A STUDY ON EFFECTIVE STRUCTURAL HEALTH MONITORING SYSTEM OF BRIDGE STRUCTURES

Akira TAKAUE
Chodai, Co., Ltd., Japan
E-mail: takaue-a@nifty.com

Abstract

Structural Health Monitoring System (”SHMS”) is to evaluate structural soundness based on correlation between excitations and responses, and additionally, is to detect structural deterioration and performance degradation seizing tendency of the chronological transition. In this paper, major purposes for the SHMS on bridge structures will be organized; additionally, effective the SHMS will be proposed on monitoring procedures and organizational operation.

Keywords: Structural Health Monitoring System, Long-Span Bridge, maintenance, design verification, traffic control

1. INTRODUCTION

Although semi permanent durability is generally expected to long-span bridges including cable-stayed bridges, structural performance is gradually degraded with time passage due to various continuous factors such as corrosion, cracks, abrasion, structural deterioration, fatigue and deformation. Therefore, appropriate maintenance management is necessary to be implemented uninterruptedly so that suitable services, which have been designed in the bridge design stage, are definitely provided. Accordingly, monitoring technique, which has sufficient capability to detect structural deterioration and performance degradation accurately, is essential to be applied in order to implement effective maintenance management.

Currently, structural health monitoring system (“SHMS”) becomes general monitoring method for long-span bridges; the main objective is to evaluate bridge soundness based upon conduct of continuous monitoring activity. SHMS is to evaluate structural soundness by utilizing various numeric data based upon correlation between excitations and responses, and additionally, is to detect structural deterioration and performance degradation by seizing tendency of the chronological transition. Accordingly, it provides informative data for planning of efficient maintenance management, and at the same time bridge administrators enable to estimate a period of that generated stresses, forces and deformations reach critical value, appropriately.

However, many existing cases of the SHMS do not utilized efficiently because the quantities of applied devices are too many so that management thereof is not performed appropriately. And some cases are unfortunately untreated without detecting device failure. Additionally, in some cases, devices have been planned and installed without studies of the behaviours of the bridge subjected to critical excitations assumed in design concepts and natural condition.

In this paper, the major purposes of the SHMS to be considered during planning stage are organized, and efficient method of sensor selection consisting of the SHMS is proposed. Besides, an example of effective monitoring methodology using visual monitoring software is introduced.

2. MAJOR PURPOSES OF SHMS

Effective SHMS firstly strongly requires establishment of definite the major purposes of the system. Currently following the three major purposes are established on the SHMS utilized the bridge structures in the world.

(1) Design verification

i) To provide data to verify the design assumption

ii) To provide data to develop appropriate analyses or methodology for other projects

(2) Structural maintenance

i) To provide data for assessment of structural deterioration and performance degradation

ii) To provide data for improvement of maintenance activities

(3) Traffic management

i) To utilize the monitoring data for traffic management or control passing on the bridge, not only during abnormal climate but also after attacked by earthquake or strong wind blows

The backgrounds of bridge structures, such as location, natural conditions, design policy, estimated traffic volume, applied design standards, maintenance policy and administrative organization, are different among the bridges. The priority levels of major purposes should be determined based on sufficient discussions technically and administratively among related organizations.

3. EFFICIENT SENSOR SELECTION

3.1 Points to consider

Periodic the labor inspection executed by bridge inspectors must be a significant role in the evaluation of the structural soundness and maintenance activities; however, it would be of arduous activity physically and economically for only the labor inspection to organize vast accumulated data requisite to understand the chronological transition of the bridge structure or meteorological conditions, such as unexpected climate, unexpected occurrence to the bridge structure and the transition of structural deterioration or performance gradation progressing slowly for a long term. Therefore, the monitoring utilizing the SHMS may have efficient advantages to provide informative data for macroscopic bridge management based upon evaluation of organized vast accumulated data; however, if a lot of number of sensors were installed, it would require tremendous investment in spite of its effectiveness. Additionally, because the SHMS consists of aggregation of electrical devices, its running cost would be quite an expense due to trouble or breakdown of the electrical devices.

Consequently, the sensor selection of the SHMS should be determined based upon specific the main purposes and the measurement objects in consideration of following the concepts.

