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IMPLEMENTATION OF A MODAL IDENTIFICATION METHODOLOGY ON THE PEREIRA-DOS QUEBRADAS CABLE-STAYED BRIDGE

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ABSTRACT

Currently more than 50% of the bridges in Colombia have moderate to severe damage due to poor maintenance, severe climatic conditions and/or intense seismic activity. Currently, visual inspection is the most common method used for the assessment of bridges in Colombia, a tedious and expensive process. The need for faster, yet cost-expensive and reliable techniques has been recognized for the Colombian government, particularly in the case of prominent structures such as cable-stayed bridges. The Pereira-Dosquebradas Viaduct, a structure in this class, was completed in 1997 to connect the southwest and the central parts of the country, a key corridor in Colombia's road network. To monitor this structure, instrumentation was installed consisting of three sub-systems that provide dynamic and static measurements through a wide variety of sensors. This paper describes the bridge and the health monitoring system. Additionally, preliminary results are obtained through implementation of a modal identification methodology using data acquired from the dynamic sub-system of the bridge.

INTRODUCTION

Extreme humidity and frequent earthquakes force structural assessment to be an important factor in the maintenance of the highway network in Colombia. The Ministry of Transportation and the National Roadway Institute (INVIAS) <*http://www.invias.gov.co*> have recognized the need for the improving upon the capabilities of current visual inspection through the development of more reliable and less expensive methodologies to assess the structural health of bridges, in particular, that of large structures such as cable-stayed bridges.

Colombia's main roadway network includes around 2000 bridges with spans greater than 10 meters, of which approximately 60% present moderate to severe damage levels (Yamin and Ruiz, 2001), (Fig. 1 and Table 1). These civil infrastructure systems are of vital importance for the national economy as millions of tons of cargo and hundred of thousands of people pass over them each year. The percentage of unsafe or damaged structures is alarming and the situation is

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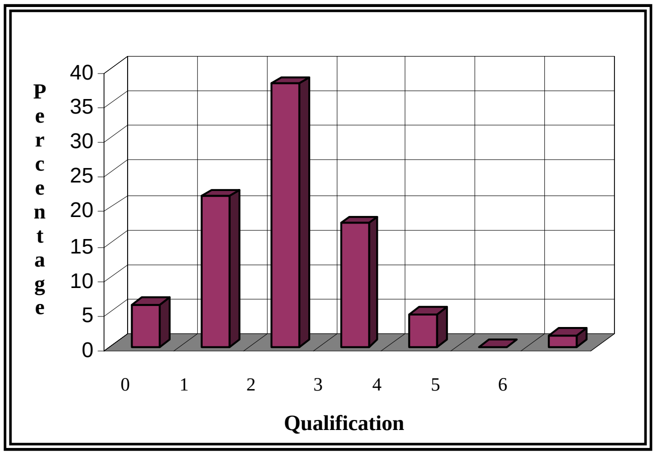

Figure 1. Bridge classification according to damage level.

Table 1. Damage level according to classification.

Qualification	Damage level
0	No damage
1	Slight
2	Moderate
3	Serious
4	Severe
5	Extreme
6	Unknown

aggravated by the armed internal conflict and the fact that the government has not implemented a continuous and efficient maintenance program. Hence it is necessary to conceive new strategies to guarantee the safety and integrity of the roadway infrastructure within the nation's unique context and propose solutions that have a positive and direct impact on the economy.

Because of their geographical location, the cities of Pereira and Dosquebradas represent strategic points within the national roadway system. The César Gaviria Trujillo Viaduct, which connects these two cities, is one of the most important systems of the country's roadway infrastructure and in 1998 it was the world's twentieth longest cable stayed bridge. Fifty-eight million US dollars were invested in the construction of the viaduct, including 1.5 million designated for more than 300 transducers for monitoring its static and dynamic behaviour (Rodriguez *et al*. 1998). These transducers include accelerometers, displacement transducers, inclinometers, temperature gauges, and corrosion sensors installed throughout the steel superstructure, the concrete piers and steel cables. Data from these instruments are acquired and sent through serial cable to a central station for processing. Currently a considerable number of the sensors are damaged due to incorrect installation and vandalism, and of the remaining sensors, the data are only being acquired with no significant amount of analysis.

Due to these conditions, the School of Civil Engineering and Geomatics of the Universidad del Valle (UV) <*http://solidos.univalle.edu.co*> in cooperation with the Electrical Engineering Faculty of the Universidad Tecnológica de Pereira (UTP) <*http://ohm.utp.edu.co*> and the Department of Civil Engineering of the Washington University in St. Louis (WUSTL) <*http:/wusceel./cive.wustl.edu*> are presently developing a real-time, level III structural health monitoring system for the Pereira-Dosquebradas Viaduct. This paper describes the preliminary and future work conducted in the development of the strategy as well as the structural configuration of the bridge and the instrumentation system already installed.

DESCRIPTION OF THE BRIDGE

In 1998, the cable-stayed viaduct between Pereira and Dosquebradas was the world's twentieth longest cable stayed bridge <*http://ohm.utp.edu.co*>. As shown in Fig. 2, the main structure of the bridge has a total length of 440 m, a central span of 211 m and two side spans of 31.3 m and 83.25 m. It has four traffic lanes and two sidewalks, with a total width of 26.15 m. The axes referenced in the figure correspond to those used in the as-built drawings.

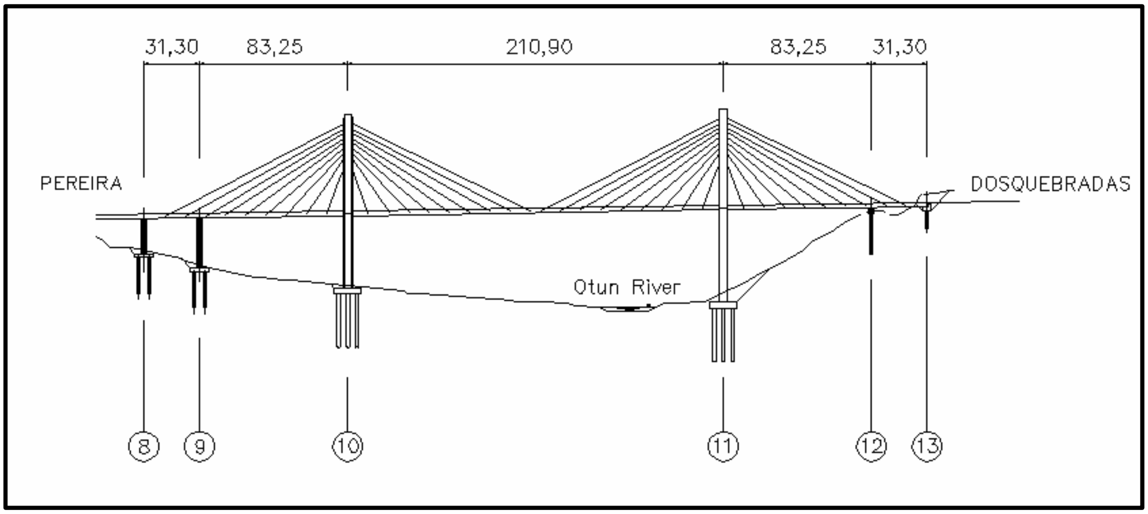

Fig. 2. Pereira – Dosquebradas Viaduct.

