MONITORING INTEGRITY AND CORROSION DAMAGE ON STAY CABLE BRIDGE SYSTEM IN MEXICAN HIGHWAYS

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ABSTRACT

One of the most significant problems in preserving the structural integrity of civil construction such bridges, roads, decks, tunnels, is the corrosion phenomena, in 1985, NACE report that in the United States, there were 300,000 bridges require cathodic protection (CP). This protection along with related repair work was projected of cost - $ 23.1 billon [1].

The use of stay cable bridges in Mexico has been expanding in the last 20 years; today already exist 10 stay cables in Mexico. Corrosion of steel is complex phenomenon affected by many environmental factor, the location of this bridges are around of the country (sea zones, high humidity zones, etc). Many bridges over 20 years shown deterioration due to corrosion, In 2010 the average age of cable-stay bridges in the Mexico was 17.5 years. As time passes it is necessary that the bridges are inspected in a more acute, the Bridge deterioration can affect their safety and serviceability and results in loss of life or injury, traffic disruption and high user costs in this way.

Keywords: Corrosion, Electrochemical techniques, concrete, steel

1. - INTRODUCTION

Stay cable and suspension bridges are the two prominent types of cable-supported bridges. In both systems, cables are supported on pylons. In Stay cable bridges, the cables are inclined and directly support the deck on the pylon(s). In suspension bridges, vertical suspender cables transfer loads from the deck to the main catenary-shaped cables. The main cables in suspension bridges are typically anchored at massive anchorages at the two ends of the bridge, whereas stay cables are anchored to the deck itself. A prominent example of stay cable bridge is the Brooklyn Bridge, designed in the 19th century by John A. Roebling. The first modern Stay cable bridge was the Strömsund Bridge built in 1955 in Sweden, which was designed by Franz Dischinger. It had a main span of 182.6 m.

The first major Stay cable bridge made of concrete pylons and girders was the Maracaibo Bridge in Venezuela, built in 1962 report; the cables of this bridge were subsequently replaced as a result of corrosion. The early bridges all had only a few stay cables, which provided support at locations where piers would have otherwise existed [2]. This concept of using cables with large spacing did not fully realize the structural (and economic) potential of Stay cable bridges. In 1967, H. Homberg used closely spaced stays (or the multi-stay system) on the Friedrich Ebert Bridge in Germany [2]. The Brotonne Bridge in France used closely spaced stays, and the cable system was based on post-tensioning technology in which parallel seven-wire strands were encased in steel pipes and grouted [3] The Zarate–Brazo Largo Bridges in Argentina were the first Stay cable bridges designed to carry railroad and automobile traffic. One of the Argentine bridges had a complete failure of one of the stays after fewer than 20 years of service [4].

In very general terms, a stay cable bridge can be described as a tension element composed of a single or multiple longitudinal Main Tension Elelments (MTEs), which is connected at one end to the bridge pylon and anchored at the other end at the bridge deck.

The rate of failures that occur in Stay cable bridges in service, due to four main factors [8] fundamental problems of design, to materials constituent, the construction procedure, and operation under live loads. These types of failures that lead to the defective materials or cracks that can spread [6] or grow, and because of charges that the structure is subjected at any given time, can collapse. Or failures have their origin in the building process [7], because there was no quality control, and therefore not meet the specifications of work. The failures are due to operating loads is because the charges presented live are great, or because the charges exceeded design, which may be due to the increase of traffic flow, or because present wind speeds higher than normal, or due to an earthquake intensity greater than the design, or by a combination of them [8].

In Table 1 show the main stay cable Bridges in México and several other bridges are under construction. These include the Baluarte Bridge in the construction stages Sinaloa State, spanning the Baluarte River between Sinaloa State and Durango State. The main bridges are very important for the road network, promoting by Secretariat of Communications and Transport (Secretaria de Comunicaciones y Transportes, SCT) and the holder of the concession is Federal Roads and Bridges and Related Services Income (Caminos y Puentes Federales de Ingresos y Servicios Conexos). Actually, mean age of main bridges in the Mexico is 17.5 years.

