Temperature-Driven Assessment of a Cantilever Truss Bridge

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ABSTRACT

Temperature-driven assessment has the potential to advance our understanding of long-span bridge behavior. The novel approach researched as part of this study is the identification and monitoring of a long-span cantilever truss bridge using the input-output temperature relationship. The goal is to use this relationship to identify and monitor unknown quantifiable information with regard to an existing structure using the structural identification process (e.g. boundary conditions, continuity conditions, force distribution, etc.). Since many structural parameters on long-span bridges are highly sensitive to temperature loads, a structure such as the Hurricane Bridge is a prime candidate for this type of monitoring. The Hurricane Bridge is a four-span, cantilever truss bridge over the Caney Fork River in DeKalb County, Tennessee, with a total length of approximately 1787 feet. It was built in 1949 and rehabilitated in 2011. The rehabilitation included widening the deck, strengthening various truss members, and installing a “catch system” consisting of four stainless steel rods around each vertical at the cantilever locations. This critical structure has a great deal of uncertainty related to performance and remaining service life. Therefore, a temperature-driven monitoring system has been designed and implemented to reduce the uncertainty associated with the: “catch system”, pin and hanger effects at cantilever locations, and bearing mechanisms. The sensing technology of this system is comprised of fifty-six vibrating wire strain gages, eight vibrating wire displacement gages, and sixty-four thermistors. Long-term data collection is on-going; however, preliminary results are presented and tasks for future research are explored.

INTRODUCTION & OBJECTIVES

In recent years, engineering practices have transformed from a mindset of replacement to rehabilitation with regard to many structurally deficient bridges. Much of this motivation stems from funding and the amount of bridges in need of repair at this time. According to the American Road and Transportation Builders Association and the 2015 National Bridge Inventory released by the Federal Highway Administration, “there are nearly 204 million daily crossings on 58,495 U.S. structurally deficient bridges in need of repair” (ARTBA 2016). Due to the increasing number of deficient bridges, monitoring techniques are being utilized more often in order to prioritize the bridges based on their performance and need for intervention.

Currently, the most prevailing technique for monitoring long-span bridges is ambient vibration monitoring. Using this method, modal parameters such as natural frequencies, mode shapes, and damping can be determined and tracked for a structure. Although this method has been utilized, ambient vibration monitoring also has challenges associated with it (Catbas 2007). Ambient vibration monitoring has difficulty dealing with environmental effects such as seasonal temperature change since they can mask damage (Peeters and De Roeck 2001). Therefore, a significant challenge for this type of approach is removing the temperature effects. The prevailing reason for the limited success of ambient vibration monitoring of long-span bridges is the limited sensitivity to structural damage (Brownjohn et al. 2011).

Alternatively, a temperature-driven concept, where thermal "loads" are treated as the excitation and the corresponding static responses are correlated, shows promise to mitigate many of the shortcomings of ambient vibration monitoring (Yarnold and Moon 2015; Kromanis 2016). Logistically, a temperature-driven approach can be performed continuously over a period of time with minimal data storage and time synchronization requirements. In addition, the equipment is relatively inexpensive and generally self-sustaining with little need for man-power resources once the system is installed and operational. The results can be recorded throughout the structure's changing environments and can potentially identify structural changes that occur as a result of seismic, wind, ice, impact, or similar nature. This is primarily due to the fact that a temperature-driven baseline is highly sensitive to many changes of structural systems (Yarnold and Moon 2015; Laory et al. 2013). Temperature-driven monitoring is particularly useful for large structures. Long-span bridges, for example, are more responsive to thermal loads than live loads, making the results easier to identify.

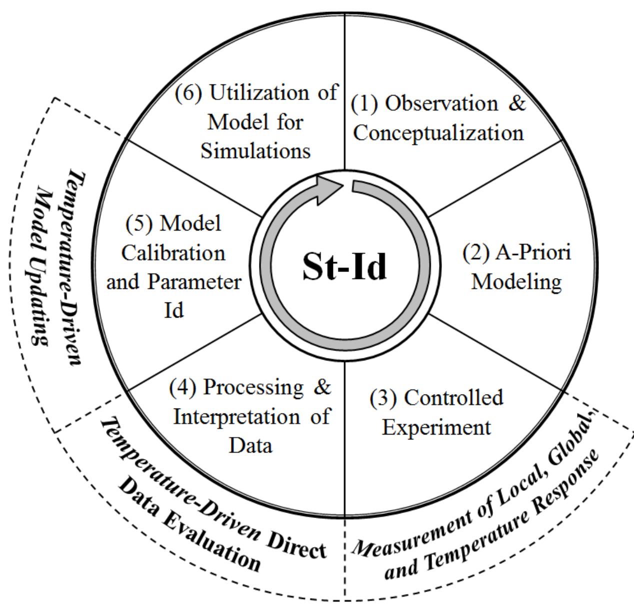

Figure 1: Structural Identification (St-Id) Process

The novel approach researched as part of this study is the identification and monitoring of a long-span, cantilever truss bridge using the input-output temperature relationship. The goal is to use this relationship to identify and monitor unknown quantifiable information with regard to an existing structure (e.g. boundary conditions, continuity conditions, force distribution, etc.) using the structural identification (St-Id) process shown in Figure 1 (Yarnold et al. 2015).

"St-Id is the process of creating and updating a model of a structure based on its measured static and/or dynamic measured response which will be used for assessment of the structure's performance for informed decision making" (Catbas et al. 2013). As shown in the figure, the process can be expanded upon to incorporate a temperature-driven approach. The temperature-driven concept is further explained below followed by illustration of the comprehensive design and implementation for the cantilever truss bridge study.

TEMPERATURE-DRIVEN CONCEPT

Since long-span bridges have a high sensitivity to thermal effects, everyday temperature exposure can excite a response from the structure. The temperature-driven concept utilizes this cause-and-effect relationship to develop a behavioral signature for the bridge. This process is detailed in Figure 2 below. The temperature variations (input) are quantifiable and can be measured simultaneously with the member strains, displacements, and/or rotations (output) that the bridge experiences in response to the thermal load. Once the behavioral signature has been determined, it can be used to update a model to represent the current condition of the structure. This process can be used for both St-Id as mentioned previously and structural health monitoring (SHM) for long-term performance tracking.

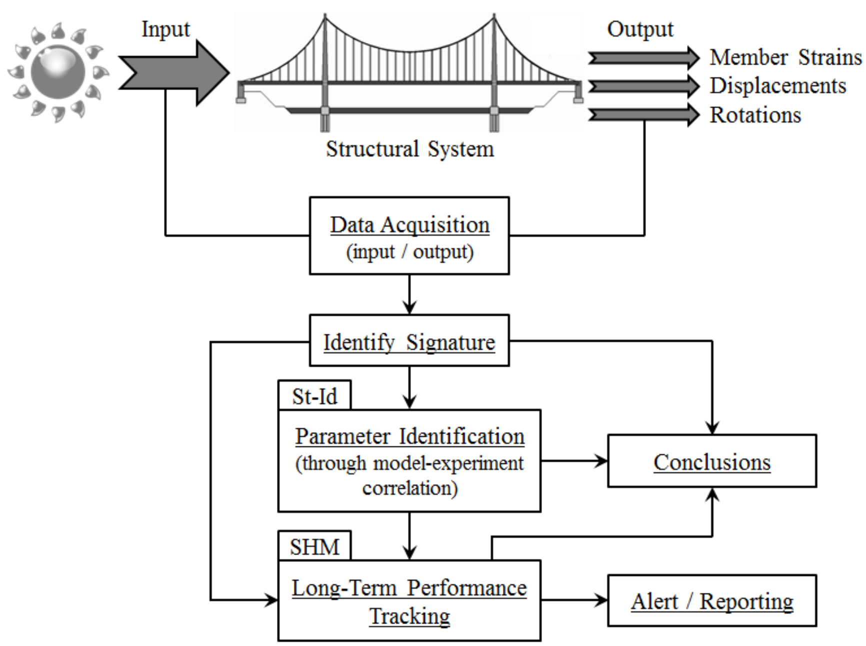

Figure 2: Temperature-Driven Concept

ASSESSMENT OF THE HURRICANE BRIDGE

Bridge collapses are not prevalent in today's age; however, they can happen. One such occurrence was the I-35W bridge collapse in Minnesota in 2007. This structure was a long-span, steel truss bridge that experienced a catastrophic failure due to a poor design and lack of redundancy (National Transportation Safety Board 2008). Motivated by this disaster, Tennessee Department of Transportation initiated a review of similar bridges in Tennessee, one of which being the Hurricane Bridge shown in Figure 3.

Figure 3: Hurricane Bridge

Located in DeKalb County, Tennessee, the Hurricane Bridge is a four-span, Warren deck truss bridge that is approximately 1787 feet in total length. Two suspended sections comprise the middle of the bridge as shown in Figure 4. One end of each section rests atop the middle pier while the other end is connected to a cantilever and the rest of the bridge via a pin and hanger detail. This bridge was built in 1949 by the U.S. Army Corps of Engineers and was rehabilitated in 1977 and 2011. The primary goals of the 2011 rehabilitation were to widen the deck, strengthen several structural members, and install a "catch system" to increase redundancy at the cantilever locations. The "catch system" consists of four, 3-inch diameter stainless steel rods installed around each of the vertical hanger members at the cantilever locations to essentially "catch" the suspended section in the event of a failure. The "catch system" is not a commonly used rehabilitation method; therefore, a large degree of uncertainty exists regarding the behavior. Recall, the intent of this study was to use a temperature-driven monitoring approach to minimize the uncertainty of the bridge with regard to the behavior of the pin and hanger, the "catch system", and the bearings.

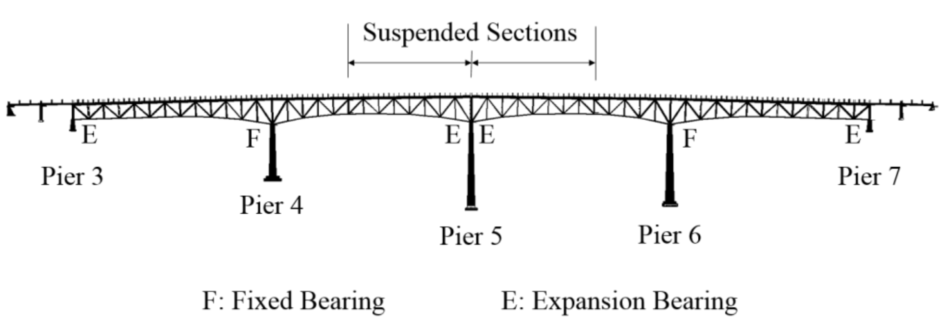

Figure 4: Hurricane Bridge Overview

Following the St-Id process shown previously, an element-level 3D finite element model of the Hurricane Bridge was created. The model includes all primary superstructure and substructure components as shown in Figure 5. A thermal load was applied to the entire structure, and the bearing mechanisms were characterized by connection elements with variable translational stiffness. The variable stiffness elements allowed for simulation of varying stiffnesses of continuity conditions such as bearings and the pin and hanger connections.

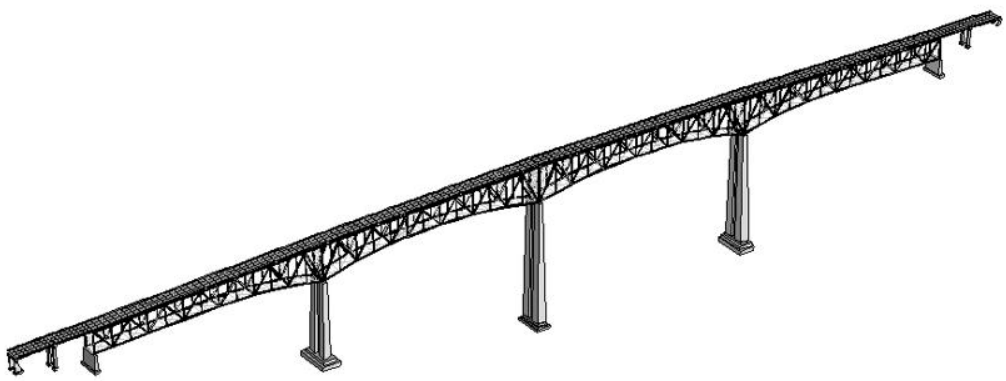

Figure 5: Finite Element Model of Hurricane Bridge

After the finite element model was complete and checked, design of the temperature-driven experiment was performed. The sensing equipment used for this project required the ability to capture the results for any scenario and the ruggedness to withstand prolonged weather exposure. Due to increased demand for monitoring assessments, sensing equipment specifically designed for this purpose was readily available. Vibrating wire strain and displacement gages were decided upon and used to identify the behavior of the bridge. Vibrating wire gages measure frequency from the excitation of a small wire within the gage. The frequency can then be directly correlated to the strain or displacement being measured.

Sensitivity studies were performed for various scenarios to determine the optimum location for sensing equipment. For example, Figure 6 shows two scenarios compared to the "As Drawn Conditions" specified in the original and rehabilitation plans. The "As Drawn Conditions" have free movement at the pin and hanger and the expansion bearings of Pier 5 and Pier 7. The scenario "Pier 7 Bearings Seized" has free movement at the Pier 5 bearings and at the pin and hanger but impeded movement (large translational stiffness) at the bearings of Pier 7 to simulate seized bearings. Furthermore, the scenario "Pin and Hanger Seized" has free movement at Pier 5 and Pier 7 but the pin and hanger mechanism has impeded movement to simulate a seized pin and hanger detail.

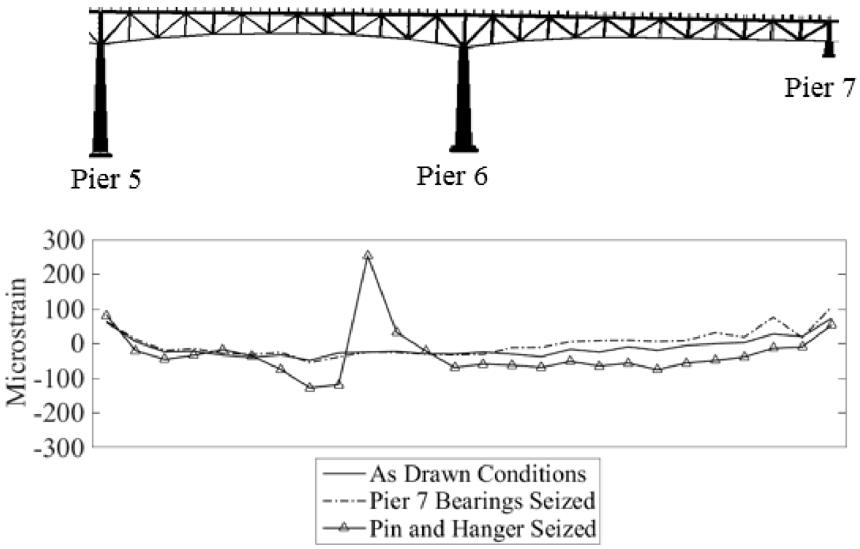

Figure 6: Sensitivity Study

Through the sensitivity studies of multiple scenarios, the optimum locations were determined to be cross-sections at the ends (Pier 3 and Pier 7) as well as the middle of the bridge (Pier 5). Additionally, the cantilever and pin and hanger locations were sufficiently sensitive to thermal loading (shown in Figure 6). Due to time, resources, and the symmetric nature of the bridge, only half of the structure was used as a test bed for this study as shown in Figure 7. Axial behavior was desired for the cross-sections; therefore, strain gages were installed at the centroid of the members to mitigate effects from bending. Two strain gages were installed per member for redundancy purposes and to identify out-of-plane bending if present. Longitudinal movement was also desired, so displacement gages were installed near the expansion joints and bearings.

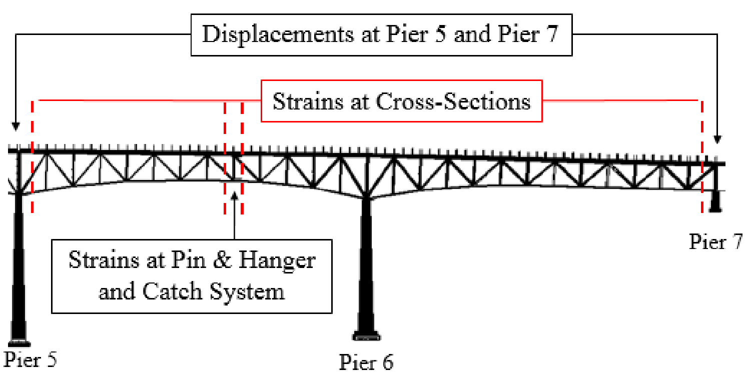

Figure 7: Instrumentation Plan Overview

Further analysis was conducted to determine the ranges need for the gages. Based on these studies, the maximum relative strains expected were approximately 2000 microstrains and the maximum relative displacements were approximately 3-inches. Therefore, 6-inch (Geokon, model 4000) and 2-inch (Geokon, model 4150) strain gages as well as 4-inch displacement gages (Geokon, model 4435) were chosen for this project. The strain gages had a standard range of approximately 3000 microstrain with a resolution of 1 microstrain and 0.4 microstrain for the 6-inch and 2-inch gage, respectively. These gages were designed for a temperature range of 68 degrees Fahrenheit below zero to 176 degrees Fahrenheit, which was satisfactory for operating in temperatures experienced in Tennessee.

Sixty-four vibrating wire gages with thermistors were installed on the bridge per the instrumentation plan shown in Figure 8. Twelve 6-inch strain gages and four 4-inch displacement gages were installed at Pier 5 and Pier 7 to capture the behavior of a full cross-section and the movement at the expansion joints and bearings. The strain gages were installed on each of the top chords, diagonals, and bottom chords at these locations. Half of the displacement gages were installed near the bearings and half were installed near the expansion joints at the end and middle of the bridge. Thirty-two sensors were used to capture the behavior at the cantilever and the pin and hanger. Eight of those sensors were 2-inch strain gages specifically designed for curved surfaces and were installed on the catch system rods.

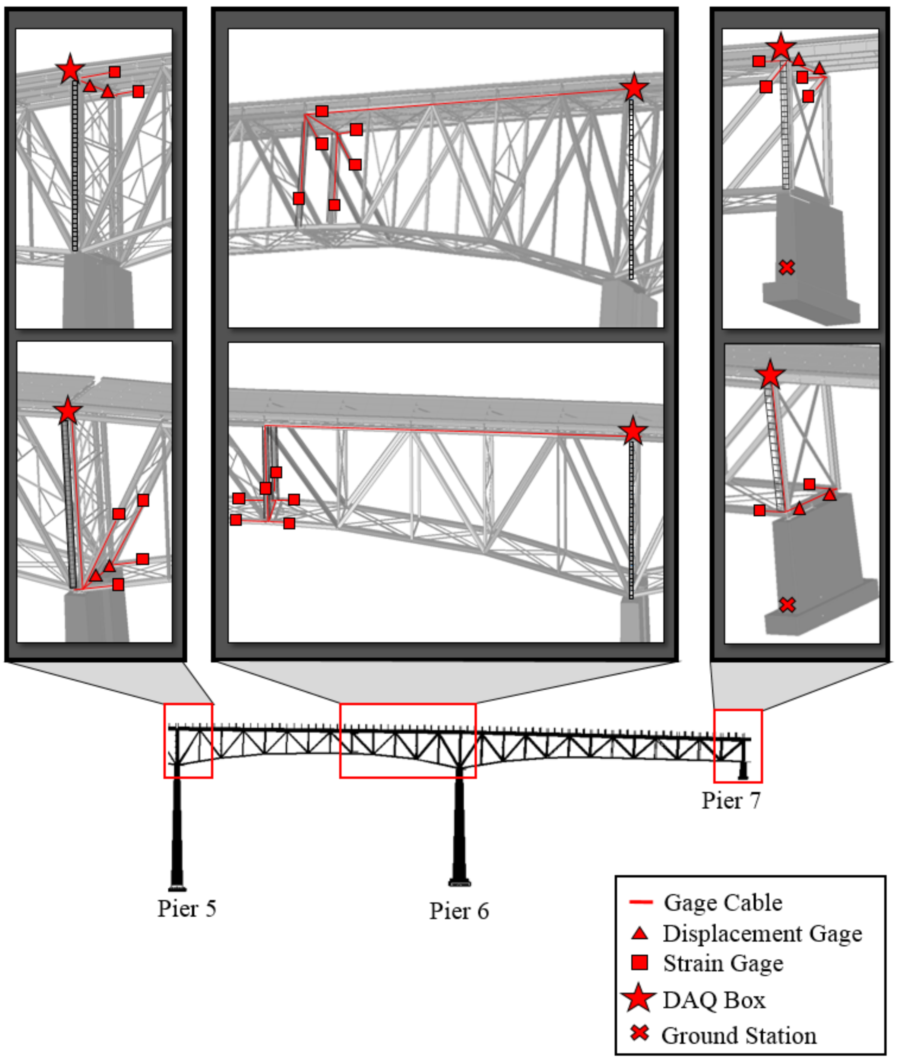

Figure 8: Detailed Instrumentation Plan

The data acquisition system (DAQ) consisted of three boxes installed on the bridge that wirelessly communicated with a ground station accessible from land (Figure 9). The ground station location was such that data collection could be completed without risking researcher exposure to traffic. Solar panels and rechargeable 12-volt batteries onsite were used to power the system. The gages were hard-wired to data acquisition equipment within the boxes on the bridge. The vibrating wire sensors were excited and recorded by the DAQ. The strain or displacement results as well as the temperature results from the gages were sent from each box to the ground station at a sampling rate of five minutes. The ground station used onsite memory storage to collect the data until it could be retrieved and analyzed.

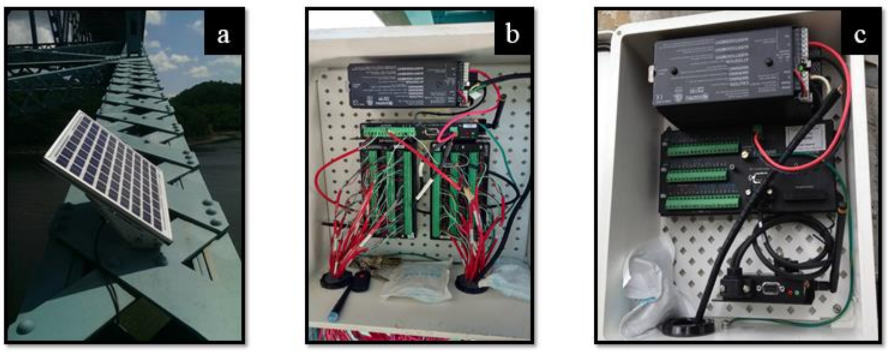

Figure 9: Monitoring Equipment: a) Solar Panel, b) DAQ Box, c) Ground Station

The installation of the monitoring system was a collaborative effort from multiple sources. Tennessee Department of Transportation contributed a snooper truck, two operators, a supervisor, and three traffic control personnel to this project throughout the duration of the installation. The research and installation team was comprised of seven graduate students and an assistant professor from Tennessee Technological University Department of Civil and Environmental Engineering. The monitoring equipment installation took a total of four days to complete. During this time, one lane of the bridge was shutdown to provide access to the structure via the snooper truck. Each strain gage required a direct bond with the steel members. The 2-inch strain gages were spot welded to the "catch system" rods (Figure 10a). For each 6-inch strain gage, a grinder was used to expose a small area of the member where the gage was to be attached. Each gage was then bonded to the member using high strength adhesives (Figure 10b). Finally, several coats of paint were applied to any exposed steel to prevent rusting. For the displacement gages at the bearings, one end of the gage was attached to the jacking beam of the truss and the other end to the catcher beam that is attached to the pier. The catcher beam was added to the structure during the 2011 rehabilitation as part of a seismic repair (Figure 10c).

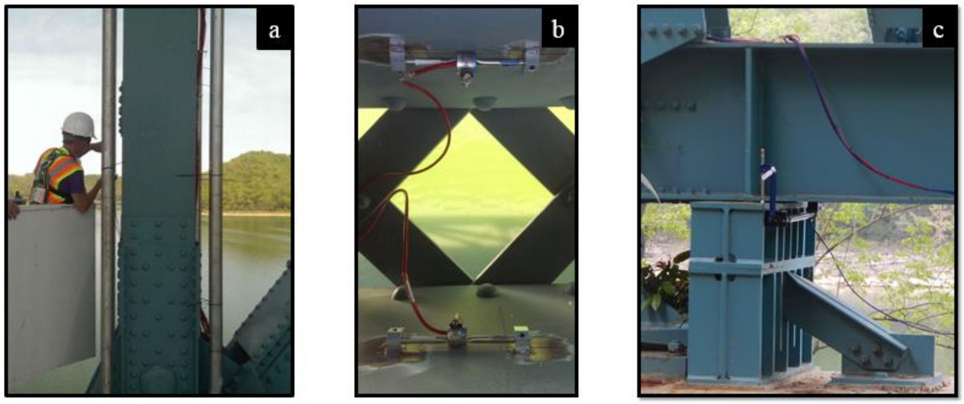

Figure 10: Installation of Sensing Equipment: a) 2-Inch Strain Gage, b) 6-Inch Strain Gage, and c) Displacement Gage

Once the equipment was installed, the system began to record and store data. Quality control checks were performed on the initial readings to confirm the system was functioning properly. Through these checks, one gage was discovered to be faulty after thorough troubleshooting efforts failed. The remaining sixty-three gages were functioning as intended. To date, approximately six months of data have been collected. A sample of some of the preliminary data is shown in Figure 11. These results are from one strain gage located on the top chord and one displacement gage near the expansion joint at Pier 7. The results clearly show the cyclic behavior of the bridge due to daily temperature changes. More importantly they illustrate the capability to capture the temperature-driven signature, which will be later used for model-experiment correlation and long-term monitoring of the structure.

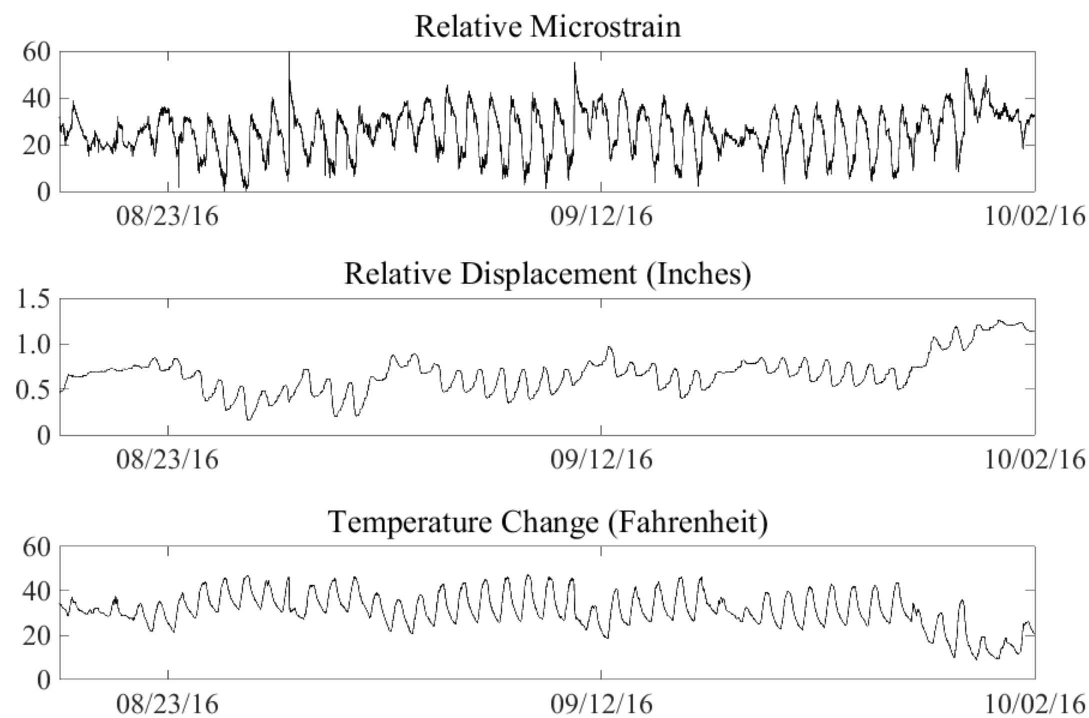

Figure 11: Sample of Preliminary Data

The preliminary data shows the complexity of the structure. Although linear behavior is expected, the data is non-linear overall as shown in Figure 12. Figure 12a and 12c are the displacement results for the middle of the bridge at Pier 5 for the expansion joint and bearing behavior, respectively. Similarly, Figure 12b and 12d are the displacement results for the end of the bridge at Pier 7 for the expansion joint and bearing behavior. The non-linear behavior could be the result of a number of situations and will be investigated to determine the cause. In addition, numerical techniques for simulating the non-linear behavior as well as tracking it long-term will be researched.

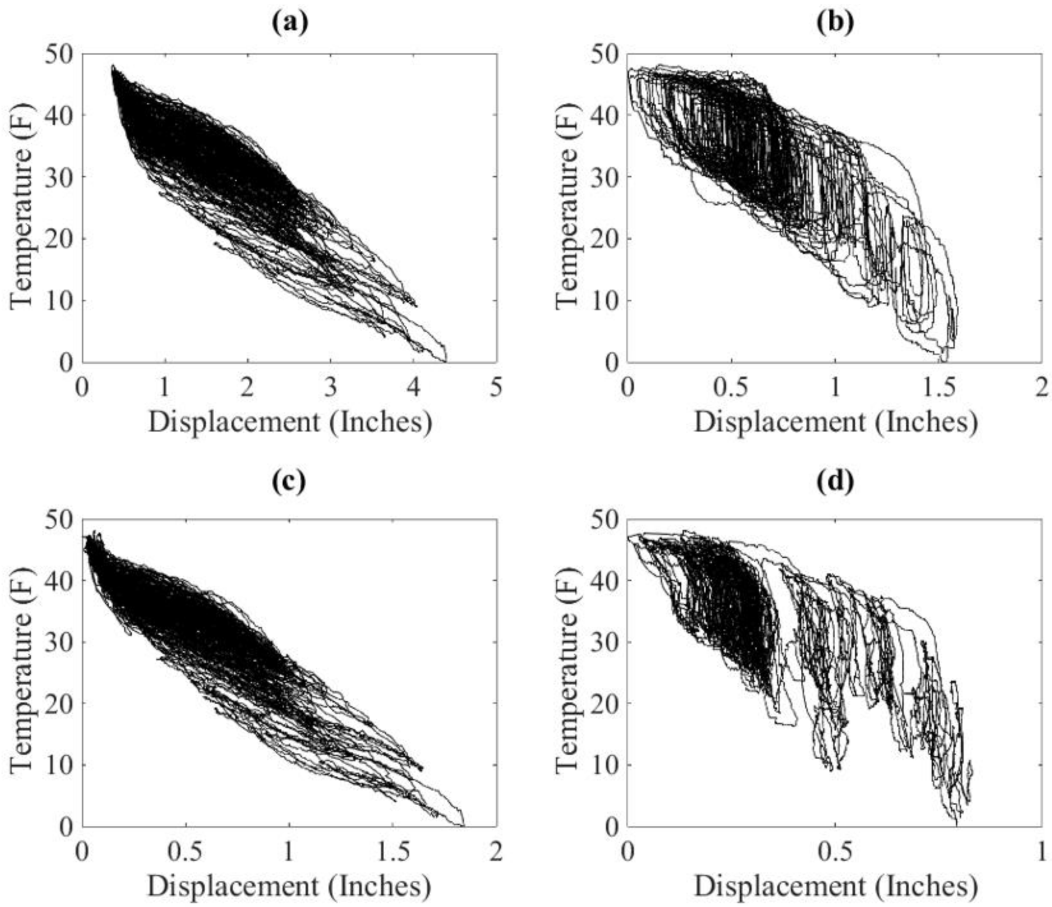

Figure 12: Measured Displacements: a) Pier 5: Relative Displacement at Expansion Joint, b) Pier 7: Relative Displacement at Expansion Joint, c) Pier 5: Absolute Displacement at Bearing, and d) Pier 7: Absolute Displacement at Bearing

CONCLUSIONS

The goal of this project is to research and further develop a temperature-driven concept to obtain quantifiable information with regard to an existing structure. As a structure with many uncertainties, the Hurricane Bridge is an opportune test bed to implement this type of monitoring system. Guided by the St-Id process, a temperature-driven monitoring system was successfully designed and installed along the Hurricane

Bridge. An element-level 3D finite element model was created and used to identify optimum locations for sensing equipment on the structure. An instrumentation plan comprised of sensing and data acquisition equipment was developed, and the equipment was installed accordingly. Long-term data collection is currently in progress, but the preliminary data indicates a potential for promising research opportunities with regard to temperature-driven structural identification and health monitoring.

FUTURE RESEARCH

The next phase of research will begin with Step 4 of the structural identification process (Figure 1). This will include extensive data processing and interpretation to gain insight into the structural behavior directly from the data. Next, Step 5 will perform model-experiment correlation to identify the unknown structural parameters sensitive to the temperature-driven baseline. The parameters of focus will be the movement mechanisms, which include the bearing systems along with the pin and hanger assembly. