Health Monitoring of Cable-Stayed Bridges- A Case Study

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Abstract

Several cable-stayed bridges have shown signs of damages mostly induced by susceptibility of stay cables to wind-induced vibrations and corrosion. This has caused some concerns among bridge owners and initiated a series of inspection and health monitoring programs. This paper reviews existing methods for inspection and monitoring of cable-stayed bridges and summarizes the findings of several projects conducted to date. A unified approach for health monitoring and problem solving for stay cables of cable-stayed bridges is described. This approach has been developed based on information gathered from evaluation of the strength and reliability of stay-cable systems for nearly 30 long-span bridges worldwide and instrumentation, health monitoring, and inspection of more than 8 cable-stayed bridges. An ongoing project for inspection and damage detection of the Luling Bridge in Louisiana, an all-steel cable-stayed bridge, is described in detail. The approach follows the new unified methodology for addressing problems directed toward stay cables and their boundaries, and includes analysis, field measurements, and inspection procedures. Global and local damage detection methods have been used to complement each other, the former for rapid identification of damage and its location and the latter for in-depth inspection and potential damage detection of suspect locations. A summary of the findings is presented, and mitigation measures are recommended in this paper.

Introduction

As primary members of cable-stayed bridges, stay cables are arguably the most important and crucial elements of the entire structure. Their well-being is therefore of paramount importance in ensuring a healthy and long life for these beautiful and elegant structures. Cables are typically comprised of high-strength steel wires, strands or bars, and in most cases, a high-density polyethylene pipe encases the steel elements. In the U.S. practice, cement grout has generally been used to fill the space inside the pipe and between steel elements, but this practice is being abandoned for newer bridges. Stay cables are typically terminated (anchored) at the bridge deck and at the tower (pylon). However, some bridges utilize curved “saddles” to eliminate anchorages in the tower, thereby, producing a cable that anchors in the deck on each side of the pylon. Neoprene rings or washers are typically provided around the cable near each anchorage to minimize flexural stresses in the stay cables at the anchorage. The neoprene rings sometimes provide minimal vibration damping.

Deterioration of main tension elements and other important stay cable components that are in contact with moisture has been found to be a chronic problem. This problem could be attributed to the failure of the protective details due to either limited understanding of the long-term stay cable behavior and inadequate corrosion barrier design or due to poor quality of construction.

Since 1990, the authors have contributed extensively to advances in cable-stayed bridge construction, design, and health monitoring. Information gathered from evaluation of the strength and reliability of stay cable systems for nearly thirty long-span bridges worldwide, and instrumentation, health monitoring, and inspection of more than eight cable-stayed bridges in the US and abroad have helped toward formation of a unified approach for health monitoring and problem solving of these aesthetic structures. The newly developed health monitoring approach is being utilized for evaluation of stay cables of the Luling Cable Stayed Bridge in Luling, Louisiana. Special circumstances around the problems observed for this bridge and a timely and appropriate planning by Louisiana Department of Transportation and Development, provided an excellent opportunity for full employment of the unified approach. This paper describes lessons learned from past experiences with cable-stayed bridges as well as the process and results of the ongoing evaluation program.

Background

Laboratory testing of more than seventy cables in testing facilities of Construction Technology Laboratories, Inc. (CTL), has provided an extensive knowledge-base of the performance of various cable and anchorage systems. The tests usually follow the Post Tensioning Institute’s Recommendations for Stay Cable Design, Testing, and Installation (PTI 2000) and include fatigue and ultimate strength as well as corrosion barrier testing, and compresses a lifetime performance of a stay cable in just a few weeks. These tests have helped to further the understanding of the stay cable system performances, and in some cases have raised concerns about certain characteristics of some of these systems. Compromise in the service life of the cables due to accelerated corrosion fatigue in presence of grout bleed water, influence of preexisting pitting in the wires, and fretting fatigue in saddle type supports are some of general findings of these experiences (Tabatabai et al., 1995).

In some cases, the abovementioned damaging effects reduced the effective service life of the test specimens by half. The results were indicative of a high potential for existence of such conditions in actual stay cables of constructed bridges, especially when considering that bridges are exposed to harsher environmental conditions. These observations led to more emphasis on evaluation and inspection of in-service cable stayed bridges. However, existing bridge inspection practices were not adequate for stay cables that are unique in many aspects. Development of a new methodology and new or customized evaluation tools seemed necessary.

In 1996, with the support of Federal Highway Administration's Highway Research Center, CTL started an extensive three-year research project for Condition Assessment of Cable Stayed Bridges. Among many outcomes of this project were development of a new non-destructive laser-based cable force and damping measurement technique and formulation of a vibration mitigation method for stay cables (Tabatabai et al., 1998; Tabatabai and Mehrabi, 2000). The force and damping measurement techniques are able to identify the global integrity of the bridge, type, location, and intensity of significant damages, and susceptibility of stay cables to wind-induced vibrations. These techniques were shortly in use to address bridge owner's concerns about the structural integrity and safety of cable-stayed bridges.

A Unified Approach for Stay Cable Evaluation

Experiences gathered from several investigations on health and integrity of cable-stayed bridges, stay cable performance testing findings, and familiarity with inspection and advance non-destructive testing methods helped development of a unified approach for stay cable evaluation. The methodology has evolved during evaluation of more than eight cable-stayed bridges in the US, and is being complemented with new techniques under consideration.

In summary, the approach utilizes preliminary inspection and force and damping measurement techniques to evaluate the global integrity and structural safety of a cable-stayed bridge with relatively minimal effort. The stay cable force array, when combined with analytical interpretation of the force changes, provides clear indications of location, type, and intensity of significant damages detected by this technique (Mehrabi et al., 1999). Damping measurement identifies the vulnerability of stay cables to wind-induced vibrations and resulting damages. These provide bridge owners a rapid, cost effective, and highly reliable tool to address their immediate concerns and to determine the need for action (Mehrabi and Ciolko, 2001).

Findings of the global integrity check or observation of existing damage and unwanted stay cable behavior can point to a need for investigation for local damage detection. The local damage detection may focus on the anchorage zone as the most critical component of the stay cables or the cable free length. An investigation of this type utilizes techniques developed or tailored for stay cables along with other customary inspection methods for bridges. Removing anchorage caps, use of visual aids such as borescopes, cable dissection, material sampling and testing are some of the means for damage detection in stay cables. Non-destructive techniques, such as the use of ultra-sound, have been successful for detection of hidden damages and flaws such as wire breaks and grout voids in the anchorage zones. New methods are under investigation for damage detection along the free length of the cables. Once the existing condition of stay cables is determined, instrumentation system can be designed and installed for continuous health monitoring of the cables and the bridge.

Retrofitting and mitigation can be designed to address the problems identified during the evaluation process. These include replacement of severely damaged cables or strands, repair of guide pipes, concrete encasement, cable cover pipe, grout voids, and design and installation of vibration suppression devices (Telang et al., 2000).

Inspection and evaluation of more than eight cable-stayed bridges in the US has led to a series of findings on the type and severity of existing damages in stay cables and surrounding (Mehrabi and Telang, 2003; Telang and Mehrabi, 2003). The significant findings from these investigations can be summarized as:

- Damping measurements have shown that majority of stay cables are susceptible to rain-wind induced excessive vibration. In many bridges, vibration of stay cables resulted in damage to cable boundaries and raised concern for the cable fatigue.
- Ultrasonic testing has been able to detect wire breaks and grout voids in anchorage zones.
- Water leakage into and out of anchorages has been observed and is attributed to damage to the seal, and lack of drainage of spaces behind the anchor heads.
- Misalignment between cable and guide pipes, observed almost in all cases, prevents proper installation and reduces effectiveness of washers and seals.
- Grout bleed water accelerates corrosion, especially in the lower anchorages.
- Cover pipe splits and bulging has occurred due to overpressure during grouting.

Structural Evaluation of Stay Cables of the Luling Bridge

The Hale Boggs Bridge, also known as the Luling Bridge, in Luling, Louisiana opened to traffic on October 5, 1983. At the time, it was the first cable-stayed bridge over the Mississippi River and had the largest navigation channel span of its kind in the western hemisphere. It has several unique features not common to bridges on the American continent, including a unique superstructure made of weathering steel. Figure 1 shows two views of the Luling Bridge. The bridge is a twin-pylon cable-stayed bridge with a main span of 1222 ft (372.5 m) and two side spans of 508 ft (155 m) and 495 ft (151 m). The pylons are modified A-shaped, and the deck cross section is composed of twin steel box girders with 76-ft (23-m) wide steel orthrotropic deck. The cables are arranged in groups of two or four, with a total of 24 cable groups or 72 individual cables. Each cable is composed of 103 to 307- 1/4 in. (6.35 mm) diameter parallel steel wires sheathed in a polyethylene (PE) cable cover pipe. The annular space between the PE pipe and wires is filled with cement grout. The PE cover pipe is wrapped with UV protection tape. The cable anchorage is "Hi-Am" type.

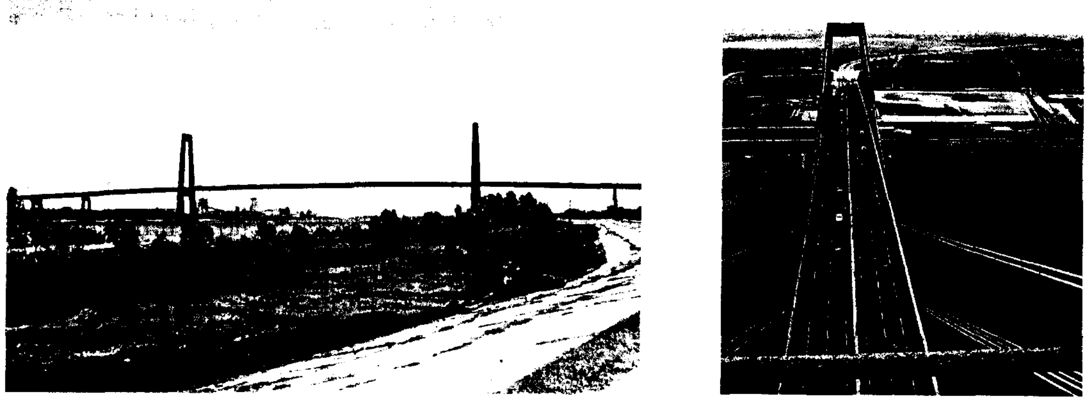

Figure 1 The Luling Bridge

The bridge is one of the most extensively studied structures of its type (Bruce et al., 1986), and Louisiana Department of Transportation and Development (LADOTD) has been following closely the issues related to health and safety of the bridge. Some of these issues are related to rusting and water leakage in the anchorage zones at the deck level, splitting of cable cover pipes during grouting process, and unplugged grout ports, all of which were symptomatic signs of conditions that could potentially compromise the safety of main tension elements of cables. In 2002, LADOTD awarded CTL a project for Structural Evaluation of the Luling Bridge Stay Cable Array. The overall evaluation program was divided into phases.

Phase 1 of the evaluation program, discussed in this paper, was designed with the objectives of assessing the extent of reported problems of the stay main tension elements and ascertaining the overall integrity of stay cable array. In addition, the objectives also included studying the consequences of the reported problems on the long-term health of the stay cables and evaluation of their susceptibility to undesirable wind-induced vibrations. The investigation included the following tasks:

- Review of bridge details and prior bridge evaluations and investigations.
- Cable force measurement and geometric survey of the bridge deck for overall assessment of stay cable condition.
- Damping measurement and analysis for wind-induced vibration susceptibility.
- Representative cable and anchorage inspection and sheathing dissection.
- Development of detailed analytical model of superstructure.
- Assessment of cable array safety, reliability, and potential failure scenarios, including development of conceptual repair and retrofit recommendations

A detailed report describing the evaluation process and the results has been submitted to LADOTD (Telang and Mehrabi, 2003). The following sections summarize the findings and recommendations.

Summary of Findings

Forces in all 72 cables of the Luling Bridge were measured using a laser-based technique. The measured cable forces were found to be below 35 percent of the Minimum Ultimate Tensile Strength (MUTS). Judging from the relatively small differences between measured and predicted forces and their distribution pattern, it is unlikely that at this time, the stay cables have suffered any significant damage. Using the finite element model of the bridge developed in this study, the source of the cable force changes was studied. The analysis showed that the force changes could be attributed to possible adjustments in the cable tension forces at the last stages of construction for deck geometry compliance, or the effect of additional dead load. These inferences were in agreement with the result of a deck profile survey conducted by LADOTD. Cable damping measurements conducted by CTL indicate that most of the cables of the Luling Bridge have very low damping and are vulnerable to rain-wind induced and other wind-induced vibrations.

Inspection of deck anchorages showed signs of rust outside and inside of the sockets. Dripping water from anchorages, and ingress and collection of water inside the sockets were evident. The likely cause is believed to be improper or broken seals at the cable exit points at the deck level, allowing rain water to flow into the closed steel box behind the anchorages, and consequently seep into the anchorage sockets through possible gaps in the cable transition zone. This has resulted in rusting inside and outside the sockets and potential corrosion of wires in the anchorage area. Figures 2 and 3 show water flowing out of an anchorage socket and corrosion inside the socket, respectively. Progression of this condition was found to be detrimental to the safety of the cables and consequently to the overall integrity of the bridge.

Figure 2 - Water in Anchorage Sockets.

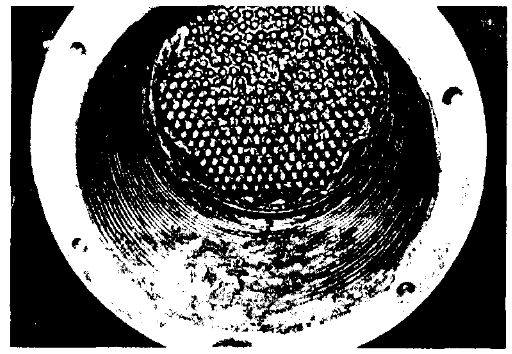

Figure 3 – Corrosion inside socket

The cable dissection at few selective locations along the free length of cables showed that the steel wires are in good condition, wherever they are adequately covered by filler grout and undamaged cover pipe. Figure 4 shows steel wires exposed during dissection process. Inspection of cable surfaces along limited lengths of selected cables revealed improper repair of cover pipes originally split during the grouting process. On some cables, deterioration of repair material and grout filler had caused bursting failure of the wrapping tape. This had exposed the steel wires to environment and caused considerable corrosion. Figure 5 shows failure of a repaired cover pipe. It is believed that a potential for this type of failure exists in all previously repaired locations and this matter needs to be addressed properly.

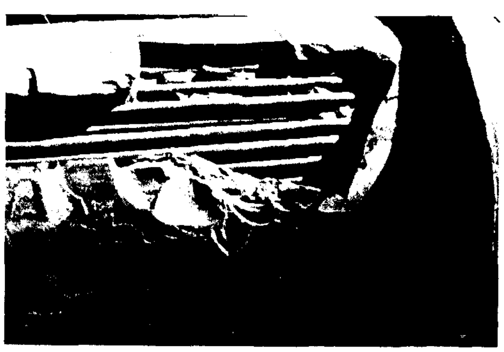

Figure 4 Dissected cable

Figure 5 -Failure **of cover** pipe

The interior of the bridge structure, including spaces housing the cable anchorages, was found to be infested with birds and rodents, resulting in collection of heavy nesting debris and waste. This was due to presence of drilled and fabricated openings that provided easy access to birds and rodents.

Recommendations

Based on the damage and defects detected throughout this inspection and testing process, and those reported by others, it is recommended that schemes and methods should be devised for rehabilitation, repair, or retrofit, as well as follow-up health monitoring of the Luling Bridge, including:

- Evaluation of cables and cable components not inspected in this phase.
- Repair of the split PE pipes, removal of defective grout, removal of rust on steel wires, regrouting, restoring the cover pipe, and rewrapping with protective tape.
- Removal of rust and other residues from exterior surfaces of non-weathering steel in the anchorage zones and repainting.
- Removal of rust from sockets, and sealing the end caps.
- Diversion of rainwater away from the anchorage zones, devising drainage system and dewatering of the steel boxes behind the anchorage bearing plates as well as the cross-girder boxes housing the anchorages.
- Blocking or screening the openings in the bridge deck and pylons to prevent accelerated corrosion caused by bird and rodent waste.
- Replacement of aged neoprene washers, and application of new or better sealers.
- Removal of debris and bird or animal waste from all areas of the bridge, maintenance of drainage channels, and elimination of potential for water or moisture entrapment.
- Design and installation of vibration damping system for cables identified to be susceptible to wind-induced excessive vibration.
- Inspection and monitoring of the bridge superstructure with a minimum scope of reviewing the trouble spots identified by earlier inspection programs.
- Integration of the existing instrumentation into an effective health monitoring and alarm system.
- Periodic cable force and deck profile measurement for ensuring the global health and integrity of the stay cables and the bridge structure.

A comprehensive inspection and rehabilitation/repair program has been planned by LADOTD and will commence shortly to address the reported problems and to apply preventive measures for enhancing the safety of this magnificent structure.

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