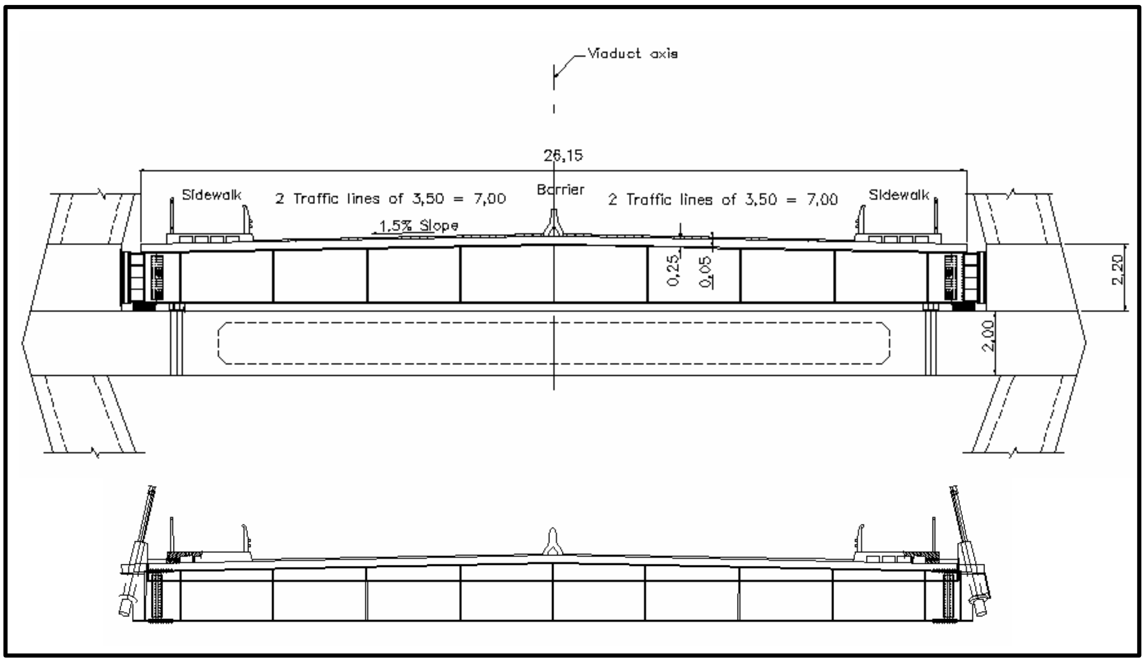

Fig. 3. Cross sections of the Bridge deck

The viaduct is a cable-stayed bridge with 72 cables connected from two principal towers. The cables have lengths varying from 32 m up to 112 m, and are made of high–strength, low–relaxation steel (ASTM A882 grade 270). The bridge deck is approximately 55 m above the river, with a longitudinal slope of 1.5% and it consists of steel (ASTM A572 grade 50) girders and joists and a post-tensioned concrete slab. The main structure includes two principal towers, three secondary piers and an abutment. All the bearings are sliding bearings except those at the principal piers, where the superstructure rests on fixed bearings. As shown in Fig. 4, the concrete towers are diamond shaped and their cross section decreases with height. These towers have a height of 56 m above the deck. The secondary piers are concrete frames, with rectangular sections. All the piers and principal towers are supported on piles with maximum lengths of 30 m.

INSTRUMENTATION

Of the 58 million US dollars invested in the construction of the viaduct, 1.5 million were appropriated for instrumentation of the structure. More than 300 transducers including accelerometers, displacement transducers, inclinometers, temperature gauges, and corrosion

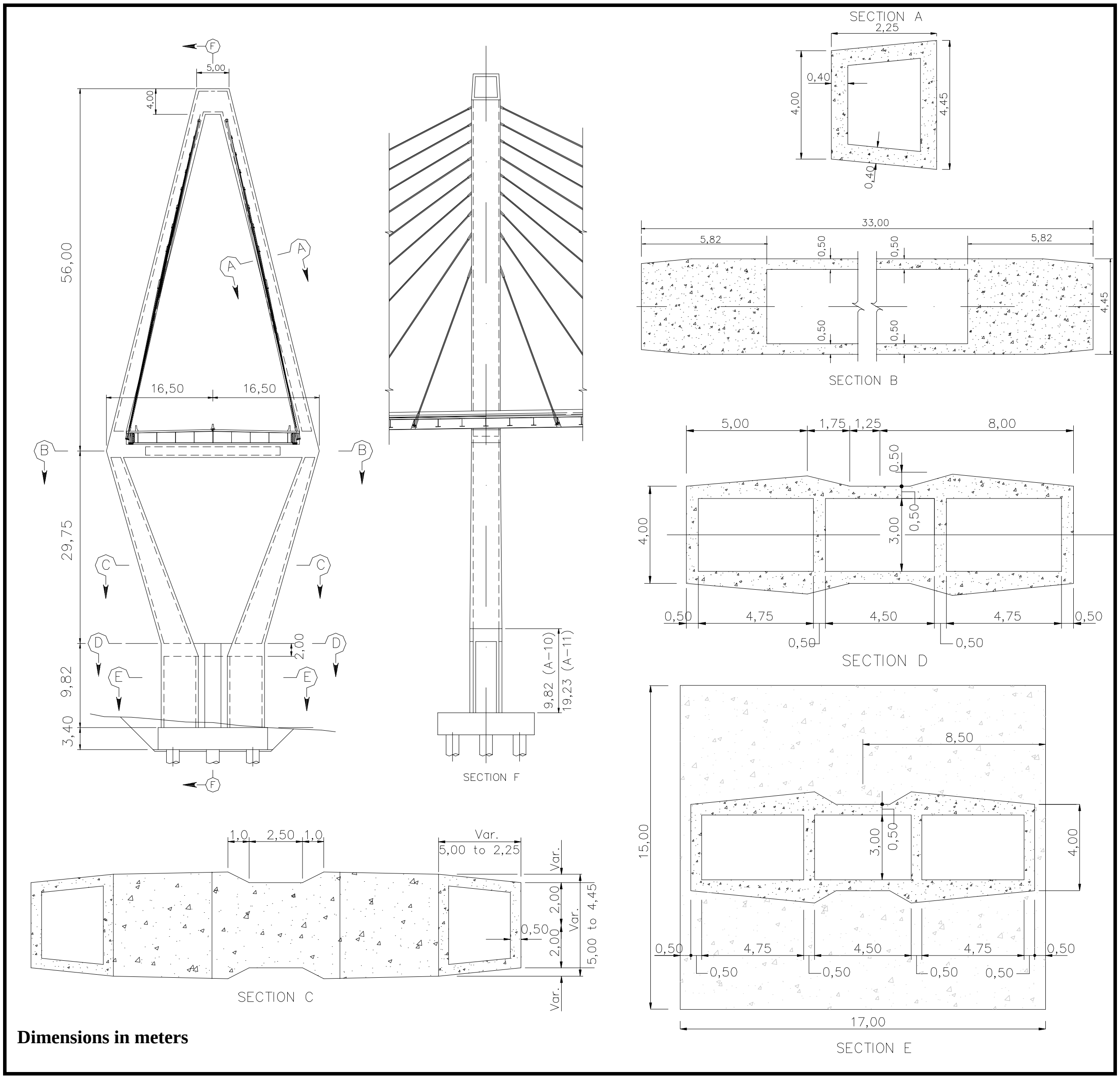

Fig. 4. Cross sections of Towers

sensors are installed throughout the steel superstructure, the concrete piers and steel cables <*http://ohm.utp.edu.co*>. Signals from these sensors are transmitted via serial cable to a monitoring station near the Dosquebradas approach of the viaduct. The viaduct instrumentation and data acquisition system can be classified into three subsystems, as described in the following sections.

