

Structural Health Monitoring of Bridges in Mexico – Case Studies

J. Ramon GAXIOLA-CAMACHO¹, Juan A. QUINTANA-RODRÍGUEZ²,
G. Esteban VAZQUEZ-BECERRA¹, Francisco J. CARRION-VIRAMONTES²,
J. Rene VAZQUEZ-ONTIVEROS¹, Francisco J. LOPEZ-VARELAS¹

¹ Autonomous University of Sinaloa, Culiacan, Mexico

² Mexican Institute of Transportation, Queretaro, Mexico

Contact e-mail: jrgaxiola@uas.edu.mx

ABSTRACT: Three case studies of Structural Health Monitoring (SHM) of bridges in Mexico are documented in this paper. Firstly, the SHM of the Papaloapan Bridge is presented. For this case study, the SHM was designed and installed for the structural assessment of this cable-stayed structure after two failures and loosening of its cables. Secondly, the structural assessment of El Carrizo Bridge is reported. Such a bridge has a box girder cantilevered structure section that was damaged after a fire provoked by an accident of a vehicle transporting Diesel. In this case, the SHM system was installed to control the overall rehabilitation of the bridge. Finally, a probabilistic SHM strategy for a reinforced concrete bridge is documented. The probability of failure is calculated evaluating displacements obtained via Global Positioning System (GPS) technology. Based on the results presented in this paper, the SHM of bridges in Mexico has been validated to be a useful and a cost-effective tool, not only for evaluating critical conditions and rehabilitation, but also for future structural integrity and prognosis of bridges.

1 INTRODUCTION

In recent years, there has been an increase in the development of Structural Health Monitoring (SHM) techniques to assess and evaluate the safety of bridges (Ko & Ni, 2005). Worldwide, different SHM systems for bridges have been implemented. For example, in the United States, Europe, Japan, China and other countries diverse SHM techniques have been proposed (Ko & Ni, 2005). For instance, the SHM of bridges helps in detecting certain problems in loading conditions that may lead to possible structural damages. Also, the SHM process can provide real-time information to assess safety after phenomena and disasters. Thus, the SHM process makes evidence available to plan the inspection, rehabilitation, maintenance, and possible rehabilitation of bridges. It is important to mention as well that the SHM may be also used to keep track of the structural integrity of bridges during construction, rehabilitation and/or reconstruction. Hence, developing and implementing a SHM system has its own challenges requiring interdisciplinary research for the application of innovative technologies that are used in other disciplines. The main objective of this paper is to present three case studies of the SHM of bridges in Mexico, demonstrating how the country efforts in implementing diverse techniques to evaluate structural integrity of bridges is giving positive results.

2 STRUCTURAL DESCRIPTION OF BRIDGES CASE STUDIES

2.1 *Papaloapan Bridge*

The Papaloapan Bridge is a cable stayed structure type with main span of 203 meters and an overall length of 407 meters. The main structure has a vertical lateral suspension system with 8 semi-harps, each with 14 cables (see Fig. 1). The bridge is located in one of the most important federal highways of Mexico, connecting the center and southeast of the country. The Papaloapan Bridge was constructed in 1995. Since 2013, this is the first fully instrumented and continuously monitored bridge in Mexico. Few years ago, the Papaloapan Bridge reported structural problems, requiring extra rehabilitation works and the installation of a SHM system for continuous remote monitoring. The main identified problems were structural deficiencies in the upper anchoring elements of the cables causing two fractures and the loosening of cables; one of them in 2000 and the second one in 2015 (Lopez et al., 2009; Carrion et al., 2017).



Figure 1. The Papaloapan Bridge.

