-controlling, self-transmission, self-running, self-acquisition, self-filtering and such, which means some functions of data managements are distributed to the intelligent sensors.

There are three approaches to achieve intelligent sensors (Teng *et al.* 2005). (1) non-integrated method. The non-integrated intelligent sensor systems are composed of the traditional sensors, message transforming electric circuits and microprocessors with digital bus interface. The intelligent sensor systems are achieved by attaching the microprocessors with digital bus interface based on the original non-integrated transmitter and the intelligent software is used for communication, control, adaptive, self-compensation and self-diagnosis. (2) Integrated method. The intelligent sensors are in micron order with the micro machining technology and large-scale integrated electric circuits based on the silicon material. (3) hybrid method. According to the needs and possibilities, various integrated segments of the system are combined in a multi-block chip with different combination way.

Intelligent Methods To Stress Identification

The authors proposed three intelligent methods to stress identification. The first one is the stress identification based on similarity in substructures; the second one is the stress identification using fuzzy sets and D-S theory; the third one is the stress identification using pattern identification considering uncertainties. The theories and effectiveness proofs by using the methods on finite element structures and real structures can be found their details in published papers (Teng 2010; Teng 2012; Teng 2013). The primary theory processes of these three stress identification methods are illustrated as follows.

The stress identification based on similarity was proposed using principle component analysis, cluster analysis and interpolation fitting method. The principle component analysis was used to obtain the main variables and form large number of measuring variables and to determine the elements and positions of measurement sensors. The elements or measuring data of resemble physical means or trends are clustered in one group to promote the data reliability and reduce the calculation time based on the clustering analysis method. The interpolation fitting method is used to obtain the smoother and more exactness variables for each clustering group variables. When data intervening for one clustering members, the information of neighbour clustering members is also used to harmonize the information in neighbour clustering members and promotes the reliability of information forecast of the clustering members.

The stress identification based on fuzzy sets and D-S theory was proposed to identify the stress distribution using measurements of limited strain sensors. Firstly, the structure is divided into several regions according to the similarity and the most unfavourable region is selected to be the key region for stress identification, while the different numbers of the strain sensors are located on the key region and the normal regions; secondly, the different stress distributions of the key region are obtained based on the measurements of the strain sensors located on the key region and the normal regions separately, in which the fuzzy pattern recognition is used to identify the different stress distributions; thirdly, the stress distributions obtained by the measurements of sensors in normal regions are selected to calculate the synthesized stress distribution of the key region by D-S evidence theory; fourthly, the weighted fusion algorithm is used to assign the different fusion coefficients to the selected stress distributions obtained by the measurements of the normal regions and the key region, while the synthesized stress distribution of the key region can be obtained. Numerical study on a lattice shell model is carried out to validate the reliability of the proposed stress identification method. The simulated results indicate that the method can improve identification accuracy and be effective by different noise disturbing.

The stress identification using pattern recognition considering uncertainties was proposed and strain sensors and deformation measurements were both used in the proposed stress identification method. There are some uncertainties which are existed in structural health monitoring system, especially in the measurements collected from sensors and the effectiveness of the sensors, considering these uncertainty, the best pattern selected may not be the real best one. The proposed method modified the selection on patterns. Firstly, the measurements were divided into several parts, and there must be a best pattern for each part of measurements, while several best patterns can be obtained from these parts of measurements. Secondly, the identified stress values were synthesized by fusion method. Thirdly, the input patterns for the pattern recognition were changed to two kinds of measurements which are from strain sensors and displacement sensor. The analysis and comparisons were given and the conclusions are: (1) the number of the sensors are important parameter for stress identification, while the more the number of the sensors, the more precise in identified stress values; (2) the placements of the located sensors are another important parameters for stress identification, while the sensors are located near the identified structural member, the identified stress value is better; (3) the identified stress values are better when two kinds of sensors are used rather than one kind of sensors.