- Structural property
- Natural environment
- Design policy
- Specific measurement objects and usage
- Economic efficiency
- Reliability of the sensors

In order to carry out the sensor selection in consideration of above concepts, a methodology realizing effective sensor selection based on risk analysis is proposed.

3.1.1 Target bridge

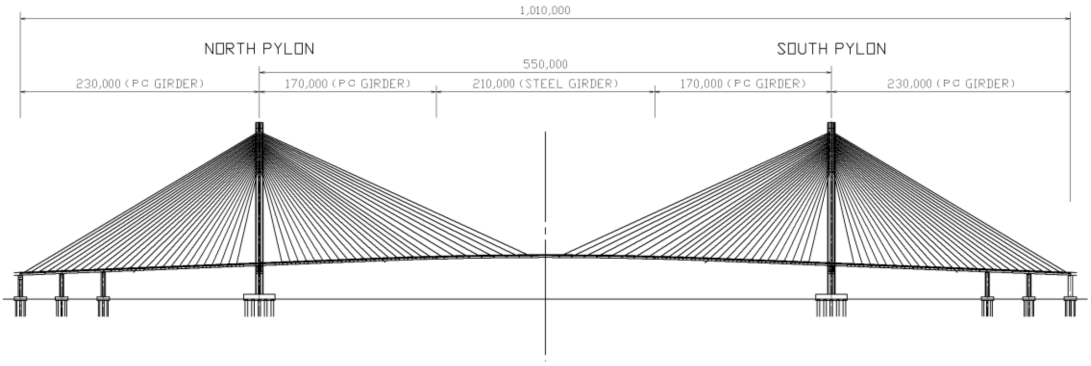

Figure 1: Side View of Can Tho bridge

The figure 1 shows the target bridge as an example, Can Tho Bridge located in Vietnam, for the sensor selection in consideration of risk analysis. The structural specifications are follows.

- Bridge length is 1010m, the girder consists of steel deck and PC deck, in which the center of the girder is 210m length steel deck, and other area is PC deck
- Pylon foundations are constructed in river bottom
- 6 traffic lanes

3.1.2 Preparation of risk analyasis matrix

Structural property, natural condition and design policy are totally evaluated, and following risk analysis matrix is prepared shown in the figure 2.

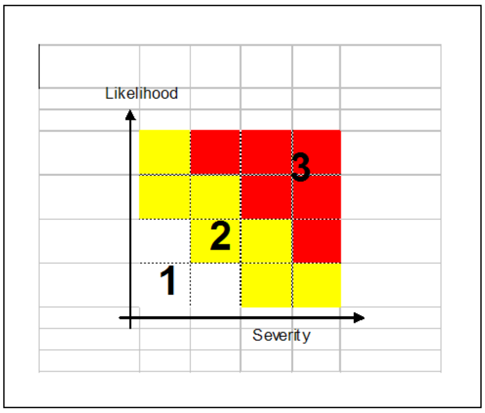

Figure 2: Risk Analysis Matrix

In the matrix, vertical axis defines the values of the likelihood against a risk; horizontal axis defines the values of the severity against the risk. And the integrated values defined as the criticality is obtained by multiplication of such the two values. Then, following conditions are considered shown in the figure 3.

1) Severity
- 4 = Risk of collapse of the structure;
- 3 = Risk of major damage to the structure without collapse;
- 2 = Local damage;
- 1 = No damage

2) Likelihood
- 4 = Occurring several times a year;
- 3 = Occurring approximately once a year;
- 2 = Occurring approximately once every 10 years;
- 1 = Occurring approximately once every 100 years;

3) Criticality
- 3 = $L*S \geq 8$: Surveillance is recommended
- 2 = $7 \geq L*S \geq 3$ Surveillance is to be discussed
- 1 = $2 \geq L*S$: Surveillance is not necessary

Figure.3: Analysis condition

The table of the likelihood and the severity against risks, which above methodology of the matrix is applied to the target bridge, are organized as shown in the following table.

