Integrating Bridge Structural Health Monitoring and Condition-Based Maintenance Management

Y.Q. NI*, K.Y. WONG**
*Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong (ceyqni@polyu.edu.hk)
**Highways Department, The Hong Kong Special Administrative Region Government, Hong Kong

Abstract. The development of structural health monitoring (SHM) technology has evolved for over fifteen years in Hong Kong since the implementation of the "Wind And Structural Health Monitoring System (WASHMS)" on the suspension Tsing Ma Bridge in 1997. Five cable-supported bridges in Hong Kong, namely the Tsing Ma (suspension) Bridge, the Kap Shui Mun (cable-stayed) Bridge, the Ting Kau (cable-stayed) Bridge, the Western Corridor (cable-stayed) Bridge, and the Stonecutters (cable-stayed) Bridge, have been instrumented with sophisticated long-term SHM systems. These SHM systems mainly focus on the tracing of structural behavior and condition of the long-span bridges over their lifetime. Recently, a structural health monitoring and maintenance management system (SHM&MMS) has been designed and will be implemented on twenty-one sea-crossing viaduct bridges with a total length of 9,283 km in the Hong Kong Link Road (HKLR) of the Hong Kong – Zhuhai – Macao Bridge of which the construction commenced in mid-2012. The SHM&MMS gives more emphasis on durability monitoring of the reinforced concrete viaduct bridges in marine environment and integration of the SHM system and bridge maintenance management system. It is targeted to realize the transition from traditional corrective and preventive maintenance to condition-based maintenance (CBM) of in-service bridges. The CBM uses real-time and continuous monitoring data and monitoring-derived information on the condition of bridges (including structural performance and deterioration mechanisms) to identify when the actual maintenance is necessary and how cost-effective maintenance can be conducted. This paper outlines how to incorporate SHM technology into bridge maintenance strategy to realize CBM management of bridges.

Introduction

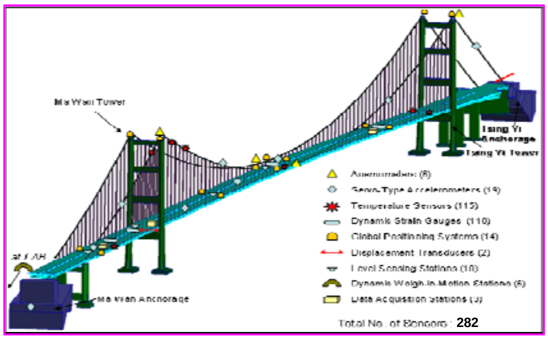
It has been increasingly recognized that the field monitoring data from structural health monitoring (SHM) systems deployed on long-span bridges are very helpful to verify design assumptions and parameters, to alarm abnormal loading and response, to assess structural integrity after disasters and structural serviceability during extreme events, to issue early warnings on structural damage/deterioration, and to instruct the design of similar structures in future [1-2]. The development of SHM technology in Hong Kong has evolved for over fifteen years since the implementation of the so-called "Wind And Structural Health Monitoring System (WASHMS)" on the suspension Tsing Ma Bridge in 1997. Five long-span cable-supported bridges in Hong Kong, namely the Tsing Ma (suspension) Bridge, the Kap Shui Mun (cable-stayed) Bridge, the Ting Kau (cable-stayed) Bridge, the Western Corridor (cable-stayed) Bridge, and the Stonecutters (cable-stayed) Bridge, have been instrumented by the Highways Department of the Hong Kong Special Administrative Region (SAR) Government with sophisticated long-term SHM systems [3-7]. The SHM systems also were periodically updated in order to effectively execute the functions of structural condition monitoring and structural degradation evaluation under in-service condition.

Recently, a SHM and maintenance management system (SHM&MMS) has been designed and will be implemented on twenty-one sea-crossing viaduct bridges with a total length of 9,283 km in the Hong Kong Link Road (HKLR) of the Hong Kong – Zhuhai – Macao Bridge of which the construction commenced in mid-2012 [8]. Different from the WASHMS that was mainly focused on the monitoring of environmental loads, bridge features and bridge responses, the SHM&MMS is an integrated system combining SHM and bridge maintenance management. This new system will render the monitoring data and monitoring-derived results directly useful for decision-making on and prioritization of bridge inspection and maintenance. It gives much more emphasis and efforts on realizing condition-based and life-cycle maintenance management with the aid of SHM system. After briefing the WASHMS currently operating for the five cable-supported bridges in Hong Kong, this paper introduces the functions and features of the SHM&MMS devised for the twenty-one viaduct bridges in the HKLR, and outlines how to realize the integration of SHM and condition-based maintenance (CBM) management.