2.2 *El Carrizo Bridge*

The second case study presented in this paper is El Carrizo Bridge. It is a 487 meters complex bridge with three different type of structures. The largest section is a 364 meters long cable-stayed section that continues with another 70.6 meters double cantilever structure and ends with a 38 meters simple supported segment with post-tensioned Nebraska type girders. The stayed structure has four semi-harps with 14 cables each, and a deck with steel segments. The double cantilevered structure has two widely spaced post-tensioned box girders with steel cross-section girders to support the reinforced concrete deck. The main span has a total length of 217.3 meters. This structure is the second most important bridge of the Mazatlan-Durango federal highway. It is located in north-western part of Mexico. It is an essential element of the route that connects the Gulf of Mexico with the Pacific Coast. The Carrizo Bridge suffered considerable damage on January 12, 2018 because of an accident on the bridge in which it was involved a truck tanker with 34,000 liters of fuel that caused a large fire and severe damage on the double cantilevered section. Considering the high uncertainty about the condition of the bridge and the effects of the structural rehabilitation, CAPUFE, the government agency in charge of federal highways in Mexico, requested to the Mexican Institute of Transportation to install a monitoring system and evaluate the rehabilitation process to guarantee the structural integrity of the bridge (Sanchez, 2018).



Figure 2. El Carrizo Bridge.

2.3 *Juarez Bridge*

The Juarez Bridge is located in Culiacan, Mexico. It is a reinforced concrete bridge that was built more than 45 years ago, and it has a length of 200 meters (see Fig. 3). This bridge helps to connect the northern with the southern part of the city. However, very recently, users of this bridge reported non-tolerable movements of the structure, which may lead to compromise the structural integrity of it, representing a problem for users who interact with the bridge every day. The main problem of the Juarez Bridge is that it presents considerable vibrations in its vertical component. In general terms, such vibrations are associated to loading and the state condition of the bridge. Based on the above discussion, it was necessary to perform the SHM of the Juarez Bridge to determine its structural condition (Vazquez-Becerra et al., 2017).



Figure 3. Juarez bridge.

3 STRUCTURAL HEALTH MONITORING SYSTEMS

This part of the paper documents the SHM systems that were installed in every bridge under consideration. All the features and compounding beneficial factors of the SHM systems are summarized. However, because of the lack of space, limitations of them are not discussed in this paper. Such limitations are widely available in the literature.

3.1 Papaloapan Bridge SHM System

The SHM system for the Papaloapan Bridge was based on fiber optics sensors. Such a SHM system has 24 strain gauges, 24 accelerometers, 1 displacement sensor, 8 tiltmeters and 5 temperature sensors. The SHM system was energized with 96 photovoltaic solar cells, 36 deep cycle batteries and their controllers. The local monitoring system included a FO interrogator, 1 multiplexor and one computer. Additionally, the SHM system included 2 video cameras, one weather station and one seismological station. The SHM system is currently communicated via satellite to the monitoring center for bridges and intelligent structures in the Mexican Institute of Transportation. The sensors were distributed to analyze the dynamics of the bridge deck and the two towers, respectively. Thus, the strain gauges were located in the next way: 10 under each one of the main girders of the bridge deck, and one on the side at half height of each tower. Also, on the top of each one of the four towers, 2 tiltmeters and 2 accelerometers were fixed. The other 16 accelerometers were placed on the middle of cables 4 and 11 of each semi-harp (see Fig. 4).

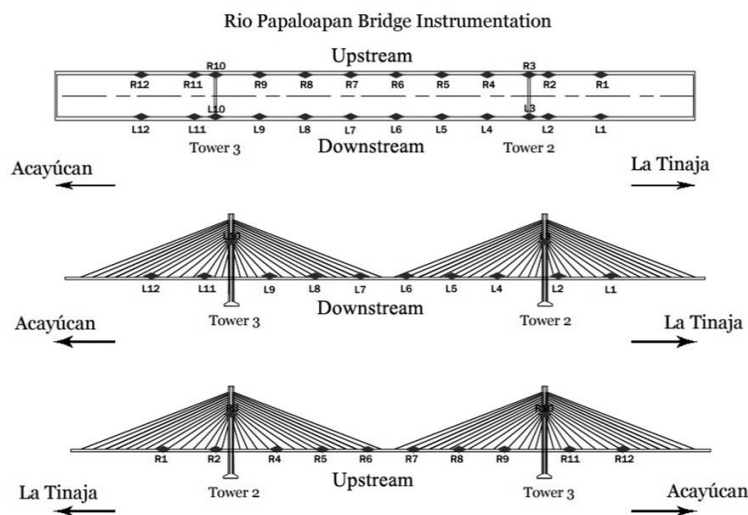


Figure 4. SHM Distribution diagram for the Papaloapan Bridge.

