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DESIGN AND CONFIGURATION OF A LARGE SCALE BRIDGE MONITORING SYSTEM FOR LONG TERM EVALUATION

J. A. López-López,
Instituto Mexicano del Transporte, México

B. Hernández-Sánchez
Instituto Mexicano del Transporte, México

J. A. Quintana-Rodríguez
Instituto Mexicano del Transporte, México

F. J. Carrión-Viramontes
Instituto Mexicano del Transporte, México

S. E. Crespo-Sánchez
Instituto Mexicano del Transporte, México

ABSTRACT

The bridge inventory in the Mexican federal highway system is about 10,000 bridges, considering the freeways and toll highways; and among them, at least 100 bridges are rated as important and/or strategic from an economic stand point of view. For that reason, the Integral Program on Bridge Safety was started in 2010 and, along with others; it considers a project for the remote permanent monitoring of these significant structures and the operation of the Center for Bridge Remote Monitoring (*CMPEI*). In a first phase, the project considers 16 bridges, includes 6 type bridges in a research program to develop parametric models for the most common bridges in the highway inventory for structural capacity and residual life evaluation, considering simple dynamic and static tests.

In both cases, full scale instrumentation for large bridges and basic instrumentation of type bridges, the basic instrumentation considered FBG optical sensors, counting accelerometers, strain gages, extensometers, and inclinometers. Complementary instrumentation was video cameras, weather station and seismological station. A local center in the bridge concentrates, pre-process and controls the data collection and transmission to the CMPEI. Data post processing is carried out in the Monitoring Center, where a large data center stores and handles information into 3 different levels: alarm for immediate actions, performance monitoring for short term monitoring, and structural evaluation for prognosis and long term planning.

Author's email: jalopez@imt.mx, bernardohs@gmail.com, carrion@imt.mx, jaquintana@imt.mx, screspo@imt.mx

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J. A. López-López[1], B. Hernández-Sánchez[1], J. A. Quintana-Rodríguez[1], F. J. Carrión-Viramontes[1] y Saúl E. Crespo-Sánchez[1]

[1]Instituto Mexicano del Transporte, Sanfandila, Pedro Escobedo, Querétaro, México.

1 ABSTRACT

The bridge inventory in the Mexican federal highway system is about 10,000 bridges, considering the freeways and toll highways; and among them, at least 100 bridges are rated as important and/or strategic from an economic stand point of view. For that reason, the Integral Program on Bridge Safety was started in 2010 and, along with others; it considers a project for the remote permanent monitoring of these significant structures and the operation of the Center for Bridge Remote Monitoring (*CMPEI*). In a first phase, the project considers 16 bridges, includes 6 type bridges in a research program to develop parametric models for the most common bridges in the highway inventory for structural capacity and residual life evaluation, considering simple dynamic and static tests.

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2 1. INTRODUCTION

Structural Health Monitoring is a process designed to provide prompt and accurate information of the condition and performance of a structure. The main goal is to have an early damage detection system capable to evaluate the remaining structural capacity and prognosticate its future behavior under normal and extreme conditions, and based on these, to define the optimum maintenance strategies and to calculate its structural reliability and residual life Aktan et al. (2002) and ISIS Canada (2001).

In the federal highway system of Mexico, which is administrated via the Ministry of Communications and Transportation, there are almost 7200 bridges SCT (1992-1). The average age of these bridges is 39 years and it is considered an old bridge inventory, but in the past years the inventory growth rate has increased as a result of the infrastructure modernization program, where large and special bridges are being built (figure 1). This

particular situation poses several challenges for bridge inspection and maintenance; while most of them are old and short span bridges that require particular type of inspections and analysis to evaluate structural capacity and residual life; there is an increasing number of special bridges that have need of distinct inspection and monitoring techniques to assure their structural integrity under present and future conditions.

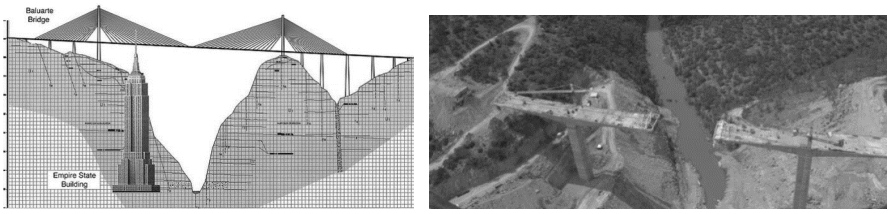

Figure 1. Baluarte Bridge, the Latin-American´s highest cable stayed bridge (under construction).