Table 1 Main stay - cable bridges in Mexico

No.	Bridge Name	State	Span, m	Year
1	Tampico	Tamaulipas	360	1988
2	Mezcala	Guerrero	311	1993
3	Dovali Jaime	Veracruz	288	1984
4	Quetzalapa	Guerrero	213	1993
5	Río Papaloapan	Veracruz	203	1995
6	Barranca El Zapote	Guerrero	176	1993
7	Barranca El Cañon	Guerrero	166	1993
8	Grijalva	Veracruz	116	2001

1.1 Corrosion

Steel structures exposed to soil and water corrodes from the first day, they are placed in service. The life of the structure primarily depends on the rate of corrosion of the structure in a given environment. The rate of corrosion depends on the availability of water and oxygen in alkaline environments. In acidic environments, corrosion can proceed even in the absence of oxygen and water. There are several examples of water mains and pipelines that experience corrosion on a daily basis. In fact, U.S. Department of Transportation Office of Pipeline Safety [9] regulations expressly prohibit operating a coated pipeline without any cathodic protection. The Code of Federal Regulations further stipulates that the level of protection achieved by cathodic protection must be documented every 2 months to ensure that corrosion will not lead to leaks and explosions [10].

Mexican Civil Engineers generally focus in damage of the bridges in structural paterns, left behind chemical causes or enviormental factors, follow this idea the criteria of inspecion and monitoring bridge are:

The following list cites some of the issues involved in the inspection, maintenance, and repair of stay cables, presents methods identified in the literature to address these issues, and briefly summarizes their known pros and cons and other factors [4].

- General inspections (visual)—Visual inspections are, in the great majority of cases, the only method used for Stay cable bridges.
- Assessment of MTE condition in free length (magnetic flux leakage)—this system has a long history in the inspection of industrial cables and ropes.
- Assessment of MTE condition (cable force measurements)—this approach is the most widely used, and sometimes misunderstood, nondestructive evaluation method.

- Assessment of MTE condition (radiography)—theoretically, this method has the potential to successfully assess conditions of cable anchorages where there is access to the perimeter.
- Detection of wire breaks as they happen (acoustic monitoring) — test laboratories performing qualification fatigue tests of stay cables have long used this method to detect wire breaks in the cable specimens as they happen.
- Detection of grout voids inside high-density polyethylene (HDPE) pipe sheathing (impulse radar) — Hand-held impulse radar equipment can be placed over the cable and moved longitudinally to identify potential grout voids inside the cable sheathing.
- Repair of large grout voids (vacuum grouting)—this method has long been used in posttensioning tendon applications.
- Cable force measurements (vibration-based using laser vibrometer)—A laser vibrometer is used to measure small vibrations of the cable from a large distance.
- Cable force measurements (vibration-based using accelerometer)—Similar to the laserbased method described previously.
- Cable force measurements (based on measurement of cable sag)—although the tension in a cable is related to the square of the fundamental frequency, it is also inversely proportional to the cable sag; therefore, measurements of the cable sag can also be used to estimate cable tension.
- Detection of hidden splits in HDPE (infrared thermography)—Hand-held infrared thermography equipment can be used to detect splits in HDPE pipes that are hidden under the protective tape.
- Assessment of cable vibrations (long-term monitoring using accelerometers)—When cable vibration problems are suspected, sensors (accelerometers) can be mounted on select cables to monitor vibrations over a period of several weeks, months, or years.
- Assessment of cable damping (vibration decay method)—There are different approaches to measuring cable damping. In one, an accelerometer is first attached on the cable.

As we can see these techniques does not involve the corrosion process as a strong cause of bridge collapse

The scope of this study is to highlight the importance of the corrosion process in the strands, anchorage zones, and the steel reinforcement in concrete, in this way the stay cable bridge present both problems.

2.-EXPERIMENTAL METHODOLOGY

The methodology used in the study consisted of evaluating and diagnosing bridge. First step is a detailed visual inspection was performed. The next step was locating the steel reinforcement in structural elements to be tested, measuring delaminations by sounding; corroborate delaminations areas using a spring-driven hammer. Electric continuity verification of steel reinforcement, concrete resistivity measurement, electrochemically measured in selected areas, obtaining drilled cores of represent concrete this samples were analyzed by SEM.

2.1. Detailed visual inspection

Visual inspection of the bridge included a site visit, an inspection to determine the physical condition of the structure, the completion of a data sheet with the structure history and its surrounding environment, identification of any damage on each element, and the creation of a photo record.

2.2. Detection of hidden corrosion defects by sounding

Initially, the effects of the damage by corrosion in steel may not seen at a glance, since the delamination happens internally and does not manifest on the exterior surface of the structure. When a delamination exists, the space between the solid and loose concrete produces a particular sound that allows identification of the affected area. This technique, according to the ASTM Standard D4580 [11] and combined with measurements of potential and resistivity, allows identification of active corrosion that are not visible from the surface. This acoustic inspection technique was applied, with impact on the surface of the concrete.