Intelligent Methods To Damage Identification

More and more large span structures have been built or are being built and their health is concerned about by civil engineers and investors, which arises to the problem of studying on several damage identification methods to give estimation on the health of the structure and the identification on damage location and damage degree. The damage identification methods in civil engineering are mostly based on dynamic characteristics, which have difficulties when applied to practical structures. Meanwhile, the strains of the structural important elements can give more exactly and more directly information for damage identification on damage location and damage degree. The information fusion for acceleration sensors and strain sensors is used for making a strategic decision on damage identification and the Dempster-Shafer evidence theory is used as the information fusion strategic decision, in which the strategic decision information fusion is a method to give the final decision based on the decision made by each kind of sensors according to some principle and some synthesized evaluation, that is, the final damage identification results are given based on the damage identification results using the structural dynamic characteristics and strain measurements. In addition, a finite element model of large span space shell structure is built and several damage cases of it are simulated, in the example, the structural dynamic characteristics damage index and strain measurements damage index are used to give the damage identification results, combining which the final damage identification result by strategic decision fusion is given too, while the method is proofed to be reliable and effective according to comparing the three kinds of damage identification results mentioned above. More details can be found in Lu’s paper (Lu 2009).

CONCLUSIONS

This paper has presented the applications to real large space structure, such as the structural health monitoring system of Shenzhen Civic Center and the structural health monitoring system of Shenzhen Bay Stadium. For each structural health monitoring system application, the description 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 in the paper. The presented real structural health monitoring systems can offer the references to the design of the structural health monitoring system for a project. As following, some intelligent structural health monitoring methods are presented, including the intelligent methods to stress identification on the locations free of strain sensors and the intelligent methods to damage identification using two kinds of measurements from sensors. With the simulation on real structures, the intelligent methods are all proofed to be effective and efficient for stress identification and damage identification. However, the intelligent structural health monitoring systems are still needed to improve in intelligent sensors and intelligent methods using bio-inspired.

ACKNOWLEDGMENTS

The work is supported by National Science Foundation of China, National Key Project No. 50678052, and Support Project for New Teacher from Harbin Institute of Technology Shenzhen Graduate School.

REFERENCES

Barr, P.J, Woodward, C.B., Najera, B. and Amin, M.N. (2006). "Long-term structural health monitoring of the San Ysidro Bridge", *Journal of Performance of Constructed Facilities*, 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", *Engineering Structures*, (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", *Engineering Structures*, (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.

Liu, M., Frangopol, D.M. and Kim, S.Y. (2009). "Bridge system performance assessment from structural health monitoring: a case study", *Journal of Structural Engineering*, 35(6), 733-742.

Lu, W. and Teng, J. (2009). "The acquisition method for structural synthesized damage identification decision based on information fusion", *The First International Postgraduate Conference on Infrastructure and Environment*, Hong Kong, China, June 2009, 454-460.

Ng, G.W. (2003). *Intelligent systems – fusion, tracking and control*, Research Studies Press Ltd.

Park, G., Rosing, T., Todd, M.D., Farrar, C.R. and Hodgkiss, W. (2008). "Energy harvesting for structural health monitoring sensor networks", *Journal of Infrastructure Systems*, 14: 64-79.

Qu, W.L., Teng J., Xiang, H.F., Zhong, L., Liu, H., Wang, J. and Li, G.B. (2006). "Intelligent health monitoring for roof space truss structure of the Shenzhen Citizen Centre under wind load", *Journal of Building Structures*, 27(1):1-8.

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., Liu, H. J., Lu, W. and Zhu, Y.H.(2005). "Intelligent sensor system for the structural health monitoring", *Proceedings of the 2nd international Conference on Structural Health Monitoring of Intelligent Infrastructure*, Shenzhen, China.

Teng, J., Xiao, Y.Q., Liu, H.J. and Lu, W.(2007). "The hardware and software inplementation of the health monitoring system for large span space structures", *Proceedings of the International Conference on Health Monitoring of Structure, Material and Environment*, Vol. 1, 141-145.

Teng, J. and Lu, W. (2010). "Efficient structural health monitoring by limited strain measurements", *Proceedings of '10 Earth and Space Conference*, Honolulu.

Teng, J., Zhang, T. and Lu, W. (2012). "Structural stress identification using fuzzy pattern recognition and information fusion technique", *Journal of Civil Engineering and Architecture*, 6(4): 479-488.

Teng, J., Lu, W. and Wu, F. (2013). "Implementation of structural health monitoring to a real large span steel roof and analysis on its stress identification", *Structural Health Monitoring for Life Cycle Management of Large Civil and Hydraulic Infrastructures*, Jeju, Korea.

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.