Up to now, bridge inspections are based on visual examinations every two years and most bridge rehabilitations are based on corrective maintenance. Special inspections are done when damage extent is evident, as in the case for corrosion, scouring and large structural cracks SCT (1992-2). From these inspections, the structural condition of all bridges is rated according to a qualification index that goes from 1 (excellent condition) to 5 (critical condition), and it is conditioned to the inspector's experience and limited to what can be observed. In the case of special large bridges, every 10 years are evaluated through dynamic and static tests, and specific nondestructive are applied when needed.

Main limitations of the actual inspection strategies are:

- Internal defects or damages are not detectable.
- There is no evidence of the damage evolution.
- Structural condition is rated according to subjective criteria.
- No history of the structural behavior of the bridge, either in normal or extraordinary conditions.
- Structural capacity and residual life are not evaluated.
- Actual information is not sufficient for a structural prognosis, or to evaluate different maintenance strategies.

3 2. BRIDGE SAFETY INTEGRAL PROGRAM

The Mexican Ministry of Communications and Transport (SCT) started in 2010 the Bridge Safety Integral Program that was divided into 6 elements or systems as it is indicated in figure 2. The main component of the program is the Bridge Management System, which it will be an updated version of the SIPUMEX, the actual management system. Complementary to this, on one hand is the system for Inspection and Analysis of Scouring and Corrosion, designed for two of the most common and complex problems in Mexico; on the other hand, the system for the development of Models for Prognosis and Structural Capacity, in order to evaluate bridge life prediction and capacity. Finally, the Center for Bridge Remote Monitoring, with the *in situ* bridge instrumentation, and the Early Warning System and the Emergency Management

Systems, were designed for the permanent remote monitoring of the most important bridges in Mexico, or for those bridges with particular structural problems.

Figure 2. Main components of the Bridge Safety Integral Program.

In particular, the Bridge Management System is based on the initial concept proposed by the Mexican Transport Institute (IMT), identified as SIAPC-II. This management system, that includes the actual bridge inventory data, is complemented with a geographically reference data base, drawings, reports, photographic reports, inspection reports and all the available design and maintenance information put into electronic formats. The SIAPC-II management system includes one module for the calculation of the structural capacity and life prediction of bridges, and another module for the maintenance cost estimation. With this platform, it will be possible to define and carry out optimum bridge rehabilitation programs based on the actual bridges conditions, the available budget and the economic impact on all the highway system Carrion et al (2005).

4 3. CENTER FOR BRIDGE REMOTE MONITORING

The Center for Bridge Remote Monitoring (*Centro de Monitoreo de Puentes y Estructuras Inteligentes, or CMPEI*), is a major component of the Bridge Safety Integral Program, and its main objective is to receive and analyze the data obtained from all the different types of sensors installed on selected bridges for remote monitoring to evaluate their structural behavior and integrity, to predict their structural condition within a certain time period and with all these, to guarantee their condition at any time, to alert on possible critical situations and to increase the maintenance efficiency.

The *CMPEI* proposes a structured platform for the remote and continuous monitoring of the most important bridges in Mexico, where bridge inspections will not only be visual, but also include dynamic and static tests that will be carried out systematically and at low cost. Complementary, simulation models of these bridges will be developed and calibrated on a regular basis for detailed analysis and evaluation, where damage would be detected from an early warning subsystem. At the same time, extraordinary events, such as earthquakes, hurricanes, or overloading, will be monitored and evaluated in detail, so immediate actions would be taken if necessary. Finally, the continuous

monitoring will provide information of the structural indexes for life prediction under different conditions and to optimize maintenance, on a permanent basis.

In general, the monitoring scheme considers three different levels for the continuous structural evaluation. The first, through the direct monitoring of sensors data, which are the bases of the alarm system to identify critical or extreme conditions on a particular bridge; the second, is over the performance of structural indexes, which are calculated from the raw data (like modal analysis) to give a synthetic data base that could be used for long term monitoring and to evaluate structural global-time trends. The third monitoring level considers the use of simulation models with raw data to detect and evaluate damage, evaluate extraordinary events or for field controlled tests.

Bridge instrumentation has been divided in several phases; the first considers 16 bridges, where 10 are identified as those among the most important ones in Mexico for their size, type and economic significance in the Mexican highway network (figure 3); while the remaining 6 are a representative selection of the three most common class of bridges in the federal highway, identified as “type bridges”, and that represent almost the 90% of the bridge inventory. These bridges will be monitored to obtain direct field information of their structural behavior that will be used to develop parametric models for structural capacity and life prediction. The main application approach, considers the use of field data obtained from simple and fast dynamic and static tests, that provide the information for the structural analysis using the parametric models that are mainly defined by the geometric parameters, age and bridge type (figure 4).

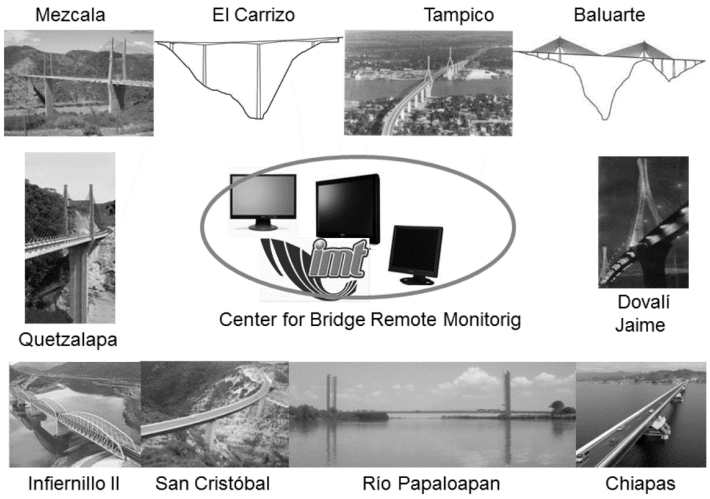

Figure 3. 1st instrumentation phase for 10 long span bridges.

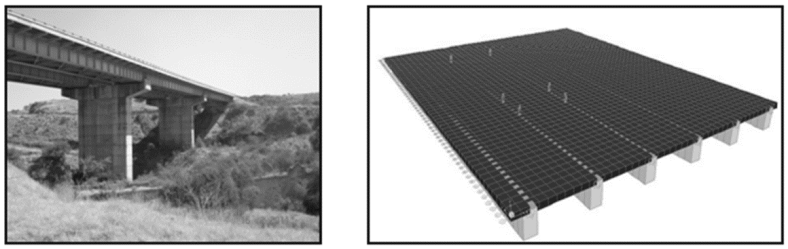

Figure 4. Two of the most common "type bridges": steel I beam, and reinforced concrete.

Future phases of the CMPEI will consider other long span bridges or bridges with particular problems, including scouring, corrosion or structural damage due to accidents, where instrumentation will be defined according to the particular case.

5 4. INSTRUMENTATION DESIGN AND CONFIGURATION OF BRIDGES

The general instrumentation concept for large and important bridges is based on fiber Bragg grating sensors (FBG) to measure strain, deformation, angles, acceleration and temperature. Complementary information is obtained from a weather station, a seismograph and video cameras. A local center at the bridge, with a computer and a FO interrogator, will concentrate and process the first level of information from the sensors that will be registered up to a scanning frequency of 100 Hz. Data processing and mining strategies are developed to simplify analysis and transmission to the CMPEI. The instrumentation concept is described for two of the bridges: Baluarte and the Río Papaloapan.

Baluarte Bridge Instrumentation

This bridge will be among the most important and largest bridges in Mexico. It will be commissioned in 2012 and is located in the limits of the states of Durango and Sinaloa, in the north east of Mexico, and it is one of the roughest geographic regions in Mexico in the Sierra Madre. The monitoring system was originally designed to monitor the construction and operation of the bridge, but later, it was decided that the permanent monitoring will be installed after commissioning. The overall monitoring design considered the following sensors:

- 4 bidirectional inclinometers on the two main piles (2 on the basement and 2 on the top)
- 1 Seismograph (out of the bridge)
- 1 weather station (wind velocity and direction, temperature, humidity and rain)
- 128 FBG strain sensors for the bridge deck (steel)
- 10 FBG strain sensors for the piles (concrete)
- 22 FBG accelerometers for the bridge deck and piles
- 24 FBG accelerometers on pre-defined cables (3 in each semi-harp)
- FBG temperature sensors (as needed)
- 1 FBG displacement sensor for the bridge joint
- 2 video cameras
- 2 local monitoring systems (master-slave)
- 1 energy supply solar system

Río Papaloapan Instrumentation

The Río Papaloapan Bridge is one of the most important bridges in Mexico and is located in the highway network that communicates the south east of Mexico with the center, connecting the country with the oil fields and refineries at that region. This

bridge in particular, has already reported several structural problems J. Alfredo López et al (2009) and after a rehabilitation process, it was proposed a monitoring system to guarantee its structural integrity Francisco Javier carrion viramontes et al. (2010) (figure 5).

The proposed instrumentation system for the Río Papaloapan is:

- 1 seismograph
- 1 weather station (wind velocity, temperature, rain, humidity)
- 16 unidirectional FBG accelerometers for the cables
- 4 bidirectional FBG accelerometers on the top of the piles
- 24 FBG strain sensors for the bridge deck (concrete)
- 4 bidirectional FBG inclinometers on the top of the piles
- 1 FBG displacement sensor for the bridge joint
- 5 FBG temperature sensors
- 2 video cameras
- 1 local monitoring system
- 1 energy supply solar system

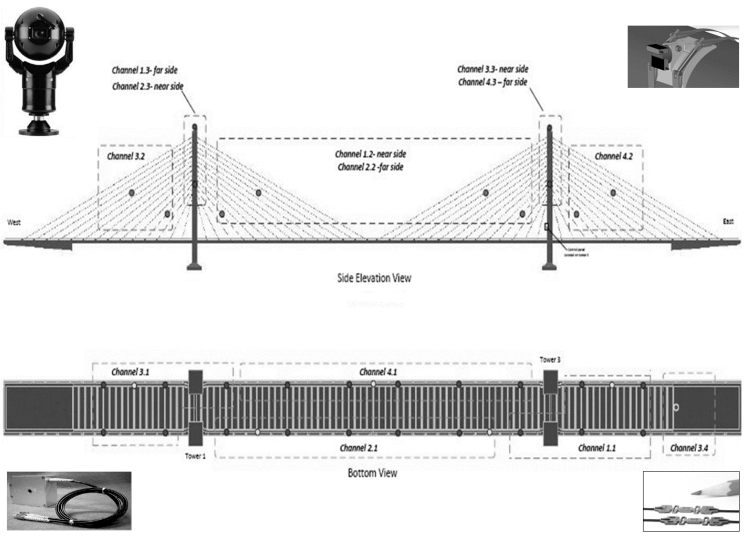

Figure 5. Full scale instrumentation for permanent remote monitoring of large bridges

In general, the FBG sensors were decided due to their sensitivity, performance and long term reliability. Although one outcome for these sensors is the installation cost, it was found that in the long term the maintenance and operation will be cheaper. The idea of a local monitoring system in the bridge is to enable some simplifications for the data transfer and management, including video. The FBG sensors were classified in two groups: those that measure direct parameter structural parameters (strain, acceleration, angle), and those used to measure temperature to compensate the FBG measurements. All sensors were integrated with a FO multiplexor and one FBG interrogator with a computer with high storage capacity and an interface for remote communication.

The energy supply was designed with photovoltaic solar cells to supply 22.56 KW, with batteries for 1448.17 AH. Due to the bridge location and design, it was decided to place the solar cells horizontally, although it was not the best configuration, but it reduced the risk of damage due to strong winds and some other externalities. As a consequence, the number of cell increased and thus, three different positions were considered to have enough space for the cells. Two sets of cells were located in two towers next to the video cameras; the third set, the largest, with the local monitoring system and to supply energy for the computer and sensors.

The computer used for local monitoring, was designed with two communication alternatives: one for remote communication to the CMPEI that included FO local Internet connection, or wireless satellite, microwave, 3G, 4G or radio communication, depending on the service available at the bridge (figure 6). The second alternative, considered Wi-Fi or Bluetooth for local wireless communication within the bridge, considered for direct access to the main local computer at the bridge, without necessity of physical access to the system (not easily reachable).

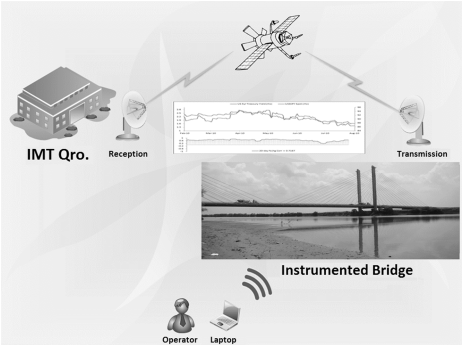

Figure 6. Illustration of the communication alternatives on the bridge

6 5. DATA PROCESSING AT THE CMPEI

The Center for Bridge Remote Monitoring (CMPEI) is located at the Mexican Transport Institute at Sanfandila, in the state of Queretaro. It considered a Monitoring Room equipped with computers for management and control of the information, work stations for analysis and structural simulation, plotters, printers, high resolution scanner for large drawings, 24” monitors, 50” monitors and a projector. The heart of the center is a HP EVA 4400 system (2011) for high capacity data processing, with an 8 TB hard disk arraignment for high storage capacity, velocity and performance, connected with a fiber optics 8 TB bus. The system operated with VMware software for virtualization (2011) that enables a high flexibility for different configurations and operations (figure 7).

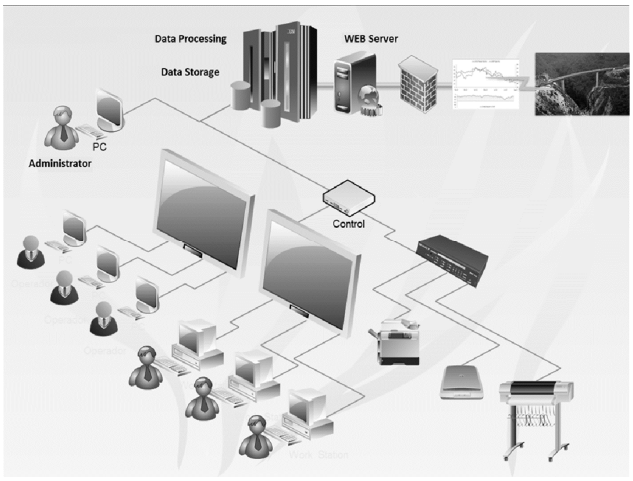

Figure 7. Sketch of the Center for Bridge Remote Monitoring System

At the analysis level, the CMPEI considered two different sets of information. The first is focused on the analysis for damage identification and evaluation; and the second considers the analysis for structural prognosis and long term structural reliability. In both cases, a simulation finite element model or models are the base of the analysis; therefore, calibration of these models is a key aspect that it will be solved with tests under controlled conditions (static and dynamic) on the bridges.

Figure 8 shows the three different actuation levels according to the particular event: alarm, diagnosis, or prognosis. In general, each level has different actuation scenarios and involves different authorities according to each situation. Externalities involve ordinary or extraordinary events, and those involved for actuation depend on the warning system defined by the CMPEI, and the information protocols. In this particular case, most of the information will be provided to those departments involved with the maintenance and operation of the highways, but also include government authorities and public safety departments. The main exit from the CMPEI is the Intranet of the Ministry of Communications and Transport, but also it can use a system to send phone messages or alarms. At the same time, authorized users may have access to the monitoring system to historic read information, reports or real time information from any bridge, including images and graphs.

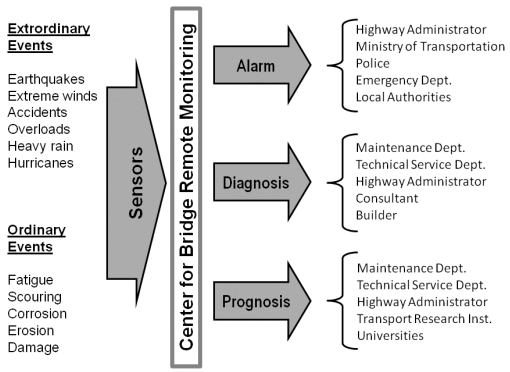

Figure 8. Actuation levels for short and long terms

For the alarm and warning system, several levels will be defined according to the sensor and structural parameter associated. In some cases statistical data can be used to define normal operational conditions, as well as abnormal or critical conditions. In some other cases, the limits of the alarm system will be defined from the design data or structural performance, or the materials performance. Additional criteria for the alarm system would be the operational legal limits, like vehicle gross weight limits or vehicle size.

7 5. CONCLUSIONS

At the present, worldwide, there an increasing demand for remote monitoring systems for bridges, and Mexico is not an exception. The Center for Bridge Remote Monitoring (CMPEI) has been initiated in 2011 with an initial capacity for at least 20 bridges and in its first phase, considers 10 of the most important bridges in the country. At the same time, for the most common bridges, it also includes the monitoring of type bridges to generate a knowledge base for the development of parametric models to calculate structural capacity and residual life using experimental data from simplified dynamic and static tests. Finally, bridges with specific problems can also be included, for example, to monitor scouring or corrosion damage.

For its capacity and flexibility, the CMPEI can grow to monitor a larger number of bridges, but also it can include tunnels or other type of structures within the wide range of structures in the highway network. As a result, it can be said that the monitoring center is a fundamental step given by the Mexican government toward the modernization of the infrastructure management, design and operation; and from that, the next step will be the intelligent highways and infrastructure.

On the practical application, the CMPEI is not only a research platform, but also a source of reliable information to optimize bridge maintenance and to increase their structural reliability. Detection and evaluation of damage is a fundamental part of the analysis, but also the rehabilitation data base is also important for an overall operation of a bridge management system. The permanent remote monitoring will provide valuable information of the structural performance of bridges in different conditions (normal or abnormal), but also to give data of the highway system behavior and a prognosis on structural reliability of the bridge. From all these information, planning and maintenance will be supported from reliable information and, in general, this will increase the transport productivity.

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