Static Subsystem

This subsystem is designed for monitoring “slowly-varying” phenomena such as variations due to temperature changes, foundation settlement, and concrete relaxation. It consists of 4 A.G.I.S. pendulums (model PD/2000/R), 5 SISGEO inclinometers (model S522SV10), 52 A.G.I.S. inductive displacement transducers (model EBC/S/1000), 4 Rayelco joint separation sensors (model PT-420-40), 32 A.G.I.S. temperature gauges (model TM/C/100), and a meteorological station which includes a pluviometer, radiometer, barometer and a thermohygrometer (Fig. 5). The pendulums are placed at the top and bottom of the piers to detect rotations with a resolution of $5x10^{-6}$ rad, while the inclinometers determine the change of tilt in the deck and have a sensitivity of 40 mV/° up to 10 degrees. The displacement transducers measure deformations of up to 8 mm in the girders with an accuracy of 0.005 mm and the joint separation sensors detect displacements of up to 1000 mm with a precision of ±0.1 of full scale. The temperature gauges are embedded in the deck and work in a measurement range from -50 to 100 °C with a sensitivity of 0.1°C.

The data of this subsystem are acquired and multiplexed by A.G.I.S. Acquisition Units (model RAD48) each with 48 differential mode channels, 8 KB RAM memory for operational parameters and a 256 KB memory card for data storage. Data from the corresponding sensors are acquired automatically every six hours through serial RS-232. Finally, the information is downloaded to a computer at the monitoring station for further analysis.

Dynamic Subsystem

Designed for monitoring “fast-varying” phenomena due to traffic, wind and seismic loads, this subsystem consists of 29 piezoelectric accelerometers from SIG SA (6 uniaxial accelerometers model AC31, 12 biaxial accelerometers model AC32 and 11 triaxial accelerometers model AC33), 3 YOUNG anemometers (model 05103) and 24 A.G.I.S. strain gauges (model SM/A/100/D) for detecting deformations in the girders with a measurement range of ±1500 με (Fig. 6). Trigger levels, set from the monitoring station, can be specified to initiate data acquisition at sampling rates that are usually set at 128 or 256 Hz. This subsystem provides information of the dynamic loads and viaduct response. Wind velocity and direction across the deck is monitored as well as longitudinal, transverse and vertical acceleration of the deck, piers and cables.

In this subsystem, data are acquired, filtered, digitized (12 bits) and multiplexed by 32 SIG units (model SMACH SM2), each with 3 dynamic channels and a 512 KB memory card for data. The data are sent from the SMACH units to interconnection nodes through serial RS-232 and the communication between the nodes is made through serial RS-422. Finally, the information is collected by a SMACH central unit in the monitoring station and pre-processed for further analysis.

