DESIGN OF THE STRUCTURAL HEALTH MONITORING SYSTEM FOR THE THIRD BRIDGE OVER THE PANAMA CANAL

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ABSTRACT

A signature bridge is an important part of the nation's infrastructure because of the function it serves, but also because its attests to a country's economic strength and technological advancement. Panama, is building a major cable-stayed bridge with a design life of in excess of one hundreds of years so it would be beneficial to monitor it so that any departure from assumptions made during design are detected early. During its service life, circumstances and conditions may change, resulting in different types and magnitudes of live load, material variations, natural disasters, and human factors. To ensure safety, the operational functionality and durability of the bridge, it is important to have a comprehensive understanding of the reliability of its structural components. Therefore, a Structural Health Monitoring (SHM) system is needed. This paper outlines a proposed SHM plan for what will be the world's largest cable-stayed bridge with a concrete superstructure – The Third Bridge over the Panama Canal at the Atlantic Side. The proposed bridge, which has a 530 m main span, is located in Colon, Panama, one of the most corrosive environments in the world. The paper summarizes the overall objectives, the design principles, recommended types and locations of sensors. The proposed SHM system will include the following aspects: sensor arrays, a data acquisition and transmission system, data processing and control, a health diagnosis methodology, early warning alarms, and a security assessment process. An important focus of the system will relate specifically to durability and the monitoring of corrosion in reinforced concrete. Data collected will support and help optimize decision-making on future maintenance and repair. Tension force monitoring in cable-anchorage system will be proposed as well to detect changes that might occur due to corrosion or fatigue.

INTRODUCTION

Transportation holds the economic lifeline of a nation. The construction and maintenance of bridges is essential for a nation's infrastructure, and symbolizes the economy development and technology improvement of the nation as well.

Cable-stayed bridges are magnificent long-span bridges that have been extensively constructed throughout the world. They have been chosen due to their rigidity, good aerodynamics, good seismic resistance, aesthetics, and in most of the cases, due to their constructability. Avoiding the disruption of maritime operations, which is the case in the Panama Canal. Within the last century, two cable-stayed bridges have been constructed over the Panama Canal: the Centennial Bridge (420 m), and the Third Bridge at the Atlantic Side (530 m), and there are plans to build a new one in the Pacific Side (+/-500 m) that will carry a light rail.

Structural health monitoring (SHM) systems can be a useful tool to ensure safety, serviceability, durability, and sustainability of structures. By permanently installing a number of sensors, continuously measuring relevant parameters, we can record the real loads, environmental conditions, real behaviors, and real evolution process and performance of a structure during its service time. Anomalies and/or deterioration or damage that may induce adverse effects on service or safety can be detected and evaluated through these systems. SHM help us to understand the behavior or a real, full-scale structure under synthesized loads and environmental conditions. Furthermore, these systems and technologies allow a better understanding of the influence of natural disasters, which are hard to simulate in small-scale models or in an accelerated durability test in the laboratory. SHM is a new safety and management tool that ideally complements traditional methods like visual inspection and modelling. Monitoring even allows a better planning of the inspection and maintenance activities, shifting from scheduled interventions to on-demand inspection and maintenance [1].

THIRD BRIDGE OVER THE PANAMA CANAL AT THE ATLANTIC SIDE

The Third Bridge over the Panama Canal at the Atlantic side consists of a dual carriageway Cable-Stayed Bridge with a vertical clearance of 75 m (246 ft), a total length of 1050 m (3445 ft) and a main span of 530 m (1739 ft). Each carriageway consists of two 3.6 m (11.8 ft) width lanes, two 1.8 m (6ft) external shoulders and two 0.6 m (2ft) internal shoulders to provide satisfactory capacity and emergency for commercial vehicles.

The main cable stayed bridge comprises five spans with twin towers with an upper Delta shape. The cable supported superstructure is in the form of continuous box girder. The cable stayed bridge span arrangement is 79m + 181m + 530m + 181m + 79m (Fig. 1).