Table 1: The Likelihood and Severity for Risks

Probability / Severity		Material															Vehicle Loads		Incident Loads (Excitations)									Others		
		Ground			Concrete				Mild Steel			High strength Steel																		
		Scour	Settlement	Liquefaction	Neautralization	Rebar corrode by Neautral	Rebar corrode by Chloride	alkali-aggregate reaction	Fracture by Corrode	Buckling	Fracture by Fatigue	Brittle fracture	Brittle fracture of H.T.B	Fracture by Corrode	Relaxation of Tensile for	Fracture by Fatigue	Overloading	Traffic accident	Abnormal deformation by w	Abnormal local vibration	Abnormal overall vibratio	Ocean waves	Tsunami	Vehicle fire	Large ship allision	Ship allision	Earthquaki	Inaddecuate maintenance	Vandalization	Sabotage
Elements	Likelihood (1 to 4)	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	4	3	2	4	2	2	1	2	2	3	1	2	1	1
Foundation	North Pylon	3	2	1	3	3	3	3	3	*	*	*	*	*	*	*	1	*	1	*	1	2	3	*	4	2	3	1	1	1
	South Pylon	3	2	1	3	3	3	3	3	*	*	*	*	*	*	*	1	*	1	*	1	2	3	*	4	2	3	1	1	1
Sub Str.	Piers	3	2	1	3	3	3	3	*	*	*	*	*	*	*	*	1	*	1	*	1	2	3	*	4	2	3	1	1	1
	Pile Cap	3	2	1	3	3	3	3	*	*	*	*	*	*	*	*	1	*	1	*	1	2	3	*	4	2	3	1	1	1
Pylon	Tower	1	1	1	4	4	4	4	*	*	*	*	*	*	3	*	2	2	4	1	4	1	3	2	4	2	3	1	3	3
	Anchorage	1	1	1	*	*	*	*	4	*	4	*	*	*	3	4	2	*	4	2	4	*	*	*	*	*	2	2	4	4
Cables	Cables	*	*	*	*	*	*	*	*	*	*	*	*	4	3	4	2	2	4	2	4	*	*	4	*	*	1	2	4	4
	Anchorage	*	*	*	*	*	*	*	*	*	*	*	*	4	3	4	2	2	4	2	4	*	*	4	*	*	1	2	4	4
Deck	Deck	*	*	*	*	*	*	*	4	3	4	3	3	4	3	4	3	2	4	2	4	*	*	3	*	*	2	2	4	3
	Bearing	*	*	*	*	*	*	*	3	*	3	*	*	*	*	*	2	*	4	2	4	*	*	2	*	*	3	2	4	3
	Expantions	*	*	*	*	*	*	*	2	*	2	*	*	*	*	*	3	2	2	2	2	*	*	2	*	*	2	2	2	2
	Anchorage of Cable	*	*	*	*	*	*	*	3	3	3	*	*	*	*	4	2	2	4	2	4	*	*	3	*	*	3	2	2	2

Then, the integrated values defined as the criticality is obtained by multiplication of both the values, the likelihood and severity, shown in the following table.

Table 2: The Criticality for Risks

Probability / Severity		Material															Vehicle Loads		Incident Loads (Excitations)									Others		
		Ground			Concrete				Mild Steel			High strength Steel																		
		Scour	Settlement	Liquefaction	Neautralization	Rebar corrode by Neautral	Rebar corrode by Chloride	alkali-aggregate reaction	Fracture by Corrode	Buckling	Fracture by Fatigue	Brittle fracture	Brittle fracture of H.T.B	Fracture by Corrode	Relaxation of Tensile for	Fracture by Fatigue	Overloading	Traffic accident	Abnormal deformation by w	Abnormal local vibration	Abnormal overall vibratio	Ocean waves	Tsunami	Vehicle fire	Large ship allision	Ship allision	Earthquaki	Inaddecuate maintenance	Vandalization	Sabotage
Elements	Likelihood (1 to 4)	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	4	3	2	4	2	2	1	2	2	3	1	2	1	1
Foundation	North Pylon	6	4	1	6	6	6	6	6	*	*	*	*	*	*	*	4	*	2	*	2	4	3	*	8	6	3	2	1	1
	South Pylon	6	4	1	6	6	6	6	6	*	*	*	*	*	*	*	4	*	2	*	2	4	3	*	8	6	3	2	1	1
Sub Str.	Piers	6	4	1	6	6	6	6	*	*	*	*	*	*	*	*	4	*	2	*	2	4	3	*	8	6	3	2	1	1
	Pile Cap	6	4	1	6	6	6	6	*	*	*	*	*	*	*	*	4	*	2	*	2	4	3	*	8	6	3	2	1	1
Pylon	Tower	2	2	1	8	8	8	8	*	*	*	*	*	*	6	*	8	6	8	4	8	2	3	4	8	6	3	2	3	3
	Anchorage	2	2	1	*	*	*	*	8	*	8	*	*	*	6	8	8	*	8	8	8	*	*	*	*	*	2	4	4	4
Cables	Cables	*	*	*	*	*	*	*	*	*	*	*	*	8	6	8	8	6	8	8	8	*	*	8	*	*	1	4	4	4
	Anchorage	*	*	*	*	*	*	*	*	*	*	*	*	8	6	8	8	6	8	8	8	*	*	8	*	*	1	4	4	4
Deck	Deck	*	*	*	*	*	*	*	8	6	8	6	6	8	6	8	12	6	8	8	8	*	*	6	*	*	2	4	4	3
	Bearing	*	*	*	*	*	*	*	6	*	6	*	*	*	*	*	8	*	8	8	8	*	*	4	*	*	3	4	4	3
	Expantions	*	*	*	*	*	*	*	4	*	4	*	*	*	*	*	12	6	4	8	4	*	*	4	*	*	2	4	2	2
	Anchorage of Cable	*	*	*	*	*	*	*	6	6	6	*	*	*	*	8	8	6	8	8	8	*	*	6	*	*	3	4	2	2

Above table enables to organize following the results.

Table 3: Results of the risk analysis

Criticality	Members	Risks	Monitoring	Inspection
12	Deck Expansion	Over Loading	Monitoring of vehicle loads	Periodic Inspection
8	Foundation, Pylon, Deck	Material deterioration	-	Non-destructive Inspection
	Pylon, Cable, Deck	Wind Loads	Anemometer	Periodic Inspection
	Foundation, Pylon, Piers	Ship allision	Ship Monitoring, Disp Guge	Periodic Inspection
	Cable	Vehicle fire	Vehicle Monitoring	-
6	Sub structures, Foundation	Scour, Settlement	-	Periodic Inspection
4	Pylon, Cable, Deck	Sabotage	Monitoring	Monitoring

Based on the results, the following sensor selection can be determined.

Table 4: Results of an example of sensor selection

Criticality	Members	Risks	Sensors
12	Deck Expansion	Over Loading	Weigh-In Motion System, Strain gauge for fatigue prediction
8	Foundation, Pylon, Deck	Material deterioration	GPS, Thermo-couples, Air thermometer, EM Sensor, Accelerometers, Optic fiber displacement gauge
	Pylon, Cable, Deck	Wind Loads	Anemometer, GPS, Thermo-couples, Air thermometer

	Foundation, Pylon, Piers	Ship allision	CCTV
	Cable	Vehicle fire	CCTV
6	Sub structures, Foundation	Scour, Settlement	Scour sensor, Inclinometer, GPS, Displacement gauge
4	Pylon, Cable, Deck	Sabotage	CCTV

4. EFFECTIVE DATA PROCESSING

4.1 Usage and Analysis of Measured data

Primitively, the SHMS must enable to evaluate the bridge soundness diagnosing the structural initial damages, chronological transition of behaviors subjected to various excitations and environmental conditions. Therefore, establishing appropriate the SHMS functionally and economically effects informative advantages in the maintenance activities and the traffic controlling; however, the collected data for some of the bridges in the world transmitted from applied the sensors are not appropriately incorporated into maintenance or evaluation systems; efficient evaluation of the bridge soundness is not performed in such the bridges. Hence, following six items are proposed as management policies to evaluate the precious data obtained by the selected devices determined based on risk analysis in consideration of the major purposes of the SHMS

- Enhancement of Visual Monitoring Software
- Sensitivity Analysis based on various excitations and Detailed analysis of Risks
- Determination of Trigger values and Alert system
- Feedback of the major purposes
- Feedback of the risk analysis
- Examination and close discussion for collected data among related organization

4.2 Enhancement of Visual Monitoring Software

In order to execute effective monitoring, enhancement of visual monitoring software is strongly necessary. The software should have the function of not only real time measurement but also long-term tendency. Additionally, the measurement results should be operated simultaneously with meteorological data and CCTV, which should be confirmed visually in order that administrators who do not have expert knowledge of bridge structure can evaluate in elementary levels.

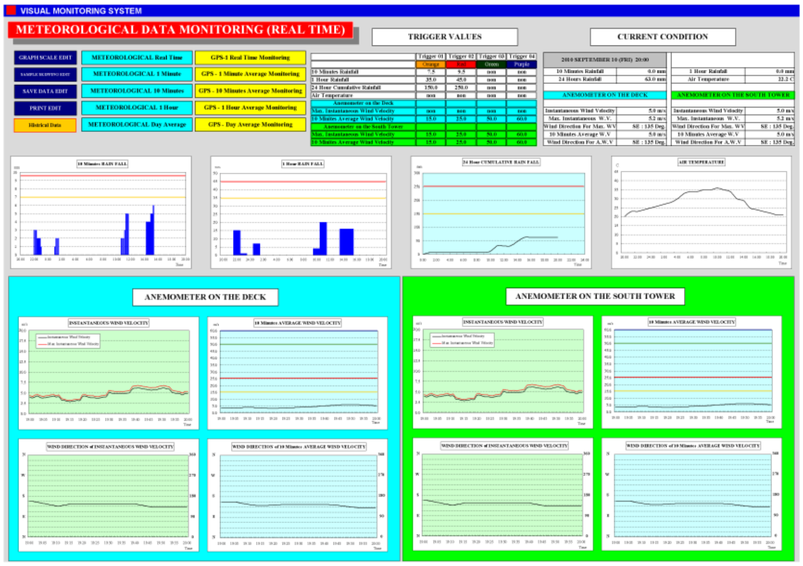

Figure 4 Conceptual image of the Software of Visual monitoring software

4.3 · Sensitivity Analysis based on various excitations and Detailed analysis of Risks

Sensitivity analysis between bridge behaviour and expected excitations and loads is also important item to determine risk areas, such as:

1) Dangerous area: Over the proof strength assumed in the design stage

2) Warning area: Over the serviceability limit state

3) Safety area III, Safety area II and Safety area I

Above areas are determined based on the results of risk analysis, sensitivity analysis and design policies of the bridge engineers in depth.

5. CONCLUSIONS

In this paper, an efficient method of sensor selection consisting of the SHMS, in consideration of risk analysis including structural properties, natural conditions and design policy of the bridge, is proposed. Besides, an example of effective monitoring methodology using visual monitoring software is introduced. Even if such the selection and visual monitoring software were installed in the SHMS, a package including definite major purposes of the SHMS and feedback of the risk analysis would be requisite within at least every 5 years after bridge completion.

For the future, more efficient methodology to determine the sensor selection based on risk analysis will be necessary, and newly developed visual monitoring software called as total evaluation system including trigger values, the results of sensitivity analysis and recorded data of periodic labour inspection, which can evaluate structural soundness will be developed and introduced.

References

Sunaryo SUmitro "Akashi Kaikyo Bridge and Tatara Bridge", *Current and Future Trend in Long Span Bridge Health Monitoring System in Japan, The national Science Foundation on Health Monitoring of Long Span Bridges,* University of California.

Emst Lauren (2004) "Great Belt Bridge", *The 4th International Cable Supported Bridge Operator's Conference,* 16-19 June 2004, Coventry University, UK.

Kai-yuen Wong, King-leung Man and Wai-yee Chang (2001), "Tsing Ma, Kap Shui Mun, Ting Kau Bridge", *Monitoring Hong Kong's Bridges Real-Timie Kinematic Spans the Gap*, July 2001, GPS WORLD.

Limin Sun, Qiwei Zhang, Airong Chen and Zhixing Lin (2006) "Cable vibration control countermeasures and structural health monitoring system design of Sutong Bridge", *2nd International Conference on Bridge Maintenance, Safety and Management,* 18-22 Oct. 2006.