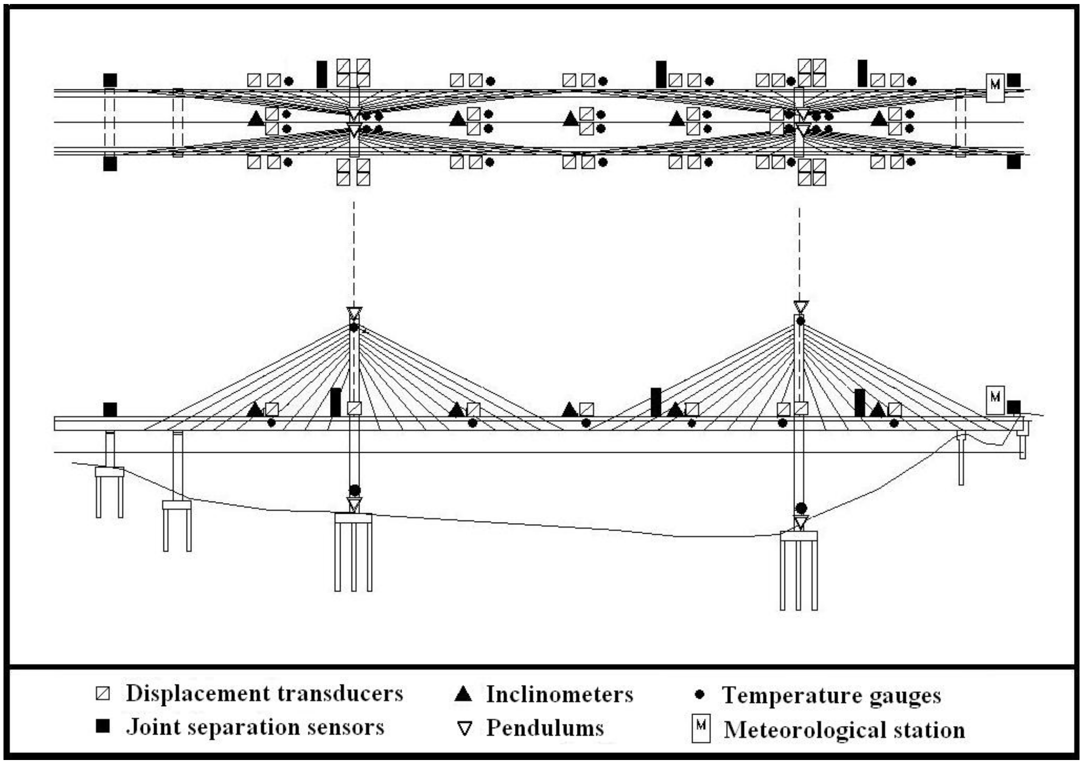

Fig. 5. Static Subsystem.

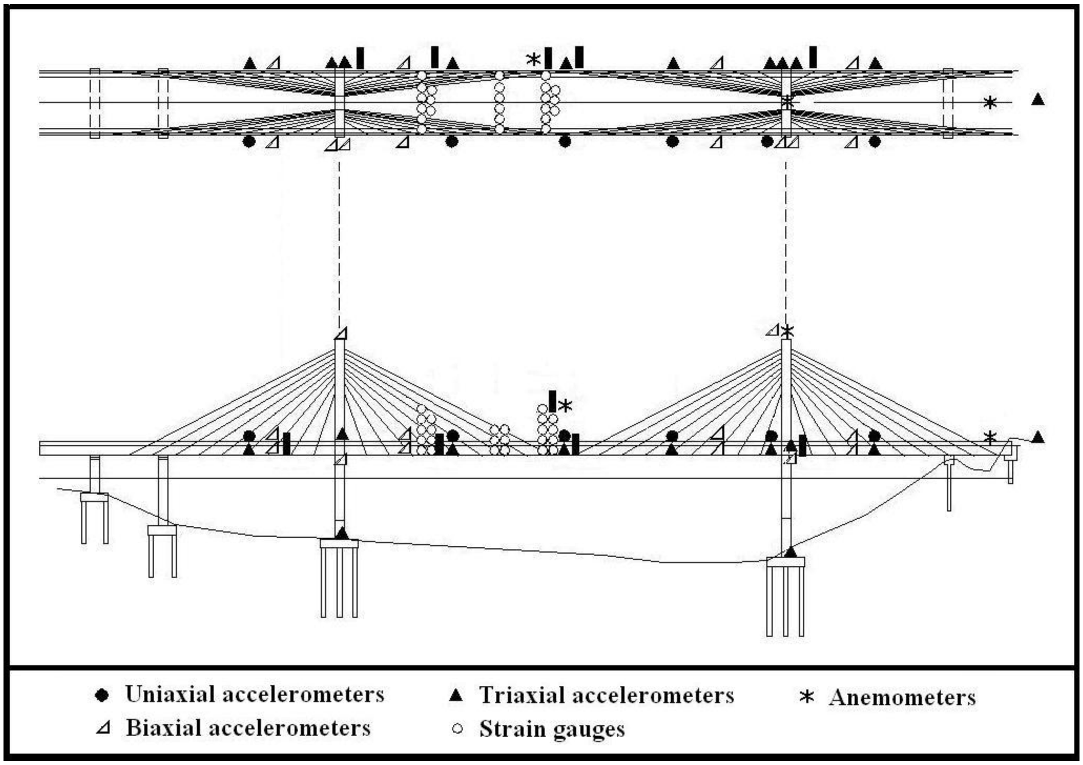

Fig. 6. Dynamic Subsystem.