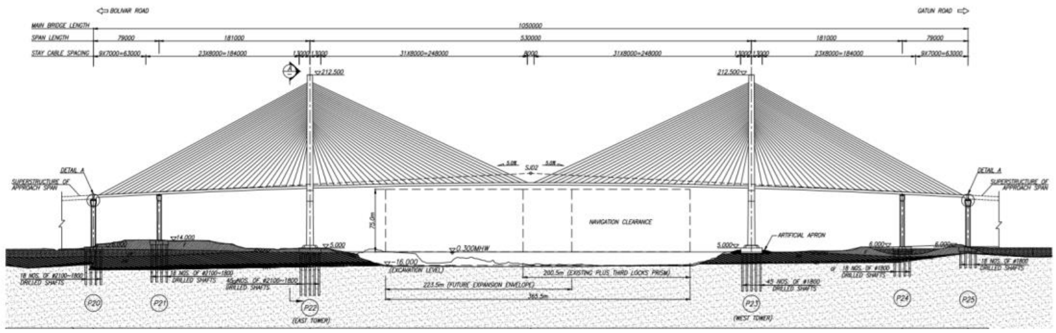

Figure 1: General Layout

The deck superstructure is composed by the cast-in-situ concrete box girder. The total width of bridge deck is 23.6m and the depth of deck girder structure (edge) is 2.6m, as shown in Fig. 2. It is supported by stay cables radiating out from the two towers. A diaphragm is proposed at every 7-8m with rib width of 220~300mm. The prestressed concrete main girders have 33 units of cast in-situ segments on each side of tower and are being constructed by balanced cantilever method. The bridge was designed following AASHTO Specifications [2] to resist strong-motion seismic impact (10% probability of exceedance in 50 years), vessel collision and wind loads.

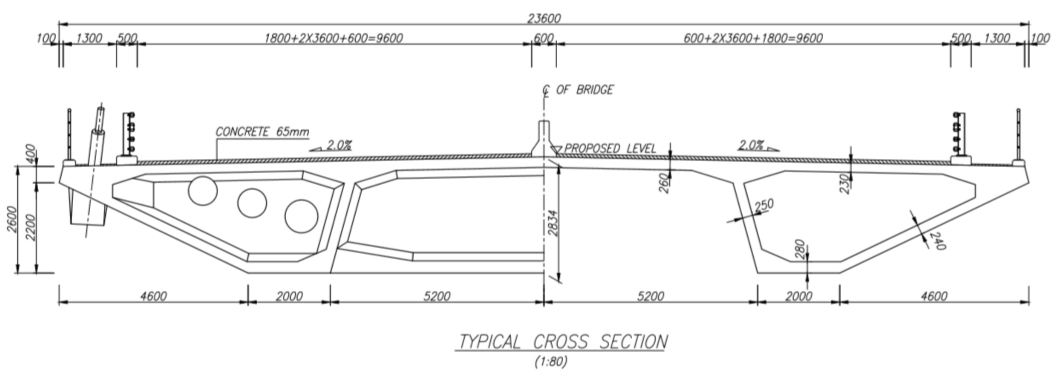

Figure 2: Typical section of deck

DESIGNING AN SHM SYSTEM

When designing a monitoring system, it is fundamentally important to design as an integrated system, which has all data flowing to a single database and presented through a single user interface. The integration between the different sensing technologies can be simultaneously installed on the structure, for example, fiber optic sensors, vibrating wire sensors, weather stations and corrosion sensors, can be achieved at several levels. Different sensors can be connected to the same data-logger: otherwise, several data-loggers can report to a single data management system, which is generally a personal computer installed either on site or at a remote location. Even though many of the sensors and systems provide their own software for data management and presentation, one of the goals of this design would be to provide a single integrated interface that does not require the end user to learn and interact with different user interfaces.

There are several functional requirements that must be considered when designing SHM system:

a. The system must implement advanced techniques, good performance, long term stability, and economic value rationality.
b. The system must have the capability to transmit data, process view, archive document and share long distance information.
c. The system must be able to collect data synchronously, real-time, long term, and hierarchically.
d. The system must have capability to assess, control, and calibrates itself.
e. The system must be able to identify damages and evaluate structural health.

f. The system must be reusable and upgradable [3].

Having the potential responses and locations, the goal was to select the sensors that have the appropriate specifications to sense the expected responses and that are appropriate for installation in the specific environmental conditions and under the technical constraints found in the structure.
Each monitoring project presents its peculiarities and although it is possible to standardize most elements of a monitoring system, each application is unique in the way they are combined. It is however possible to classify the monitoring components according to several categories. A Structural Health Monitoring (SHM) System is composed of the following modules:

1. Sensory System
2. Data acquisition and transmission system
3. Data processing and control system
4. Structural health evaluation system
5. Structural health data management system, and
6. Inspection and maintenance system [4]

Modules 1 and 2 are sensors, data loggers and cabling networks for signal collection, processing and transmission; Modules 3, 4 and 5 are computer systems assigned with different functions of system control and system operation. Module 6 has the purpose of performing the inspection and minor maintenance works for modules 1 and 2. This modular architecture approach has been used in the Sutong Bridge [5] and the Donghai Crossing.