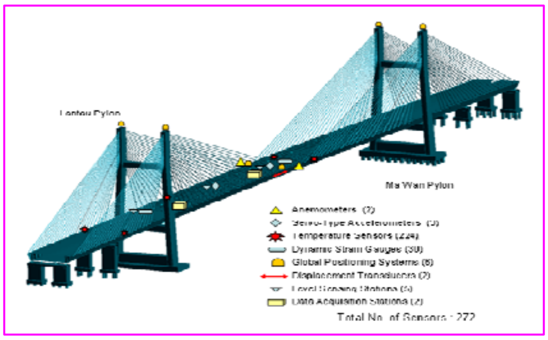
2. WASHMS Currently Operating for Cable-supported Bridges in Hong Kong

The WASHMS for the five cable-supported bridges in Hong Kong was designed and implemented for real-time monitoring of four categories of physical parameters: (i) environments (wind, temperature, seismic, humidity, corrosion status, etc.), (ii) operational loads (highway traffic, railway traffic), (iii) bridge features (including static features such as influence coefficients and dynamic features such as modal parameters), and (iv) bridge responses (geometrical profile, cable force, displacement/deflection, strain/stress histories, cumulative fatigue damage, etc.). Figure 1 illustrates the WASHMS deployed on the five bridges. In accordance with a modular design concept [5], the WASHMS is composed of six modules, namely, Module 1 – Sensory System (SS), Module 2 – Data Acquisition and Transmission System (DATS), Module 3 – Data Processing and Control System (DPCS), Module 4 – Data Management System (DMS), Module 5 – Structural Health Evaluation System (SHES), and Module 6 – Inspection and Maintenance System (IMS). The SS and DATS are sensors, on-structure data acquisition units (DAUs), and cabling networks for signal collection, processing and transmission. Table 1 summaries various sensors and DAUs permanently installed on the five bridges. The DPCS is a computer system for the execution of system control, system operation display, and processing and analysis of data. The DMS refers to a database or data warehouse system for the storage and retrieval of monitoring data and analysis results. The SHES, which is the core of the WASHMS, is a high-performance computer system equipped with appropriate software and advanced analysis tools for the execution of finite element analysis, sensitivity analysis and model updating, bridge feature and response analysis, diagnostic and prognostic analysis, and visualization of analyzed results. It includes an on-line structural condition evaluation system and an off-line structural health and safety assessment system. The IMS is a laptop-computer-aided portable system for the inspection and maintenance of the WASHMS itself.

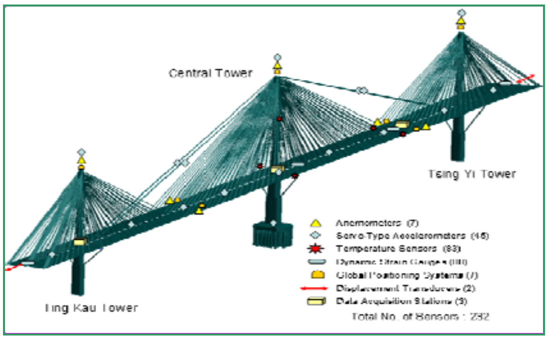
The WASHMS was devised for the objectives: (i) to have a better understanding of the structural behavior of the cable-supported bridges under their in-service condition; (ii) to develop and validate the bridge evaluation techniques based on measurement results; (iii) to setup/calibrate/update the monitoring and evaluation models and criteria for describing and limiting the variation ranges of the physical parameters that influence bridge performance



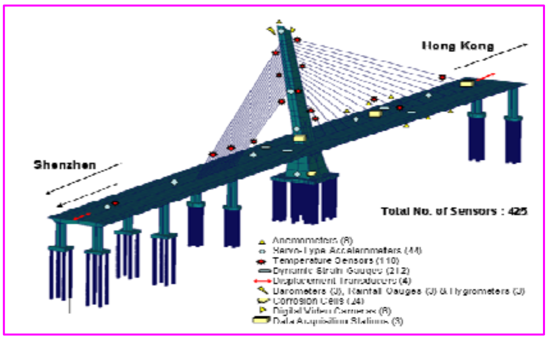
(a) Tsing Ma Bridge (TMB)



