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## DAMAGE DETECTION ON A CABLE STAYED BRIDGE USING WAVE PROPAGATION ANALYSIS

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### ABSTRACT

The Global Search Method (GSM) is being proposed for global evaluation of complex structures. This method is based on the analysis of the flexural wave propagation and the comparison of the real structure responses to those from a calibrated simulation model representing the non-damaged condition. Then, the differences are associated to changes in the structural parameters (stiffness, damping, mass, and geometry) or the boundary conditions, and related to a specific region or location within the structure to locate damage and quantify its overall structural effect. The effectiveness of the GSM was evaluated on a cable stayed bridge where damage was simulated when a cable was removed during rehabilitation; dynamic tests were done using a Falling Weight Deflectometer to control the dynamic impact load and previously analogous tests were done to calibrate the finite element model. Results show that the GSM has the ability to identify and quantify damage, where sensitivity increases when the sensors are closer to damage. In the bridge case, damage could not be detected when the distance of the sensors was greater than 65 meters from damage because of signal attenuation.

**KEYWORDS :** *Damage detection, Wave propagation, Stayed bridges*

### INTRODUCTION

The Rio Papaloapan Bridge is located in the La Tinaja-Acayucan highway, in the state of Veracruz, Mexico. It was commissioned in 1995, and it is a stayed bridge with a span of 203 meters and an overall length of 407 meters. The bridge has 112 cables in 8 semi-harps with 14 cables each; semi-harps are numbered from 1 to 8 (figure 1), and cables are also identified from 1 to 14, starting with the shortest [1]. After 5 years of service, the upper anchorage element of cable 11, semi-harp 7, failed in 2000. In this case, a full fracture took place under normal operational conditions near the weld joint of the anchorage and the A-50 structural steel plate (embedded in the concrete tower).

To determine failure cause, the construction process was analyzed and laboratory destructive and nondestructive tests evaluated the mechanical properties and the internal condition of the constitutive material. From those, it was found that the anchorage element was cast manufactured with poor quality control and defective heat treatment; as a result, a large pore and inclusions content were found and the steel microstructural grain size was large enough for a brittle material with properties that didn't meet the design standards [2-4]. Moreover, it was also necessary to evaluate the internal and microstructural condition of the 111 remaining anchorage elements in the bridge, and as a consequence, an ultrasonic inspection was developed to evaluate the anchorage

elements in service, with particular focus on the microstructural condition and identification of internal defects (pores and large inclusions). After the nondestructive inspection, it was found that 16 anchorage elements in service were structural deficient with large microstructural grain size (brittle) and/or large content of internal defects (pores, cracks or inclusions) [5].

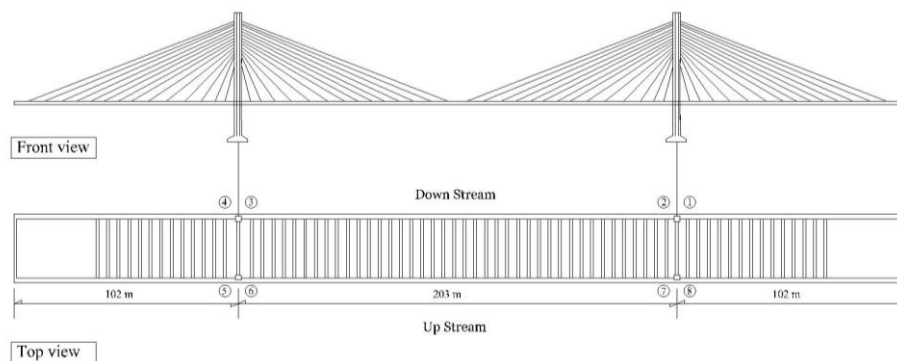


Figure 1: Rio Papaloapan Bridge layout.

The main bridge rehabilitation process included the replacement of the 16 defective elements and 4 additional “good condition” elements for full evaluation and to get representative statistical data of the mechanical and micro-structural characteristics of the remaining 92 anchorage elements in the bridge. This information was used for a reliability analysis for a 30 years scenario [6].