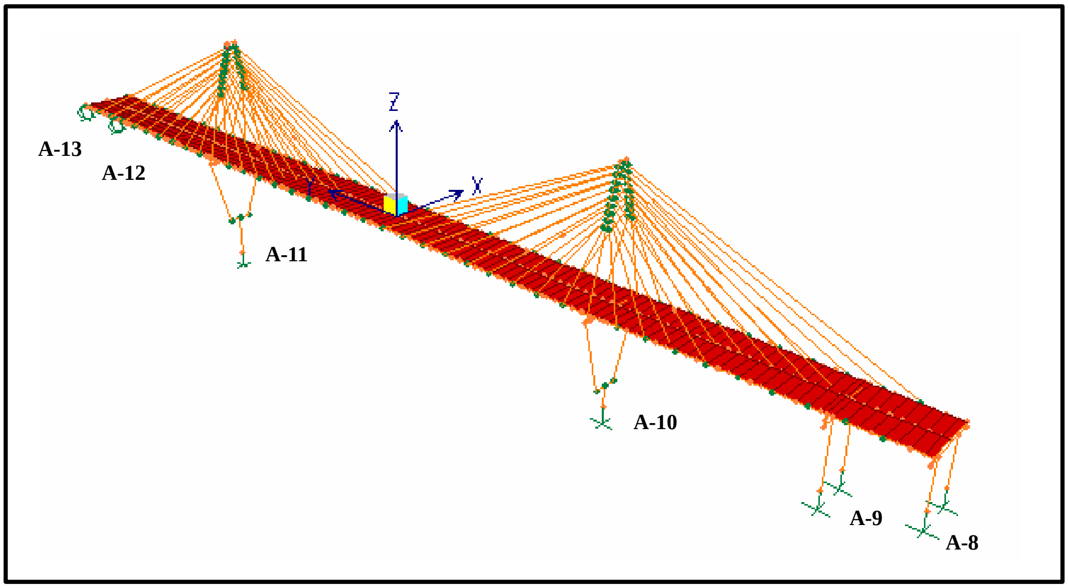

Fig. 7. Finite Element Model of the Viaduct

Corrosion Subsystem

This subsystem consists of 136 sensors for detecting corrosion in the steel reinforcement of the concrete piers and deck slab. These sensors consist of three electrodes embedded in the concrete (two of copper and one of steel), each approximately 10 cm long. By measuring the current that flows through the electrodes due to a constant DC voltage drop, the level of corrosion can be determined. As variations in corrosion levels are expected to be very slow, measurements are performed manually once every six months.

PRELIMINARY RESULTS

Analytical model

A three dimensional finite element model of the viaduct was developed by Jaramillo and Palacios (2000), using SAP2000, as shown in Fig. 7. The bridge geometry was modeled according to the as-built drawings. The finite element model employs frame elements to model steel girders and joists, the concrete frames, the principal towers and the cables. The concrete slab was considered as a mesh of membrane elements. The finite element model has a total of 606 nodes, 928 frames and 242 shells.

The areas and inertias of the steel beams were calculated assuming a composite section with the concrete slab. An effective width of 1 m was considered in this assumption. The reinforcement was taken into account to calculate the section properties of the principal towers, due to the high compression stresses produced by the tensioning of the cables. The cables were considered as beam elements with a low flexural stiffness, assuming the contribution of each internal wire in the cable. Because the attachment points of the cables to the deck are above the neutral axis of the deck, and the attachment points of the cables to the tower are outside the neutral axis of the tower, rigid links were used to connect the cables to the tower and to the deck. The use of rigid links ensures that the length and inclination angle of the cables in the model agree with the drawings. The third concrete frame and the abutment located on the Dosquebradas side were considered as simple vertical restraints at the respective nodes. Frame elements without internal strain were used to connect the outer beams of the deck with the towers and frames, and releases were assigned to allow longitudinal displacement (Y) and rotations about the X and Z axes while restricting the deck from moving laterally. Additionally, the principal towers provide a longitudinal restraint to the deck. Soil-interaction structure was taking into account by adding rotational springs around X and Y directions at the support joints of the towers.

The model was calibrated by modifying the boundary conditions so the first two natural frequencies (0.433 Hz and 0.488 Hz) coincide with the experimental frequencies obtained from the viaduct's response to the Armenia earthquake (Colombia-1999). Due to the lack of the corresponding ground motion record at the viaduct, Galíndez and Rivera (2002) used a transfer function approach to compare the analytical response with the recorded accelerations in the structure.

Additionally, Galíndez and Rivera (2002) analyzed 180 variations of the structural model to detect changes in the dynamic characteristics of the structure due to induced damages in different elements. The damages consisted of reducing the mid cross-section of the chosen element (cables and frames) by 25, 50, 75 and 100%. The deformed position of the structure was obtained by a non-linear static analysis including P-D effects, and then modal analyses were conducted to obtain dynamic properties. It was observed that although modal shapes are sensitive to most damage, the first ten natural frequencies did not vary for even extreme damage in the cables. The results imply the possibility of monitoring mode shapes rather than natural frequencies for greater sensitivity due to damage and the possibility of defining new elements that take into account cable behavior and considering initial service loads.

Experimental Identification

During January 13-16, 2003 a series of tests were conducted to verify the capabilities of the instrumentation system and the possibility of implement a structural health monitoring technique based on NExT (James *et al.*, 1993) and ERA (Juang and Pappa, 1985) for modal identification. Due to the nature of these methodologies, these preliminary tests focused on the dynamic subsystem and specifically on the accelerometer network.

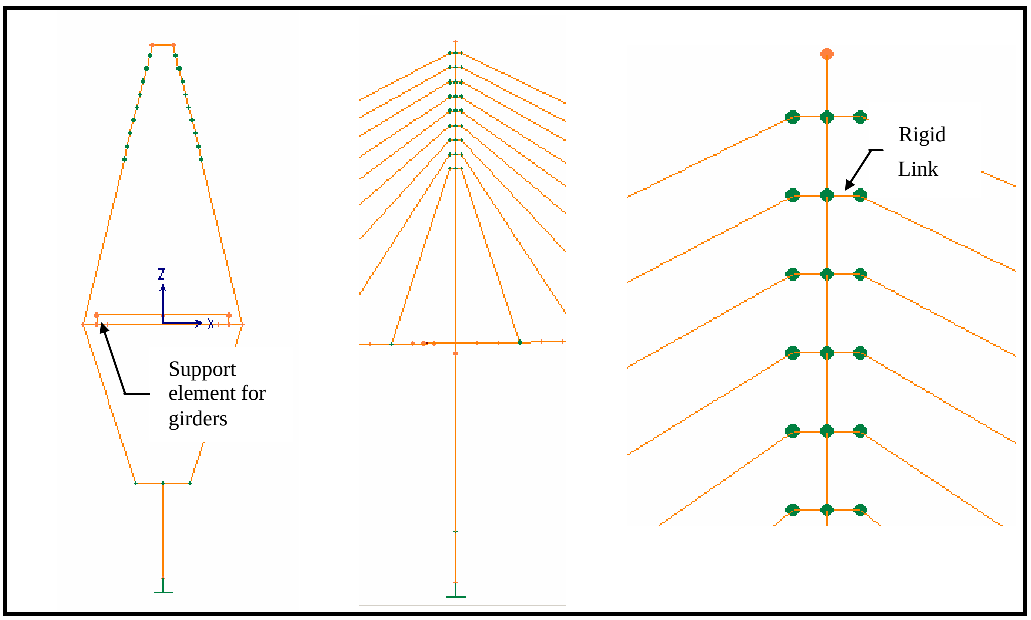

Fig. 8. Finite Element Model of the Towers

As the proposed methodologies require simultaneous data from different channels, tests were conducted to verify this condition. An order from the main computer was sent to synchronize the internal clocks of the SMACH units with the CPU clock and to trigger all the accelerometers simultaneously. The resulting time data were compared finding that all records coincided to the second, which is the precision of the recorded trigger time.

Due to the nature of the structure, the monitoring methodologies would ideally use acceleration records of approximately 10 minutes. Although the longest record taken during the tests was 125 seconds at an acquisition frequency of 100 Hz, it is possible to consecutively record various events and then analyze the cluster on the main computer.

The software used to manage the Dynamic Subsystem consists of two programs: SMACH and TERM. SMACH allows the user to modify the recording parameters such as acquisition frequency and trigger levels. TERM could be used to develop macros to control automatically the SMACH units. Using TERM, it was possible to verify the operational status of every SMACH unit. Additionally, it was found that it is possible to use the "Instrument Control Toolbox" from MATLAB to control directly the SMACH units, which will allow developing an automatic collecting and analysis program.

Fig. 9 shows a sample record and its corresponding spectral density function (SDF) from an accelerometer located on one of the cables from some of the early testing. Twenty five records of accelerations in a cable during the month of January of 2001 were available. Using the data from this cable, three natural frequencies (2.5Hz, 5.0Hz and 7.4Hz) were identified from these records. Figure 10a shows the identified natural frequency obtained using each record separately. Note that the first and second natural frequencies have a small variation with respect to the record number, while the third natural frequency has a slightly larger variation. Figure 10b. shows a histogram of the data plotted in Fig. 10a.

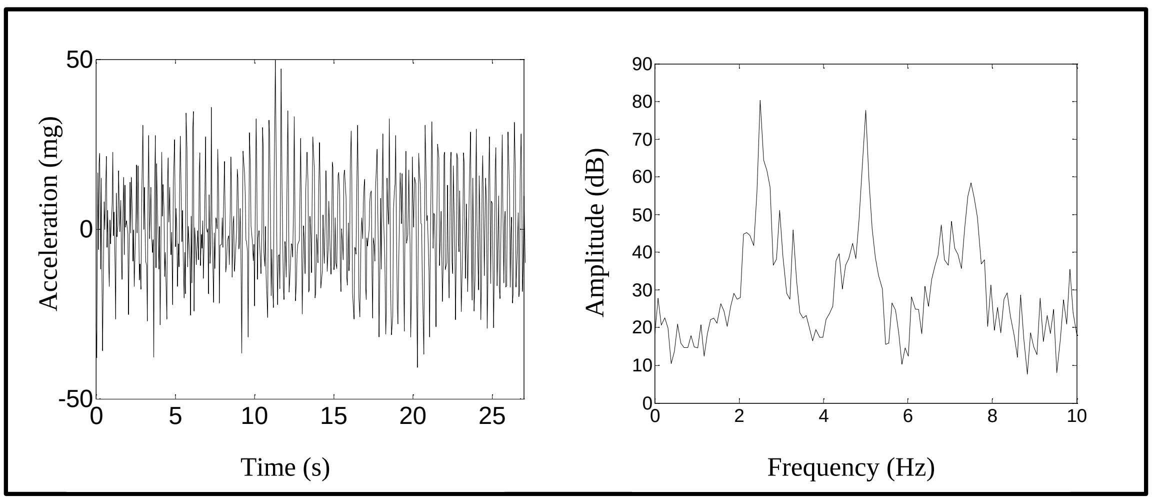

Figure 9. Sample Record and Spectral Density Function.

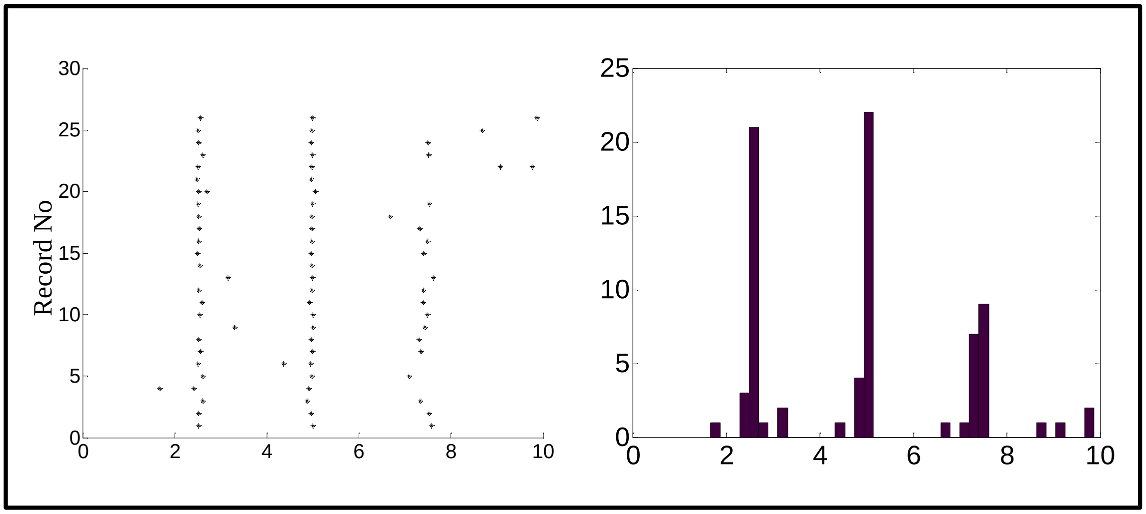

Figure 10. Identified Natural Frequency and Histogram of Data.

FUTURE WORK

The research team from UV-UTP-WUSTL is presently working on the development and implementation of a real-time, level III structural health monitoring strategy for identifying damage, its location, and its magnitude on the Pereira-Dosquebradas Viaduct. The proposed structural health monitoring technique is composed of two steps, as shown in Fig. 11 (Dyke *et al.*, 2000). In the first step, the Natural Excitation Technique and the Eigensystem Realization Algorithm will be used to identify the natural frequencies and mode shapes of the structural system. In the second step, a stiffness identification technique will be employed to determine the stiffness of an identification model, using the identified natural frequencies and mode shapes from the previous step (Caicedo *et al.*, 2002). By examining changes in the identified stiffnesses between the undamaged and damaged structure, we plan to locate and quantify damage.

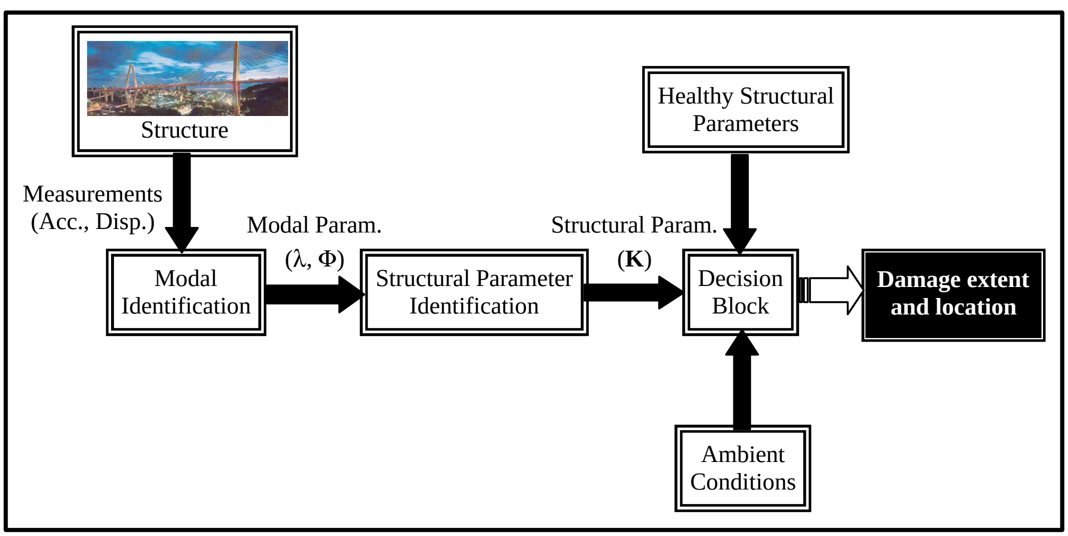

Fig. 11. Structural Health Monitoring Technique.

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