2.3. Physical impact test of concrete structures to determine the resistance

Reinforced concrete has excellent resistance to compression. However, corrosion of the reinforcing steel while causing reduced steel section, also has the added deficit of creating corrosion products of a greater volume that create tensile forces greater than the tensile strength of concrete. This causes fractures in the concrete cover. The mechanical strength of the steel decreases linearly with the section reduction, but also tension and fatigue resistance properties can be reduced substantially with small losses of section. Resistance to the compression of the concrete corresponds to the maximum stress (general rupture) of axial compression in MPA. One method to asses concrete quality is by its resistance to force: it is an indicative value to check the load capacity and the durability of concrete structures. The resistance to force was performed with a test hammer, making physical impacts on the concrete as and according to the described in the ASTM standard C805 [12].

2.4. Electric continuity verification of steel reinforcement

Electrical continuity within the reinforcing steel grid is required for the selection of future corrosion mitigation methods. Electrical continuity is determined by exposing reinforcing steel at several locations and tested using a high impedance multi-meter. Electrical continuity is also checked at the locations where there is exposed steel. As per ACI 222R-01 Standard in Section 4.3.1.6a, if the potential difference between the reinforcing bars is less than one milli-volt, then the reinforcing steel is deemed electrically continuous.

2.5. Electrical resistivity evaluation of the concrete

The resistivity is a measurement of the ability of the concrete to support the passage of ions and is therefore an estimate of how protective the concrete is to the embedded steel. For low resistivity concrete, the ion transfer through the specific media is easier and a higher likelihood of corrosion exists. The samples are tested in wet and dry conditions. Additionally, testing concrete resistivity provides useful information that can be used for cathodic protection design and provides understanding as to whether these system chosen for rehabilitation is compatible with the existing concrete, For example, concrete with less than 150 Ω-m resistivity is ideal for galvanic protection of reinforcing steel. The electrical resistivity is a material property and corresponds to the reciprocal of its conductivity; the unit of measure is Ω-m or ω-m. Largely resistivity depends of the degree of saturation of the pores of the concrete, and to a lesser degree of the hydration of the paste and the presence of salts dissolved in the aqueous phase. It is based on variables such as cement type; inorganic additives; the water/cement ratio; the porosity of the structure; among others. Since the resistivity is one of the factors that control the rate of steel corrosion in concrete, there is increased interest in determining this intrinsic property of the concrete [13].

2.6. Corrosion potential measurements

The corrosion potential (Ecorr) readings of the steel reinforcement were taken, using copper copper sulfate (Cu/CuSO4) reference electrodes (CSE). These measurements were used to locate areas of corrosion activity, establishing the potential shift area through a complete potential mapping. A 1.20 m [14] spaced grid was traced on the surface of the concrete. The reference electrode and the steel of the exposed reinforcement were connected, and a plane of the surface of each element was drawn, indicating the potential values of each node on the grid. Then, isopotential lines were drawn to generate maps of the potentials.

2.7. Sampling of concrete core for analysis

Core extraction is completed using a wet coring machine with diamond core barrel. Special care is taken in the management of samples to avoid contamination as per standard ASTM C42[15]. The core samples must have a minimum diameter of 0,005 m to 0,0075 m depending on the size of aggregate, and are cut at different depths. The cores are for chloride and carbonation testing. They are taken not only in areas where there is deterioration, but also where concrete appears to be in good condition. The use of a rebar locator allows the samples to be taken in close proximity to the reinforcing steel and to measure the depth of cover for correlation of the test to the actual depth of the steel.

2.8. Evaluation of chloride penetration

With reinforced concrete in permanent or intermittent contact with sea water, sulfates and chlorides can penetrate by osmosis, capillary action and diffusion. Chlorides initiate corrosion by breaking down the naturally protective oxide layer on the steel. Sulfates damage concrete by causing expansive compounds in the cement paste which further facilitates the penetration of the chlorides and corrosion of the steel. Any damage facilitates further contamination and the process is accelerated. The chloride ion content can be measured as a percentage by weight of the concrete as per AASHTO T260 Standard. The chloride ion content in percent by weight of concrete is measured using the 'Revised SHRP Chloride Analysis Procedure'. Chloride ion content below 0.025% by weight of concrete is considered below the threshold for chloride induced corrosion of the reinforcing steel. If the chloride levels climb above this threshold, the reinforcing steel may lose its passive layer and could initiate corrosion activity.

2.9. Evaluation of concrete carbonation

The carbonation of concrete occurs when the pH of the concrete, normally between 12 and 13, reduces to pH between 9 and 10. When this occurs, the layer of iron oxide or passive layer naturally formed in high pH concrete disappears, thus allowing corrosion to more readily occur. Concrete core samples are broken in half in the laboratory and the freshly exposed concrete is sprayed with a solution 0.15 % phenolphthalein in ethanol. Where the indicator solution is pink or purple in color correspond to a pH of 10 or higher, indicating sufficient alkalinity to maintain the passive oxide layer. Where the solution does not change color indicates a pH of 10 or less, which indicates carbonated concrete.

2.10. Characterization of the steel and concrete

On the way to make a more precise diagnosis and relying on the existing state of art technology, with the SEM (scanning electron microscopy) we can corroborate the composition, structure, topology, topography, morphology.

The SEM analyze gives the qualitative and quantitative elemental analysis with EDS (Energy Dispersive X-ray Spectroscopy or EDS). EDS can provide rapid qualitative, or with adequate standards, quantitative analysis of elemental composition with a sampling depth of 1-2 microns. X-rays may also be used to form maps or line profiles, showing the elemental distribution in a sample surface.

3.-RESULTS AND ANALYSIS

In this research we present preliminary results of Dovali bridge and some results of Mezcala bridge. The field of investigation was carried out using systematic, organized, and efficient procedures to minimize the risk of leaving out any elements of the bridge, in Figure 1 presents a general view of Mezcala and Dovali bridges.

Figure1 photographs A) deck and strands Mezcala, B) Strands Dovali, C) profile Mezcala and D) profile Dovali

Figure 2 photographs A) pile 4 Mezcala and B) pile 5 Dovali

According detailed visual inspection Dovali bridge has corrosion damage and Mezcala bridge does not present damage.

Detection of hidden corrosion defects by sounding

Initially, the effects of the damage by corrosion in steel may not seen at a glance, since the delamination happens internally and does not manifest on the exterior surface of the structure. When a delamination exists, the space between the solid and loose concrete produces a particular sound that allows identification of the affected area. Mezcala acoustic inspection result does not sounds cavities, in Figure 3 show test.

Figure 3 Detection of hidden corrosion in pile 3 Mezcala Bridge

Physical impact test of concrete

The mechanical strength of concrete is preserved, impact test of concrete shown that Mezcala does not have damage by corrosion; this test is shown in Figure 4

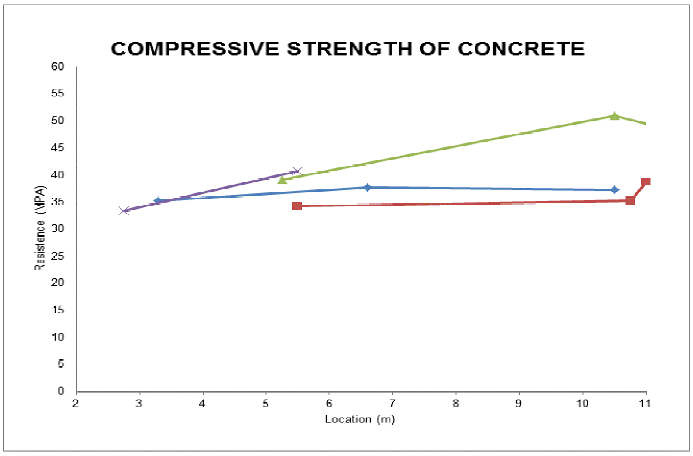

Figure 4 Compressive strength of concrete.

Electrical resistivity evaluation of the concrete

The obtain values of resistivity were greater 200 Ω-m. According to SP0308-2008 NACE the values greater than 200 Ω-m correspond to low risk of corrosion,

Corrosion potential measurements

The obtain values of corrosion potential in Mezcala bridge were in the range -15 to - 182 mV, According to SP0308-2008 NACE the values more than -200 mV correspond to low risk of corrosion. By other hand in Dovali bridge present in preliminary analyzed shown high values of corrosion potential

Evaluation of chloride penetration and concrete carbonation

In Mezcala bridge the chloride content and carbonation tests showed inappreciable content. Dovali bridge show positive presence of chloride content.

Characterization of the steel and concrete of Mezcala bridge

The morphology and composition of steel strands Figure 5 and concrete samples were analyzed by SEM these results are shown in Figure 6. The sample of concrete shows porosity and a fracture. In Figure 5B and 6B present the spectrum EDS.