3.2 El Carrizo Bridge SHM System

The SHM system for El Carrizo Bridge was designed considering only the damaged double cantilever structure section of the bridge. The continuous monitoring instrumentation was made up of strain gauges, tiltmeters and temperature Fiber Optic Sensors (FOS) as illustrated in Fig. 5.

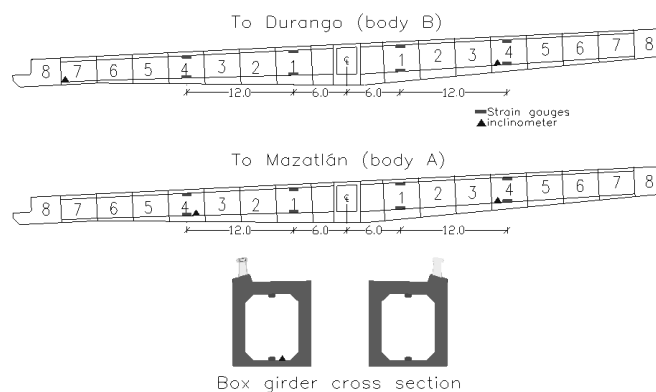


Figure 5 – SHM for permanent monitoring during rehabilitation.

The FOS system included 16 strain gauges located inside both box girders on the upper and lower sides, 4 tiltmeters and 4 temperature sensors, two on each side, as indicated above in Fig. 5. This temporal monitoring system was placed during load testing. Such a temporal sensor system involved 20 strain gauges, which were placed inside both box girders on the left and right sides, and 2 LVDT sensors at the end of the cantilever section that is connected with the cable-stayed structure. Monitoring system purposes were to evaluate continuously in real time the rehabilitation process and provide information to calculate the rating factor.

3.3 The Juarez Bridge SHM System

Six GPS receivers were used to carry out the SHM of the Juarez Bridge. The GPS technology provides three-dimensional positioning data, i.e., coordinates in X, Y, and Z, with an accuracy of sub-centimeter order (Hofmann-Wellenhof et al., 2007). In different studies around the world, it has been shown that GPS technology can be used to monitor structural deformation in bridges (Ashkenazi & Roberts, 1997; Roberts et al., 2001; Meng, 2002). The Juarez Bridge SHM system consisted on 2 Zenith Geomax, 2 Topcon Hiper V and 2 Leica SR530. They were intelligently located on the principal deck of the bridge. The displacement measurement was carried out in three periods of the day during one complete week. The three periods of the day represented peak hours of traffic. Thus, every day three measurements were performed: (1) 08:00-09:00 hrs. (Session 1), (2) 12:00-13:00 hrs. (Session 2), and (3) 17:00-18:00 hrs. (Session 3). In addition, the measuring interval of the receivers was 1 Hz during every session.

4 ANALYSIS OF THE INFORMATION EXTRACTED FROM SHM OF BRIDGES

4.1 SHM of the Papaloapan Bridge

For the case of the Papaloapan Bridge, the SHM information has been important since 2013 when the system was installed. During this period, it has been possible to evaluate the integrity of the bridge, particularly when the anchoring element of cable 1, semi-harp 5 failed by fracture on June 10th, 2015 (Carrion et al., 2017). Also, the structural behavior of the structure was monitored in 2015 and 2016 during rehabilitations, respectively. In 2015, one failure was reported in the Papaloapan Bridge. Particularly, the above-mentioned event was recorded by the SHM system on June 10, 2015, at 7:35:04 a.m., as shown in the graph of the micro-strains (See Fig. 6), i.e., it can be observed in Fig. 6 that a considerable change in micro-strains is reported between 07:35:02 and 07:35:20 hrs. This may be caused by an overloading condition on the bridge.

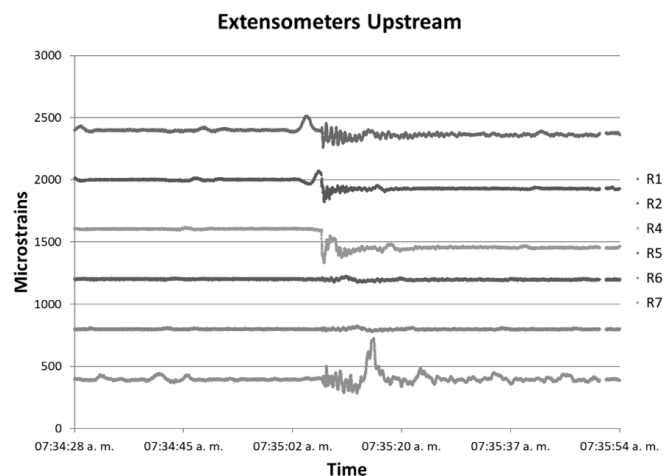


Figure 6. Micro-strain time histories of the sensors under the upstream main girder.

As an example of the evaluation of the structural behavior of the Papaloapan Bridge under different operating conditions in real time from 2013 to 2018 for an individual sensor, the statistical distribution of the axial tension load of the instrumented cable number 4 semi harp 6 is illustrated in Fig. 7. In these analyses, 15 days of time periods were considered, the main goal was to analyze changes in the statistical distribution type, the mean value and the standard deviation of this instrumented cable. It can be clearly observed in Fig. 7 that in June, when the failure happened, the Semi harp 6 cable 4 S6T4 lost around 8 tons of capacity. In addition, it is shown in Fig. 7 that, once the maintenance process is ended, the cable recovers the 8 tons. It is important to mention that different calibrations were performed to validate the model of the Papaloapan Bridge. However, because of the sake of brevity, such results are not presented here.

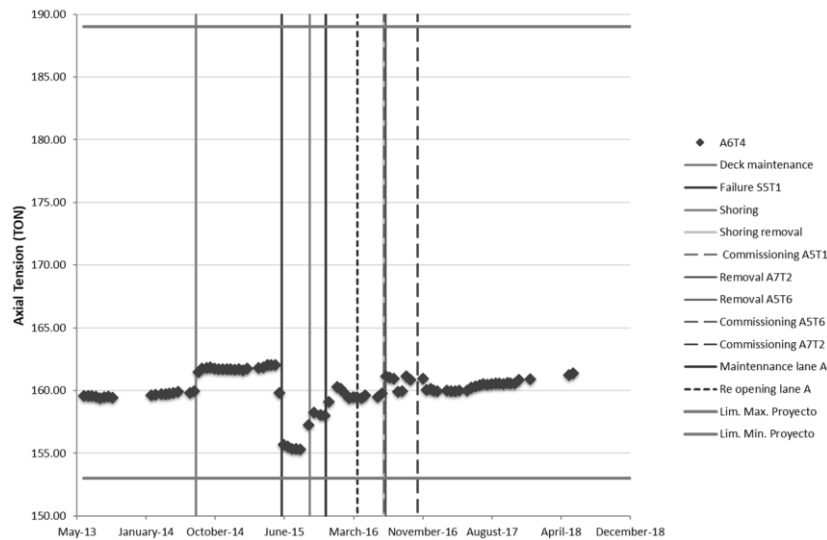


Figure 7. Tension values cable 4 semi harp 6.

4.2 SHM of El Carrizo Bridge

During the SHM of El Carrizo Bridge, the most important monitored parameters were the vibration frequencies and modes, the box girder centroid, and the statistical stress-strain responses due to live loads from traffic and absolute stress-strain responses due to changes of dead loads. Fig. 8 presents the values for the box girder centroid during rehabilitation for voussoir number one side A to Durango.

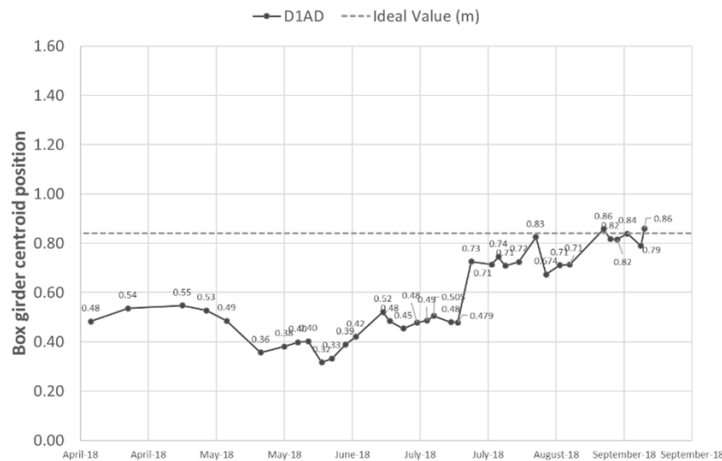


Figure 8. Box girder centroid values during rehabilitation.

It can be observed in Fig. 8 that it took around four months to stabilize the centroid of the box girder. For the case of absolute stress-strain responses, dead load changes were due to the post-tensioning of additional cables, removal of damaged bridge deck and temporary bypass lanes, or placement of new cross girders and deck sections. According to the rehabilitation stage, the alarm limits for all parameters were defined considering normal and extreme loading conditions, as well as design limits. A calibrated finite element model for all rehabilitation stages was used to understand the bridge behavior and to establish parameters limits. The calibration was accomplished through data obtained during dynamic and load testing. According to the monitoring system data and the progress status in each of the different maintenance stages, the values and variation of the first two natural frequencies were obtained through data processing of all the extensometers installed. In this sense, Fig. 9 presents the changes of the first natural frequency during rehabilitation process. It is interesting to note that Fig. 9 clearly presents the variation for the first frequency of the bridge. Also, it is observed that a significant change of this frequency was detected from June to July. Such a change was of about 0.2 Hz.

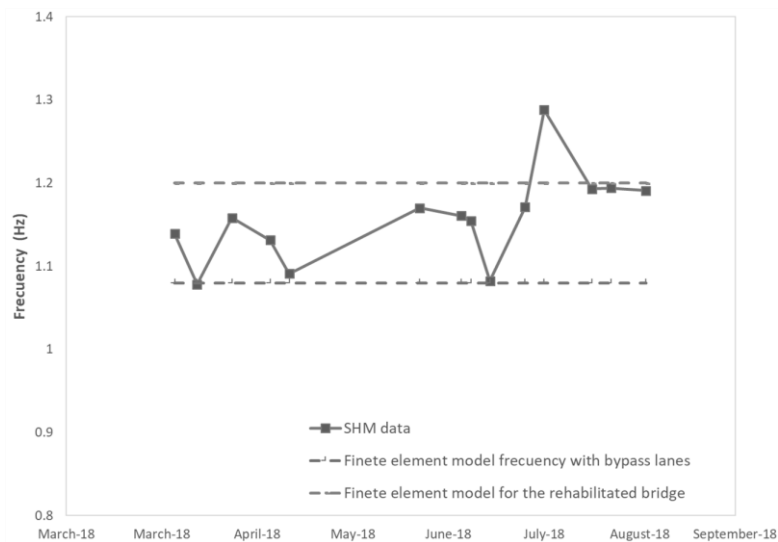


Figure 9. First natural frequency during rehabilitation.

4.3 SHM of the Juarez Bridge

The data obtained from the GPS measurements were converted to RINEX format and later analyzed for their quality with the TEQC (Test of Quality Check) software developed by UNAVCO. Also, the data was processed with the GAMIT/GLOBK scientific software in kinematic differential mode (Herring et al., 2010). The output data of the processing with GAMIT/GLOBK were geodetic coordinates referenced to the ellipsoid WGS84. Time series were converted to apparent displacement with respect to the mean value. In addition, several filters were applied to the time series to eliminate noise and errors, such as multipath. The moving average filter was used to extract the semi-static displacements from the time series, and to obtain dynamic displacements, the Chebyshev filter type 1 was applied. In this way, time series were generated in terms of semi-static and dynamic displacements obtained via GPS, respectively. Fig. 10 presents the apparent and semi-static displacements in the three components for a specific point on the bridge that presented the greatest deflection (Vazquez-Becerra et al., 2017). The results illustrated in Fig. 10 correspond to the measurements performed from 08:00-09:00 hrs. in the main deck of the bridge. On the other hand, to study the stochastic behavior of semi-static displacements, histograms were built for each of the measurement sessions. Fig. 11 presents the histogram corresponding to the semi-static displacements presented in Fig. 10. Once the PDFs

have been generated for every session and taking the deflection limits recommended by AASHTO (2010) for a span length (L) equal to 20 m, the probability of failure (p_f) is calculated (see Table 1), in average, for all measurement sessions corresponding to the Monday session. Based on the results presented in Table 1, it can be stated that the session with the highest probability of failure was the second session (12:00-13:00 hrs.), with a value greater than 80%. This may be justified since at this time of the day is the highest traffic. It is important to mention as well that the PDFs presented in Fig. 11 correspond to a Normal distribution, i.e., the semi-static displacements are presenting a Normal type distribution.

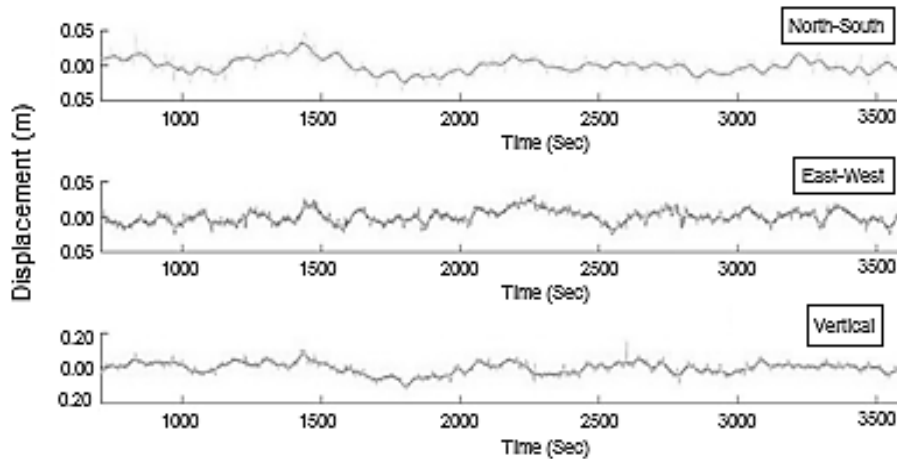


Figure 10. Apparent and semi-static displacement for the Juarez Bridge.

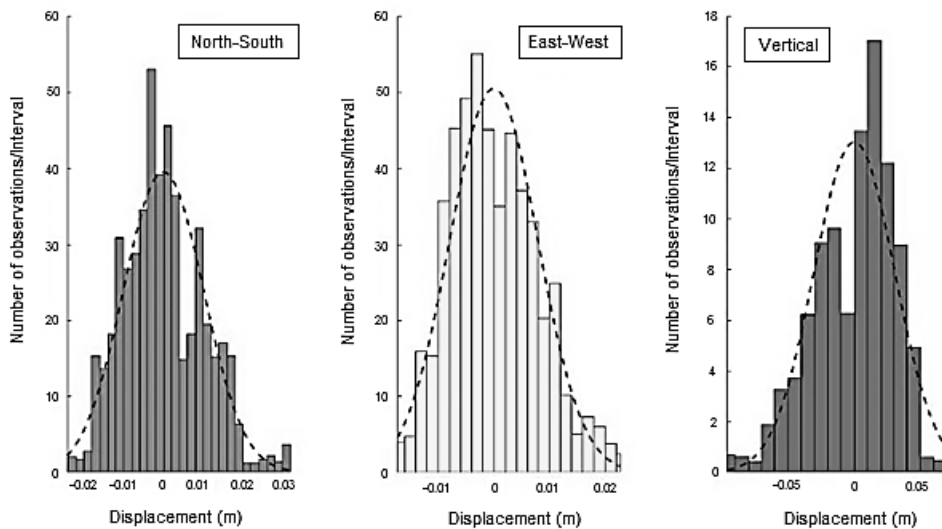


Figure 11. Histograms for the Juarez Bridge.

Table 1. Probability of failure (p_f) on the station that presents greater deformation on the bridge.

GPS session	p_f for $L/800$ (%)	p_f for $L/1000$ (%)
Monday 1	41.39	51.33
Monday 2	83.13	86.46
Monday 3	67.07	73.38

5 CONCLUSIONS

Based on the results presented in this paper, it is demonstrated that SHM systems can provide information to evaluate the structural integrity of bridges, and then, take decisions about whether a rehabilitation is necessary. Also, it was presented the implementation of sensors in the SHM of bridges located in Mexico validating that this is a step in the right direction that the Government of Mexico is taking. Three case studies were considered and different techniques to extract the performance of bridges in real time were demonstrated to be viable. Finally, SHM systems can collect data of interest of bridges, and this information may be used to calibrate finite element models of them.

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