SENSORY SYSTEM

Sensors provide the basic data for a structural health detection and monitoring system. Their performance directly determines ultimate success of the detection and monitoring methods. Sensors need to record the structural mechanical conditions, and directly transform the measured parameters like strain, displacement, acceleration into signals for output. They must sense the variation of external environmental conditions, which needs sufficient reliability, sensibility and high reaction velocity to reflect the external information promptly and accurately [6, 7]. Usually the selection of sensors takes the following factors into consideration: the type, precision, resolution, frequency response and dynamic range; the distribution positions, the influence degree of the surrounding dynamic environment and measurement noise.

The physical response occurring in bridges are measured by current, voltage, resistance, magnetic flux, acoustic and optical fibers. The objectives of a sensory system are the following [4]:

(a) To measure the local and global levels of responses;
(b) To integrate the measured data with analyzed data for correlation analysis and model updating;
(c) To acquire data in a consistent manner and retrievable manner for subsequent diagnostic and prognostic analysis of structural health and damage;
(d) Use contemporary commercially available sensors;
(e) To carry out supplementary measurements by removable/portable sensors for validation/updating of analytical models
(f) To carry out cross-calibration of different types of sensors at, at least, one typical location.

For the design of sensor modules and sensing technologies for cable-stayed bridges, three aspects should be considered: the variable type, the sensor type, and the positioning of the installed sensors. For the selection of sensory systems, the following criteria should be taken into account: operational bandwidth; magnitude and frequency response over that bandwidth; sensitivity and accuracy; power supply requirements; physical characteristics (dimensions, weight and material); environmental operating conditions such as temperature ranges; type of output signal; any signal conditioning requirements; and costs.

NUMBER AND LOCATION FOR PERMANENT MONITORING

The selection of locations to monitor depends on the configuration of the bridge, structural loading, structural materials and environmental loading. A summary of the sensors is:

WEATHER AND TEMPERATURE LOADS SENSORS

Optical fiber Bragg grating temperature sensors will be mounted on the box girder, and at the pylons. These sensors are measuring temperatures, which are correlated with the strain gauge measurements. Three (3) weather stations (ultrasonic anemoscopes [8], hygrometer, barometers and rain fall gauges) measuring wind speed, wind direction, air humidity and air temperature. Two (2) will be mounted on the top of the pylons, the other at road level. The wind measurements serve as a reference for the stay cable vibrations. The air humidity and temperature complete the meteorological information.

CORROSION SENSORS

For the cable-stayed main span, the major concrete structural components are pylons, intermediate piers and pier shafts. As the pylons are more important than the intermediate piers, one pylon is selected for monitoring. Three plane sections of the pile cap, the water-saturated zone, splash zone, and dry zone will be monitored because they represent micro-environments. Each section will be instrumented with four (4) sets of corrosion monitoring sensors at one plane section. The anchorage zone will be instrumented with ten (10) sets of corrosions. As a result, a total set of eleven (11) corrosions for each pylon will be installed on the pylons. For the superstructure, the cross-section of the box girder will be selected for permanent monitoring [9].

HIGHWAY TRAFFIC SENSORS

For measuring the weight and speed of vehicles, weigh-in-motion sensors will be used. Four (4) stations will be embedded underground in pavement. These weighbridge sensing components are optical fiber Bragg grating strain sensors that are made in steel-concrete composite structure, which have the same life with bridge itself.

ACCELEROMETERS AND GLOBAL POSITIONING SYSTEM (GPS)

Since vibration of cables is a common phenomenon, forty four (44) triaxial force balance accelerometers will be mounted on the stay cables [10]. Twenty-one (21) biaxial piezoelectric accelerometers will be installed on the deck and twenty (20) on the pylons. Six (6) GPS receivers will be installed on the top of both pylons, the middle of the main span, both ends of the main bridge, and the bank nearby the bridge, respectively. The receiver installed on the bank will be referred as the base station [11].

DEFORMATION SENSORS AND TILTMETERS

For deformation monitoring of the girder and pylon, several permanent stations around the bridge should be used during bridge construction, which will be utilized for the current monitoring task, so that all data can be later unified. There will be a total of 14 monitoring points the deck, four (4) on the piers and ten biaxial tiltmeter (10) [12] on the pylons [13].

STRAIN SENSORS

These sensors are mainly needed to observe torsions due to heavy wind and traffic. Twelve (12) optical fiber Bragg grating strain sensors will be mounted on 3 steel outriggers of the cables, one on each side. Two will be mounted on the rail level in the concrete and four will be mounted on the lower side of the bridge.

Table 1. Monitoring sensors summary

Monitoring Item	Sensor	Quantity
Weather monitoring	Ultrasonic-type anemometers	3
	Barometers	3
	Rainfall gauges	3
	Hygrometers	3
Temperature loads monitoring	Optical fiber Bragg grating temperature sensors	28
Corrosion status monitoring	Corrosion Sensors	22
Highway traffic loads monitoring	Dynamic weigh-in-motion stations	4
	Digital video cameras	2
Dynamic features monitoring	Fixed and portable servo-type accelerometers	41
Cable forces monitoring	Portable servo-type accelerometers	44

Geometry monitoring	GPS	6
	Displacement traducers	4
	Tiltmeters	10
Strain/Stress monitoring	Dynamic strain gauges	28
	Static strain gauges	12
Fatigue life monitoring	Dynamic strain gauges	12
Articulation monitoring	Displacement transducers	2
Total		227

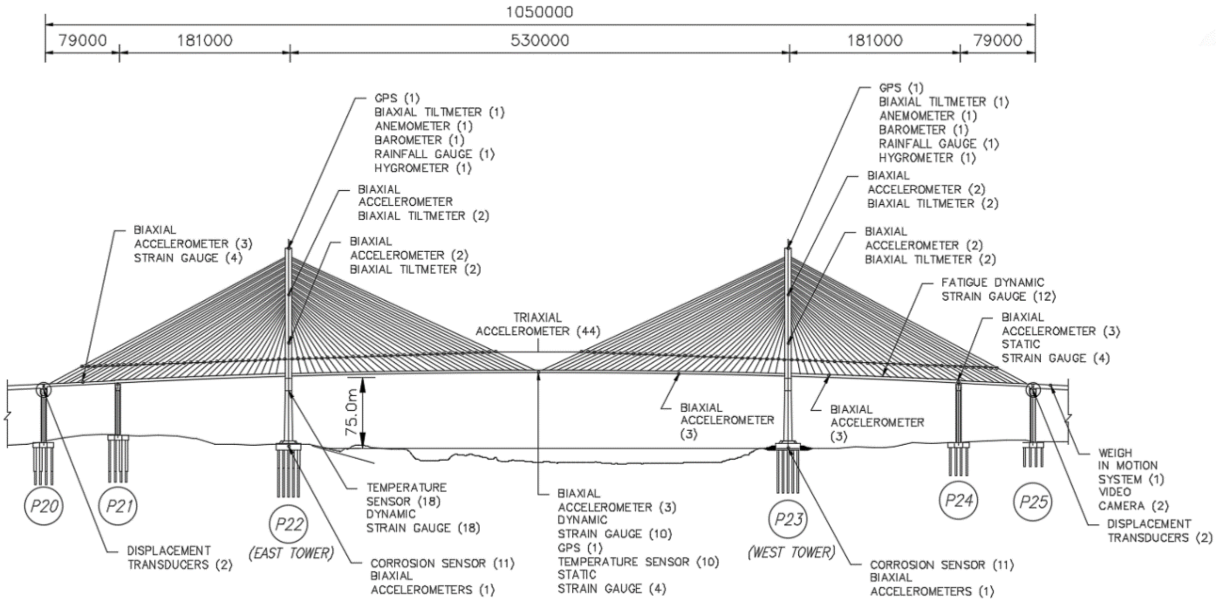

Fig. 3. Layout of Sensor System

CONCLUSIONS

This paper presents design criteria for a structural health monitoring system for the Third Bridge over the Panama Canal at the Atlantic Side, which is a cable stayed bridge. It offers a reference and guide to design a health monitoring system.

Generally, SHM system consists of six modules sensory system, data acquisition and transmission system, data processing and control system, structural health evaluation system, structural health data management system, and inspection and maintenance system. Two aspects of the design of sensor are presented: location and type of sensor. Scheme, hardware, software and data acquisition strategies are needed to be designed for data acquisition module. Technology, scheme, instrument and software data transmission are to be properly chosen. The speed and distance are two critical factors impacting scheme and technology of data transmission system.

Further research will be done in the concept of SHM by periodic Non-Destructive Evaluation (NDE) surveys since they have been used as a tool for structural maintenance and asset management.

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