Spectrum of energy Dispersive X-ray Spectroscopy (EDS) indicating the presence of Ca, O, Si, and Al, this elements belong to part of concrete, does not show Cl content and C belong to a tape using during the test.

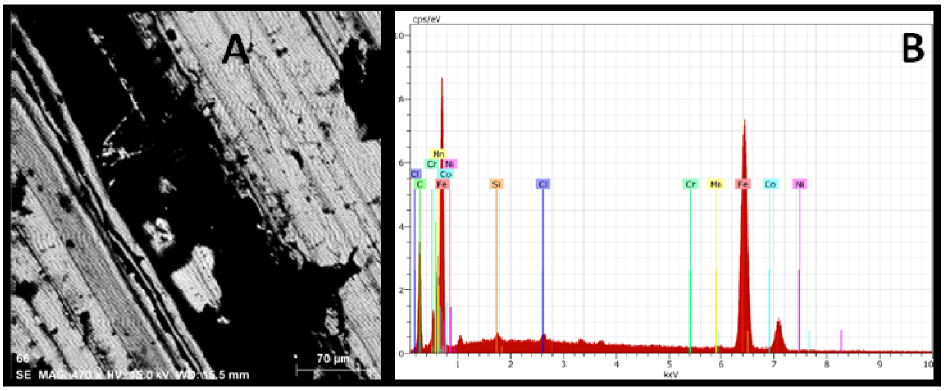

Figure 5 A) SEM micrograph and B) EDS microanalysis to steel strands sample

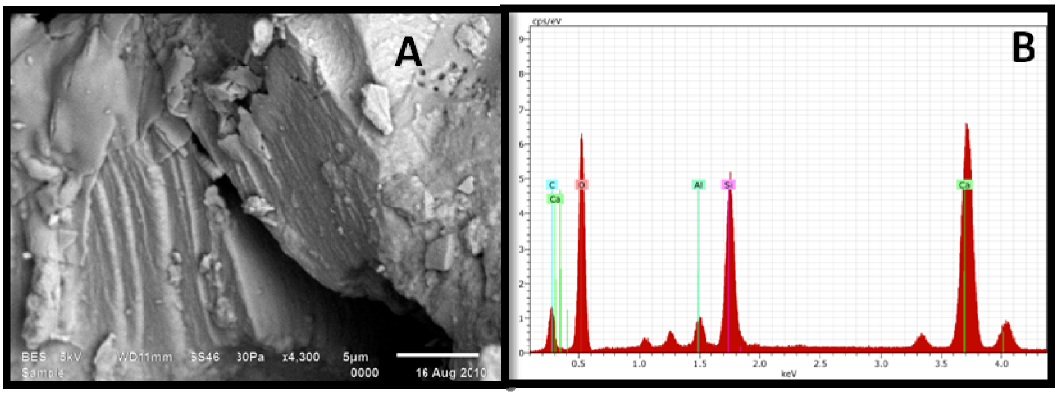

Figure 6 A) SEM micrograph of concrete and B) EDS microanalysis to concrete sample

3. - CONCLUSIONS

In Mezcala bridge, the corrosion potential readings indicated 10% of risk corrosion, The obtained results by other test as electrical resistivity, detection of hidden corrosion defects, detailed visual inspection by sounding show no corrosion evidence.

Preliminary studies of Dovali bridge suppose a corrosion evidence.

The benefit of a right diagnosis was assigned two components: holder of the concession cost and users' cost. Holder of the concession cost refers to the actual cost of implementing an event such as contract cost for repair or inspection. Users' cost refers to cost borne by the users of the bridge, drivers, for delays or detours related to activities on the bridge.

As these bridges become older; the need for effective inspection and maintenance methods and used the new tools becomes more important. Because no one method is enough, a combination of methods is necessary.

CAPUFE understand the necessity of improve novel technologies, in this way the future inspections may consider corrosion process as strong cause of bridge collapse.

ACKNOWLEDGMENTS

The authors appreciate the support offered by the Caminos y Puentes Federales de Ingresos y Servicios Conexos and its former engineering director, José Guadalupe Tarcisio Rodríguez Martínez as well as engineers Omar Ortiz Ramirez and José Roberto Vazquez Gonzalez for the facilities offered for the present study.

Thanks for the technical support to the architect Edgar Mayan and engineer Salvador Ascencio form Centro de Inovación en Integridad de Infraestructura y Ductos. The authors also thank ICF-UNAM and CIICAP.

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