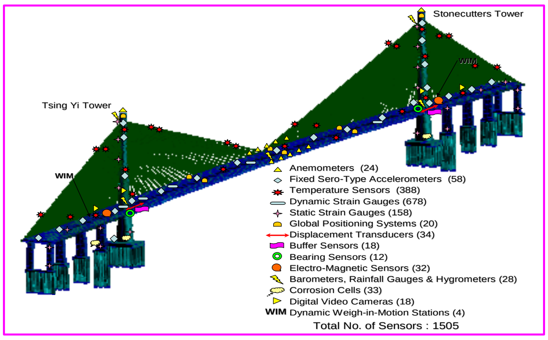
(b) Kap Shui Mun Bridge (KSMB)



(c) Ting Kau Bridge (TKB)



(d) Western Corridor Bridge (WCB)



(e) Stonecutters Bridge (SCB)

Figure 1. WASHMS for Cable-supported Bridges in Hong Kong

Table 1. Sensors Deployed on Cable-supported Bridges in Hong Kong

Type of Sensors	TMB	KSM	TKB	WCB	SCB
Anemometer	6	2	7	8	24
Servo-type accelerometer	19	3	45	44	58
Dynamic and static strain gauge	110	30	88	212	836
Displacement transducer	2	2	2	4	34
Temperature sensor	115	224	83	118	388
Global positioning system (GPS)	14	6	7	--	20
Level sensing station	10	5	--	--	--
Dynamic weigh-in-motion station	6	--	6	--	4
Barometer, Rainfall gauge & Hygrometer	--	--	--	9	28
Corrosion cell	--	--	--	24	33
Digital video camera	--	--	--	6	18
Elasto-magnetic sensor	--	--	--	--	32
Buffer sensor	--	--	--	--	18
Bearing sensor	--	--	--	--	12
Data acquisition station	3	2	2	3	8
Total number of sensors	282	272	238	425	1,505

under in-service condition; (iv) to evaluate structural integrity immediately after rare events such as typhoons, strong earthquakes and vehicle/vessel collisions, etc.; (v) to provide information and analytical tools for the planning, scheduling, evaluating and designing of effective long-term bridge inspection and maintenance strategies; and (vi) to minimize the lane-closure time required for exercising bridge inspection and maintenance activities, hence maximizing the traffic operational period of the bridges. The WASHMS deployed on the five bridges has operated continuously and steadily more than ten years. With the acquired monitoring data, a lot of investigations on condition assessment and damage detection of large-scale cable-supported bridges have been conducted [9-18].

3. SHM&MMS Devised for Twenty-one Viaduct Bridges in HKLR

The SHM&MMS was designed to handle the works of inspection, monitoring, evaluation, rating, maintenance, enquiry, management, and display for the twenty-one viaduct bridges in the HKLR of the Hong Kong-Zhuhai-Macao Bridge, as shown in Figure 2. Figure 3 illustrates the architecture of the SHM&MMS which integrates the SHM system with the inspection and maintenance strategy targeting to not only optimize/minimize the frequency of inspection/maintenance activities, but also improve the effectiveness of preventive maintenance under normal operation condition and corrective maintenance under extreme events. It is composed of the following seven sub-systems [8]:

Figure 2. Location of HKLR of Hong Kong-Zhuhai-Macao Bridge

- Condition Inspection and Inventory System (CIIS), which is devised to process the inspection works with the setup of an updatable structural condition rating system by visual inspection and an inventory system for systematic storage and fast retrieval of inspection records and inventory information;
- Structural Health Monitoring System (SHMS), which is devised to monitor the performance of the viaduct bridges under serviceability limit state by on-structure instrumentation systems with appropriate software tools for processing, analysis, and interpretation of measured results;
- Structural Health Evaluation System (SHES), which is devised to evaluate the safety and/or stability of the viaduct bridges when the monitoring criteria are exceeded by pre-built and pre-configured finite element analytical tools;
- Structural Health Rating System (SHRS), which is devised to rate the results of inspection, monitoring, and evaluation basing on criticality, vulnerability, and condition of components for prioritization of inspection works;

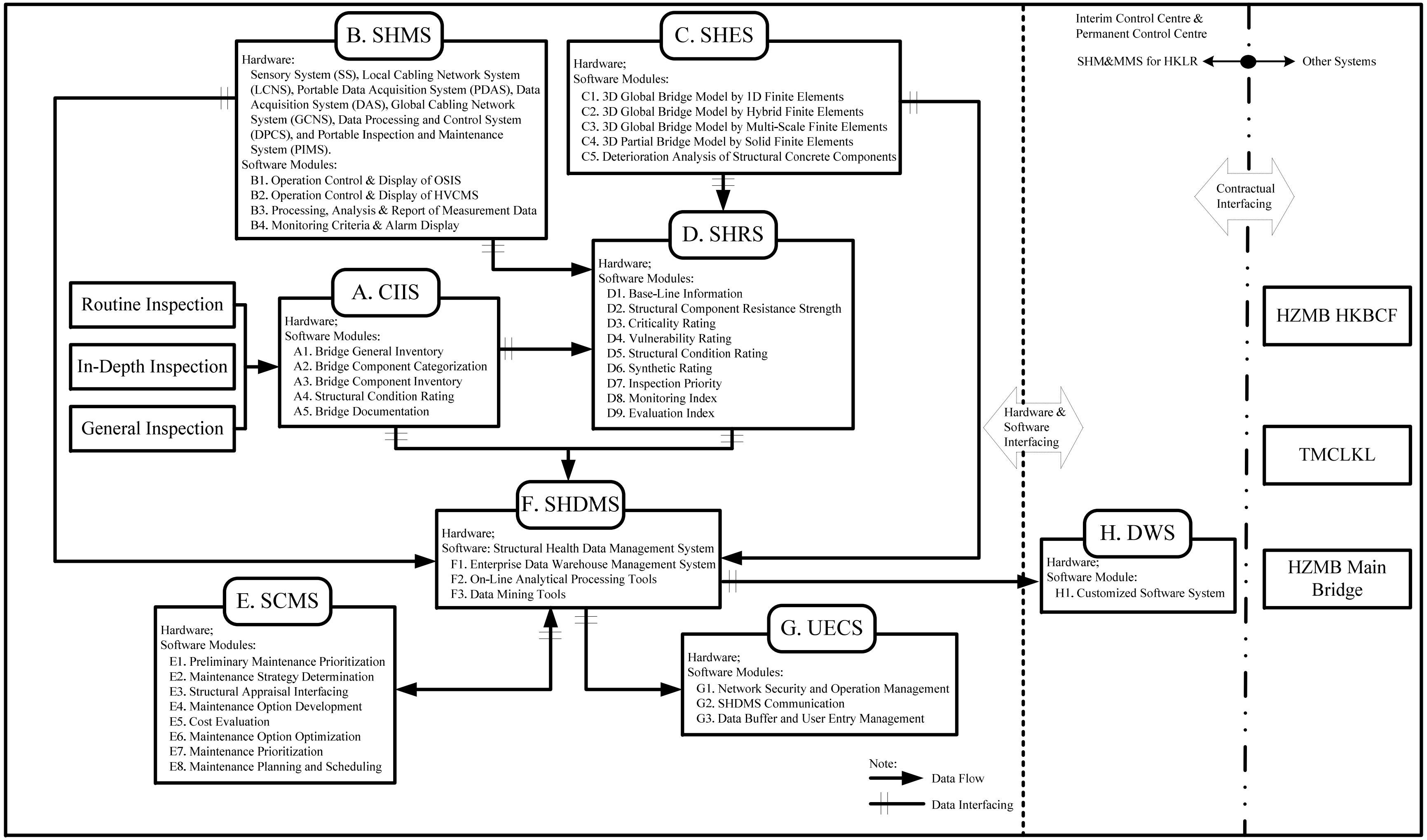


Figure 3. System Architecture of SHM&MMS

- Structural Component Maintenance System (SCMS), which is devised to determine maintenance strategy, develop/optimize maintenance options, select/prioritize maintenance components, and plan/schedule maintenance works;
- User Enquiry and Communication System (UECS), which is devised to provide facilities and security execution for distributing relevant data and information to maintenance engineers and inspectors for the execution of inspection and maintenance works; and
- Structural Health Data Management System (SHDMS), which is devised to carry out data and information management works such as systematic storage and fast retrieval of data and information, data interfacing and analysis execution including multi-platform manipulation capabilities, and multi-dimensional view of data and information.

3.1 Functions of SHM&MMS

The SHM&MMS is devised to fulfill eight main functions, namely, (i) inspection – by visual inspection with a systematic inventory and structural condition rating system, (ii) monitoring – by an on-structure instrumentation system with appropriate data processing, analysis, and reporting software tools, (iii) evaluation – by routine field calibrated finite element models and appropriate analytical methods, (iv) rating – by codified requirements of design and rehabilitation with MATLAB programming tools, (v) maintenance – by maintenance strategies, options, priorities, and availability of resources, (vi) enquiry – by data buffer and network security tools, (vii) management – by management of data and information with data warehouse management system and on-line analytical processing tools, and (viii) display – by the display wall system.

The effectiveness of the SHM&MMS is ensured through realizing the following capabilities: (i) to monitor structural and durability health conditions under the performance thresholds at serviceability limit state (SLS), (ii) to evaluate structural and durability safety when the SLS thresholds are exceeded, (iii) to rate the inspection, monitoring and evaluation results based on codified/designated criteria for inspection prioritization of structural components, (iv) to identify and quantify problematic components for existence, causes and extent of defects and/or damage, (v) to determine the required maintenance strategy and optimize the relevant maintenance options/methods, (vi) to prioritize the structural components required for maintenance, and (vii) to plan and schedule the corresponding maintenance activities. A salient feature of the SHM&MMS is the incorporation of advanced analytical and data processing tools for formulation/updating of structural components' degradation models (including deterioration rates) based on continuously monitored data and stratification/extraction of intrinsic features from extremely heterogeneous data. As a result, this system is effective to quantitatively predict the aging- and environment-induced degradation trend in structural components for maintenance management throughout the life-cycle, even if partial embedded sensors are malfunctioning after a few decades of operation. Because both the progression and causes of structural degradation are monitored and assessed in an evolutionary manner to enable CBM with knowing the defect causes, the SHM&MMS is effective for maintaining the durability and sustainability of the bridge infrastructure, reducing the maintenance cost, and avoiding unnecessary heavy maintenance operations to preserve environment.

3.2 Features of SHM&MMS

Different from the WASHMS currently operating for the five cable-supported bridges in Hong Kong, the SHM&MMS is an integrated system combining SHM and bridge maintenance management. Such a system makes the monitoring data and monitoring-derived results directly useful for decision-making on and prioritization of bridge inspection and maintenance, and therefore is greatly beneficial for condition-based and life-cycle maintenance management. Because of involving the management of a huge amount of data to achieve the combined functions of SHM and bridge maintenance management, the SHM&MMS places a special emphasis on developing an advanced data management system which includes three-tier operational data store, relational data warehouse, online analytical processing tools, data mining tools, and query tools. In consideration of the marine viaduct bridges, the SHM&MMS gives focus on durability monitoring of reinforced concrete structures and life-cycle performance prediction in line with CBM management. Figure 4 shows the combined system for structural health and durability health monitoring, which makes it possible to recognize the degradation mechanisms of the marine viaduct bridges induced by the combined actions of environmental attacks, operational loads, and aging effects.

The SHM&MMS is an upgrade of the WASHMS. Compared with the WASHMS, the SHM&MMS has made a great improvement in the aspects of functionality, buildability and operability, such as: (i) advanced data warehouse is adopted instead of database to enhance the buildability of the structural health data management system (SHDMS), (ii) synthetic rating is developed instead of conventional condition rating to enhance the buildability of the structural component maintenance system (SCMS) (detailed in the next section); and (iii) standardization of commercial software tools and customized software tools is required to enhance the buildability and extensibility of the software systems.

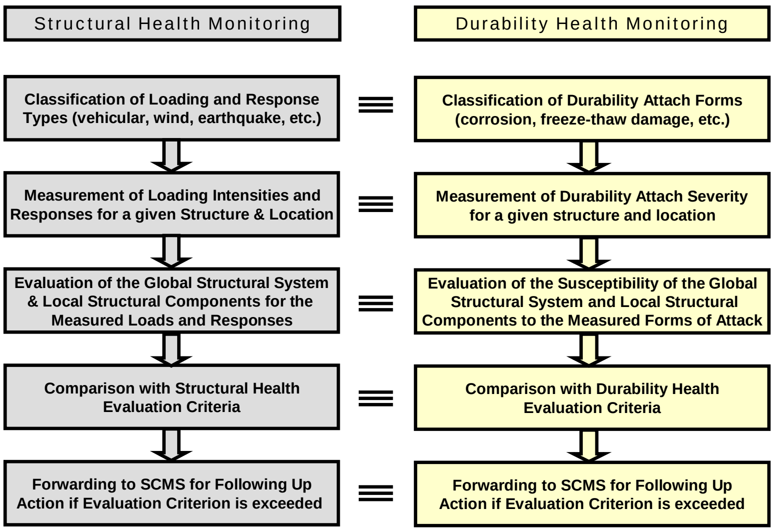


Figure 4. Combined Structural Health and Durability Health Monitoring

4. CBM of Bridges Equipped with SHM System

4.1 CBM versus conventional maintenance approach

With the SHM&MMS, the inspection and maintenance of the marine viaduct bridges in the HKLR will be improved/enhanced from the conventional corrective or preventive approach to modern CBM approach. The CBM is composed of real-time monitoring and predictive maintenance [19]. It is worth mentioning the difference between the conventional corrective or preventive maintenance and the CBM. For a long time, bridge managers have practised the corrective maintenance strategy, in which a bridge is operated until defect/failure appears. Then maintenance action, which involves repair or replacement, is taken with the intention of correcting the defect/failure. However, the occurrence of defect/failure may have expensive and far-reaching consequences (e.g., making the bridge unusable or causing accidents). To prevent the defect/failure before it happens, a different type of maintenance strategy known as preventive maintenance has evolved in time. This involves looking at the bridge's defect/failure history, and instigating maintenance to fix it before there is a high probability of its failing [20]. Preventive maintenance eliminates the severe consequence of failures; however, the benefits of preventive maintenance come at a price. Generally, the preventive strategy advises that maintenance be performed more often than is absolutely necessary (i.e., 'over-maintenance').

In recognizing that preventive maintenance has become expensive, a new type of maintenance strategy (known as predictive maintenance or CBM) has been developed in recent times. Under this strategy, a structure's condition is monitored frequently (or continuously) until it begins to give evidence of deteriorating performance or an incipient failure. Maintenance is then performed in-time to prevent an imminent failure. Compared to what the preventive maintenance can offer, the new strategy results in overall cost reduction of maintenance, while providing better asset availability and performance [20]. On the difference between predictive maintenance and CBM strategies, the former is activated by the analysis of structural condition data that is collected periodically, often manually; while in the latter approach structural condition data is acquired in a continuous manner (e.g., by a SHM system) and analyzed in real-time.

4.2 Implementation of CBM to instrumented bridges

The CBM for an instrumented bridge can be initiated according to the degradation state of the structure that is monitored through various sensors. Once the degradation characteristic crosses a specified threshold, the maintenance actions are triggered. In the SHM&MMS, the degradation characteristic measures of the marine viaduct bridges are obtained and updated with the use of real-time data from both structural and durability health monitoring systems. The two systems enable the early detection of degradation mechanisms by continuous updating of information on the performance of the marine viaduct bridges under their designated functions of load-carrying capacity and durability resistance with the co-existence of degradation effects due to aging and environments, thereby allowing the overall degradation mechanisms to be understood. The determination of the deterioration rates for the marine viaduct bridges is essential to evaluate the effectiveness of maintenance/repairing options. As the deterioration rate is a function of time, the conventional inspection approach, due to its *ad hoc* nature and lack of continuous time-history supporting data, cannot fulfil such requirement. Long-term real-time monitoring systems and analytical tools are thus required for estimating the deterioration rates at key locations/components of the marine viaduct bridges under in-service condition.

Figure 5 illustrates various potential degradation mechanisms for marine viaduct bridges (reinforced concrete structures). The decision making on the maintenance of a reinforced concrete structural component depends on two factors: (i) the deterioration status of its embedded steel tendons or steel reinforcements; and (ii) its load- carrying capacity. It therefore requires both durability and structural health monitoring. For durability health monitoring, analytical tools have to be developed to evaluate the formation and propagation of cracking and the time for the spalling of concrete cover based on the monitoring data from corrosion sensors (corrosion potentials, corrosion currents, concrete resistivity, linear polarization resistance, concrete temperature, concrete relative humidity, and gas concentration in deck and piers). After developing such analytical tools, a linkage must be established to transfer the monitoring/analysis results into an updatable and evolving rating system to facilitate the decision making on CBM and prioritization of maintenance activities. The bridge rating system is generally developed in terms of the criticality and vulnerability indices that can be formulated/updated using the design information, inspection results and monitoring data. As the structural condition is obtained from the SHM&MMS, a new synthetic rating system (Rating Cubic) will be formulated as a rating matrix in terms of the criticality rating, vulnerability rating, and condition rating of the structural components (Figure 6). The action and prioritization of condition-based inspection/maintenance for structural components will be based on the results (which are dynamically updated over time) of the synthetic rating (the rating results within Cube 1 correspond to the highest priority while the rating results within Cube 8 correspond to the lowest priority).

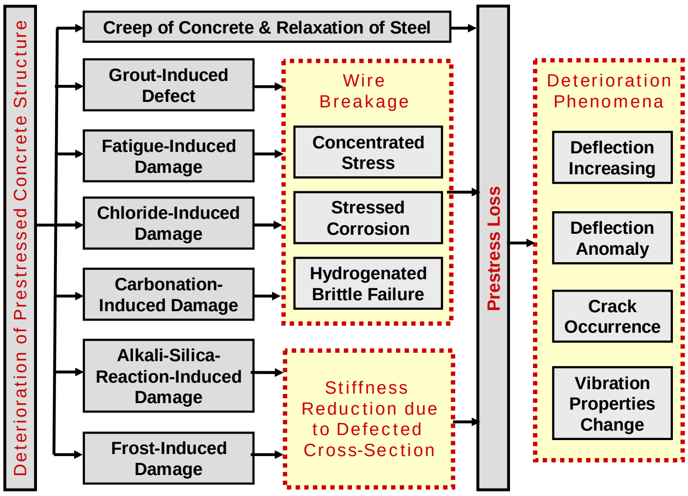


Figure 5. Degradation Mechanisms for Marine Reinforced Concrete Structures

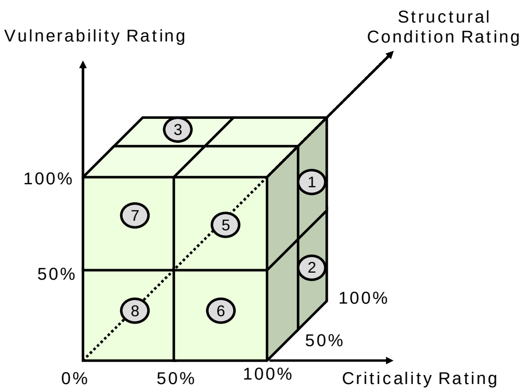


Figure 6. Synthetic Rating Cubic

5. Conclusions

The integration of structural health monitoring (SHM) and condition-based maintenance (CBM) management has been outlined in reference to the structural health monitoring and maintenance management system (SHM&MMS) to be implemented on twenty-one marine viaduct bridges in the Hong Kong Link Road (HKLR) of the Hong Kong – Zhuhai – Macao Bridge. By implementing the SHM&MMS, the maintenance strategy of the bridges will be enhanced from the conventional corrective/preventive approach to modern CBM approach, thus greatly benefiting the execution of inspection and maintenance activities of the bridges and significantly reducing the inspection and maintenance costs. Conducting CBM with the aid of SHM technology provides means to reduce/eliminate unnecessary repairs, prevent catastrophic failures, and reduce the negative impact of the maintenance operation on the profitability of the in-service bridges.

Acknowledgements

The work described in this paper was supported by The Hong Kong Polytechnic University under Grant Nos. 87KP and 1-BB68.

References

[1] Ko, J.M., and Ni, Y.Q. (2005), "Technology developments in structural health monitoring of large-scale bridges", *Engineering Structures*, 27(12), 1715-1725.
[2] Ni, Y.Q., Wong, K.Y., and Xia, Y. (2011), "Health checks through landmark bridges to sky-high structures", *Advances in Structural Engineering*, 14(1), 103-119.
[3] Wong, K.Y. (2004), "Instrumentation and health monitoring of cable-supported bridges", *Structural Control and Health Monitoring*, 11(2), 91-124.
[4] Wong, K.Y. (2007), "Design of a structural health monitoring system for long-span bridges", *Structure and Infrastructure Engineering*, 3(2), 169-185.
[5] Wong, K.Y., and Ni, Y.Q. (2009), "Modular architecture of structural health monitoring system for cable-supported bridges", in: Boller, C., Chang, F.K., and Fujino, Y. (eds.), *Encyclopedia of Structural Health Monitoring*, John Wiley & Sons, Chichester, UK, 2089-2105.
[6] Wong, K.Y., and Ni, Y.Q. (2009), "Structural health monitoring of cable-supported bridges in Hong Kong", in: Karbhari, V.M., and Ansari, F. (eds.), *Structural Health Monitoring of Civil Infrastructure Systems*, Woodhead Publishing, Cambridge, UK, 371-411.
[7] Wong, K.Y., and Ni, Y.Q. (2011), "Structural health monitoring of a suspension bridge", in: Bakht, B., Muft, A.A., and Wegner, L.D. (eds.), *Monitoring Technologies for Bridge Management*, Multi-Science Publishing, Essex, UK, 365-390.
[8] Wong, K.Y. (2012), "System design and implementation of structural health monitoring and maintenance management system for marine viaduct bridges", in: *Proceedings of the 6th International Conference on Bridge* Maintenance, Safety and Management, Stresa, Lake Maggiore, Italy, 8-12 July 2012.
[9] Ni, Y.Q., Hua, X.G., Wong, K.Y., and Ko, J.M. (2007), "Assessment of bridge expansion joints using long-term displacement and temperature measurement", *Journal of Performance of Constructed Facilities*, ASCE, 21(2), 143-151.
[10] Ni, Y.Q., Zhou, H.F., Chan, K.C., and Ko, J.M. (2008), "Modal flexibility analysis of cable-stayed Ting Kau Bridge for damage identification", *Computer-Aided Civil and Infrastructure Engineering*, 23(3), 223-236.
[11] Ko, J.M., Ni, Y.Q., Zhou, H.F., Wang, J.Y., and Zhou, X.T. (2009), "Investigation concerning structural health monitoring of an instrumented cable-stayed bridge", *Structure and Infrastructure Engineering*, 5(6), 497-513.
[12] Ni, Y.Q., Zhou, H.F., and Ko, J.M. (2009), "Generalization capability of neural network models for temperature-frequency correlation using monitoring data", *Journal of Structural Engineering*, ASCE, 135(10), 1290-1300.
[13] Ni, Y.Q., Ye, X.W., and Ko, J.M. (2010), "Monitoring-based fatigue reliability assessment of steel bridges: analytical model and application", *Journal of Structural Engineering*, ASCE, 136(12), 1563-1573.
[14] Zhou, H.F., Ni, Y.Q., and Ko, J.M. (2011), "Structural damage alarming using auto-associative neural network technique: exploration of environment-tolerant capacity and setup of alarming threshold", *Mechanical Systems and Signal Processing*, 25(5), 1508-1526.
[15] Zhou, H.F., Ni, Y.Q., and Ko, J.M. (2011), "Eliminating temperature effect in vibration-based structural damage detection", *Journal of Engineering Mechanics*, ASCE, 137(12), 785-796.
[16] Xia, H.W., Ni, Y.Q., Wong, K.Y., and Ko, J.M. (2012), "Reliability-based condition assessment of in-service bridges using mixture distribution models", *Computers and Structures*, 106-107, 204-213.
[17] Ye, X.W., Ni, Y.Q., Wong, K.Y., and Ko, J.M. (2012), "Statistical analysis of stress spectra for fatigue life assessment of steel bridges with structural health monitoring data", *Engineering Structures*, 45, 166-176.
[18] Ni, Y.Q., Xia, H.W., Wong, K.Y., and Ko, J.M. (2012), "In-service condition assessment of bridge deck using long-term monitoring data of strain response", *Journal of Bridge Engineering*, ASCE, 17(6).
[19] Cadick, J., and Traugott, G. (2009), "Condition based maintenance: a white paper review of CBM analysis techniques", *Technical Bulletin TB-017*, Cadick Corporation, Garland, Texas, USA.
[20] Neelamkavil, J. (2010), "Condition-based maintenance management in critical facilities", *Report No. RR-305*, National Research Council, Ottawa, Canada.