During the rehabilitation process, a comprehensive analysis of the bridge performance was done through several studies and field tests; from those, it was concluded that a SHM system was necessary to follow the dynamic and structural behavior of the bridge and validate and update the reliability analysis. As a consequence, a remote monitoring system based on 57 fiber optics FBG sensors was installed and commissioned in 2013, including accelerometers, temperature, tilt, strain, and displacement sensors. Complementary to the SHM system, a remote monitoring center was installed with a remote server, storage devices, workstations and complementary software and hardware for the remote monitoring, analysis and structural evaluation. The monitoring center was also designed for research and the development of specific applications for structural evaluation and prognosis. This platform is used to evaluate structural damage detection and identification algorithms, including the Global Search Method (GSM).

Considering the enormous real time data registered by the SHM system it has been necessary to develop strategies for analysis and processing for the efficient evaluation of extraordinary events such as gusty winds, earthquakes, accidents, or overloading. It is in this sense that the efficiency, sensitivity and effectiveness of damage detection methods can be evaluated taking advantage of particular rehabilitation events where controlled conditions, and such was the case the GSM that was evaluated during the rehabilitation of one cable that had to be released; dynamic tests were performed previous to the removal of the cable to calibrate the initial reference condition and the same tests were repeated after the cable’s liberation, simulating a damage condition.

## 1 DAMAGE DETECTION METHODOLOGY

The GSM for damage detection is based on the supposition that dynamic responses and structural wave propagation are affected by damage and through the analysis of these it is possible to identify damage by comparing the damage condition with the undamaged. Experimental procedure requires instrumentation with different types of sensors, and an impact device to induce a dynamic load under controlled conditions. In general, the methodology can be divided in the following stages.

### 1.1 Model Calibration

In most cases, the reference model is developed using finite elements software apposite for dynamic analysis. The calibration of the FE model is reached when the structural parameters have appropriate values to the geometry and constitutive materials, similar to the real structure, such that the model dynamic responses are almost equal to the real system [7].

The FE model of a linear system can be represented as:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{P\} \quad (1)$$

In this case, the mass, damping and stiffness matrices have the structural properties of the different materials within the structure. The calibration is a key issue for the damage identification algorithms, while an adequate calibration [7] leads to an appropriate association of changes to damage location and quantification.

### 1.2 Instrumentation

Measurement of the dynamic responses of a real structure for damage identification requires a comprehensive analysis and planning that includes a preliminary evaluation of the dynamic behavior of the structure, identification of most probable damage locations and knowledge of the deterioration mechanisms that may occur. Once the previous are defined and from the basic principles of the damage detection method, it is possible to define the location, number and type of sensors to be used. For example, modal based methods require an instrumentation system able to measure a frequency range up to the highest expected mode; while for wave propagation, frequencies must be within a higher frequency range to measure the flexural wave's propagation. In any case, these conditions define the sensors and instrumentation characteristics. As for the sensor location, modal techniques define specific locations to be measured considering the modes to be identified; while wave propagation methods do not require specific locations for sensors, but these must be close to the probable damage locations.

In general applications, accelerometers, strain, velocity or displacement sensors are used to measure dynamic behavior at a specific point within the structure; but in some cases, global sensors based on image analysis of photo-elasticity, Moiré or similar techniques, can be also used. The first type of sensors have time measurements at the specific locations where sensors are, while the second give a full image of the structure at a given time or a set of time instants [8].

### 1.3 Dynamic Excitation and Response Measurement

Several devices have been developed to generate an impact dynamic load or excitation force under controlled conditions. Regardless to the type, it must measure the applied impact force and control its time duration, so it can be used as an input for the simulation analysis to produce the equivalent simulated responses and to compare the experiment to the simulation.

### 1.4 Error Function Evaluation

Changes in the dynamic responses associated to changes in the structural parameters, can be quantified using a square least error function Equation (2), that is calculated from the difference between the experimental dynamic response at node  $j$   $\{r_{exp}\}_j$  and the response of the FE model at the same node  $j$   $\{r_{mod}\}_j$ . In this case, the vector  $\{r\}_j$  can be defined by the displacements  $\{u\}$ , the velocities  $\{\dot{u}\}$ , the accelerations  $\{\ddot{u}\}$ , or a combination of any of these. If no difference between responses is found, the structural parameters used in the model correspond to the real structure;

thus, when a change in measured, it can be inferred that damage has occurred. Moreover, if a sequential method is applied to change the values of the parameters within a range and a defined strategy, it is possible to reduce the error function that measures the difference and adjust the simulated responses to the real ones so that, the changes in the structural parameters can be associated to the location and magnitude of damage.

$$V_j = \sqrt{\frac{\sum_{i=1}^N (r_{i,j,\text{exp}} - r_{i,j,\text{mod}})^2}{N}} \quad (2)$$

The term  $r_{ij}$  represents the dynamic response at node  $j$  at time instant  $i$ , and  $N$  is the number of time data of the discretized responses. The time period and sampling rate determine the size of data in the error function. Since there is no limitation of data type in the error function, several and different sensors can be used for any structure type and configuration, for linear or non linear problems, and it can be extended to any type of mechanical vibration.

### 1.5 The Global Search Method (GSM)

To find damage a systematic search strategy changes the structural parameters sequentially to minimize the error function. From *a priori* knowledge, the parameters are changed within a predefined range with fix increments and for each condition the responses are calculated from the modified model and compared to the experimental results. The condition that minimizes the error function is taken as the damaged condition and the possibility of finding the best solution requires a large computation effort to evaluate all possible changes in the parameters.

## 2 EXPERIMENTAL PROCEDURE

To calibrate the bridge structural parameters of the FE model, two different dynamic tests were considered; the first, from the monitoring of the 112 cables during the rehabilitation process with 22 different loading scenarios due to the change of the 20 anchorage elements, the initial condition, and final rehabilitated condition. In this first case, dynamic measurements were used to evaluate the frequency spectra and from a nonlinear model, the tensions were calculated for each cable [9].

The second test consisted on dynamic tests where a controlled impact forces was applied at different points on the bridge deck. In this second case, 11 accelerometers on the deck were located on one side of the bridge between the two towers as indicated in figure 2. The impact forces were applied without traffic with a Dynatest falling weight deflectometer at different points on the deck. For this set of dynamic tests, a 2000 Hz sampling rate during 2 seconds was used for all sensors simultaneously; the experimental procedure was as follows:

- Bridge instrumentation
- Traffic control to avoid any traffic on the bridge during the tests
- Monitoring startup and acquisition of sensor measurements
- Release of impact force
- Monitoring system turn off and data storage

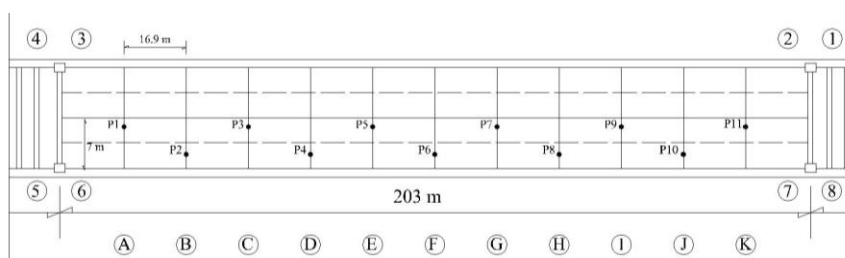


Figure 2: Experimental arrangement for dynamic testing.

A set of dynamic tests was done at 10 different impact points on the deck before freeing the cable, and a similar set of 10 impacts was also done after release. At each point, the test was done 3 times for statistical analysis. The previous set of tests was used for calibration, while the second was used to evaluate the GSM.

### 3 CALIBRATION OF THE FE MODEL

The FE model was developed using the StaDyn software, version 4.54, which is open free access software that was developed in the School of Aeronautics and Astronautics of Purdue University by Prof. James F. Doyle [7,10].

Calibration followed a four step procedure: the first considered the geometric model elaboration from design structural drawings of the bridge; the second entailed the material's properties allocation using field data and complementary typical data; the third included the design and implementation of experimental tests to measure dynamic responses as described previously; and at last, the fourth step consisted in the optimization of the model parameters to match simulation responses to the experimental ones.

The full finite element model was built with 8224 elements and 4693 nodes. The bridge deck was divided in a 12 x 580 elements grid, and the remaining elements were used for the pylons, cables and reinforced deck beams. Plate elements were used for the deck slab and frame elements, while beam elements were used for the reinforced longitudinal beams and pylons, and the cables were simulated with a modified bar element. For the boundary conditions, the 4 pylons were assumed with a fix foundation, the northern approach was taken as a fix support condition, and the southern approach as a support free to move in the  $x$  direction.

The unknown structural parameters were calculated using the dynamic responses or the initial condition, the pre-calibrated model and the software StrIdent [7,10], which is a StaDyn complementary software that solves inverse problems [11]. The model was considered as calibrated when tensions were within 10% from the experimental values with dead loads only. Figure 3 shows the comparison of the experimental tensions to those from the calibrated model.

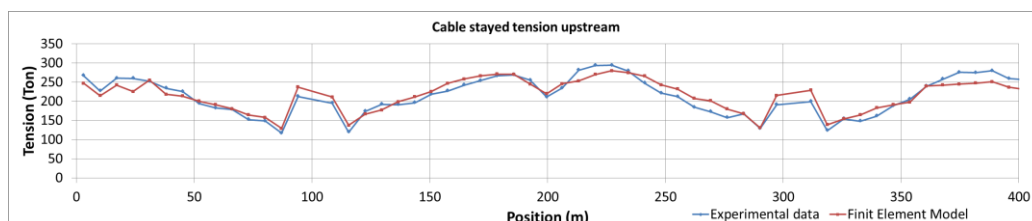


Figure 3: Experimental and FEM Tensions.

#### 4 DAMAGE IDENTIFICATION

The described condition without a cable was used as a virtual damage scenario to evaluate the performance and ability of the Global Search Method (GSM) for the detection and identification of damage. As mentioned, cable 1 of semi-harp 7 was removed for maintenance and dynamic tests were done previous to removal of the cable and after removal.

In this case, the search strategies were two: the first entailed changes on the Young Modulus or Elastic Modulus of the elements directly related to the cables, including the 112 cables themselves; and the second, assumed conditions without one cable of all 112 cables. Results from the first scenario showed little information, since changes on the elastic modulus didn't improve the error function and rupture on a cable was not possible by changing the elastic modulus due to ill conditioning. The second strategy provided information on damage as it is analyzed below.

Figure 4a shows variations on the dynamic responses for sensor 11; the Y axis represents the difference between the experimental and simulated responses, while the X axis is the position of the cable with respect to the bridge deck from left to right (figure 1) so that, for example, cable 1 of semi-harp 6 is number 15. Here 3 curves are observed: the first (squares) represents the upstream cables; the second (diamonds), denotes the downstream cables; and the third (line) symbolizes the actual position of the removed cable.

Dynamic response of sensor 11 is minimized at position 42 of the upstream cable figure 4a, which corresponds to the actual damage scenario. Figure 4b shows the same for sensor 10, where the minimum does not correspond to the real damage position and indicates the cable 1 of semi-harp 1 (position 43 of downstream cable), and the second minimum effectively corresponds to the actual damage position. It is important to note that, although the sensor 10 is not precise, it locates damage close to the actual position. When comparing sensor 10 with 11, clearly sensor 11 has higher sensitivity as it is closer to the damage location (4 meters of sensor 11 to 17 meters of sensor 10).

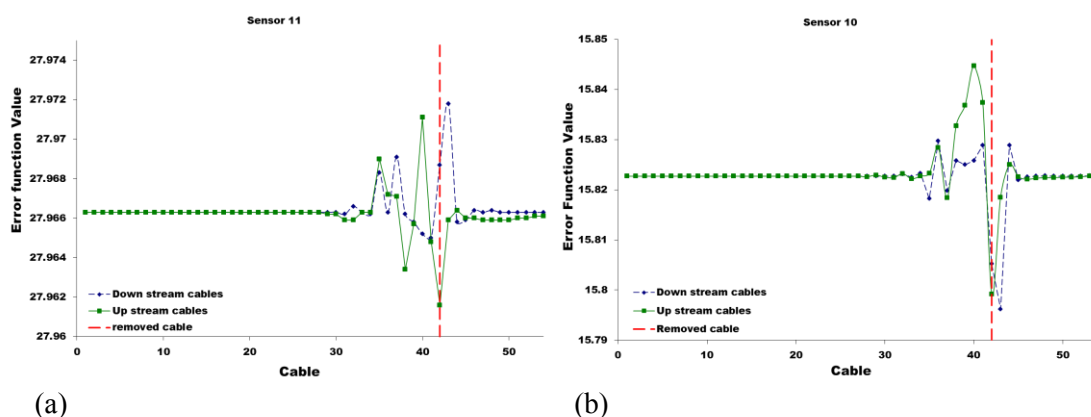


Figure 4: Objective function Values generated by the GSM. (a) Using sensor 11 data. (b) Using sensor 10 data.

In the case of sensor 9, it is different to sensors 10 and 11, since it is not able to locate the damage and even shows no error where it should be; minimums are indicated close or next, but not at the actual damaged position. Results from sensor 8 indicate damage adequately by the error function as it was for sensor 11, and somehow for sensor 10. At last, if the optimization of the error

function includes simultaneously the 4 sensor (8, 9, 10 and 11); again, the minimum location agrees with the position of the removed cable.

To analyze the GSM sensitivity with respect to the sensors position, the model calibration and the electronic noise, an overall noise was calculated with respect to the actual responses magnitude and normalized to the highest value of the reference line from the optimization process of the error function; which is the average of the optimized error of all positions. Then, the reference value is plotted to the distance and compared to different 2%, 4%, 6% and 8% noise levels, which are typical values obtained experimentally (figure 5). Clearly, from figure 5 it can be noticed that sensors 45 meters farther (like sensor 9), have little sensitivity with respect to noise and are not well suited for damage analysis of the particular simulated damage of cable 1. At the same time, if noise is reduced, including a better calibration and model response, the sensitivity increases in terms of amplitude and distance.

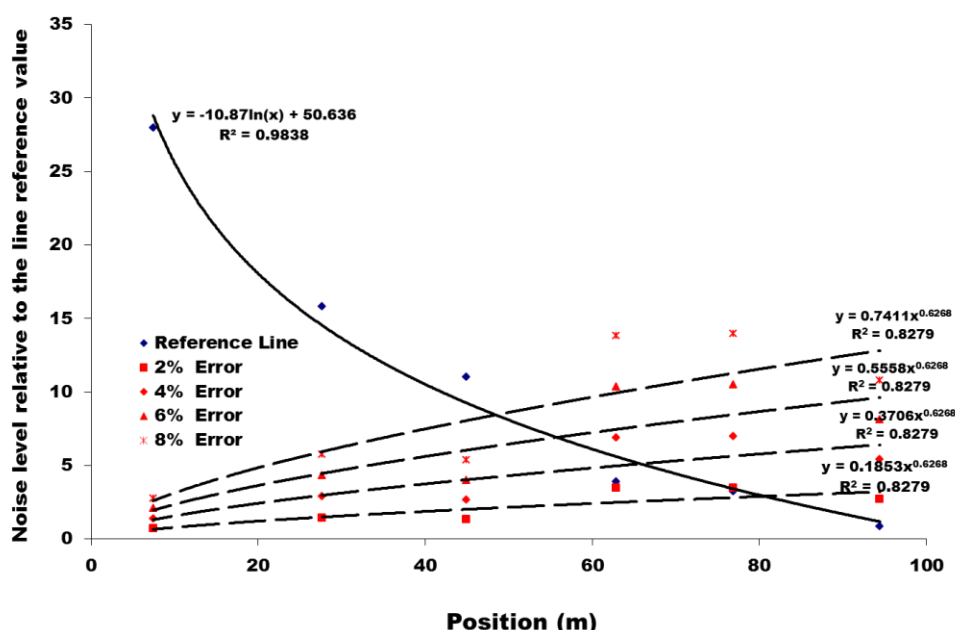


Figure 5: GSM sensitivity with respect to the sensors position.

## CONCLUSION

The Global Search Method proved to be a useful tool for damage evaluation; its sensitivity depends on three main aspects: the FE model calibration, the sensor position with respect to damage and impact position, and the noise level in the experimental tests. For the Rio Papaloapan Bridge, this distance should be no more than 65 meters due to dispersion of the dynamic responses, the present noise and the sensors sensitivity. All these factors decrease the GSM sensitivity to the point that is not possible to measure differences between a damaged and undamaged condition, regardless it is a significant change like the rupture of a cable.

Calibration of a bridge model is a complicated process due to many factors; some of them are the properties of the materials that are not always constant and the design drawings sometimes do not correspond to the real condition. Also, manufacture defects or modifications during construction are not visible, detectable or well recorded; and lastly, the model and mathematical restrictions of



the software are, in some cases, limitations for proper simulation of real practical conditions. So, for a better calibration a detailed experimental plan must be elaborated to define the best sensor selection and location, adequate instrumentation choice to reduce experimental noise, and a well suited experimental procedure. At the same time, nondestructive and destructive tests are highly recommended to have experimental probes of the mechanical, geometric and physical conditions of the structure.

The GSM can be used for calibration and for damage detection as well. But also, it can be used for the monitoring of changes within the structure due to deterioration, fatigue or time-dependent damage. Finally, to improve the methods performance, it is possible to store a set of possible damage responses and use them for reference in future analysis, without repeating simulations under the same conditions; this, opens up the possibility for Genetic Algorithms or Intelligent innovating algorithms.

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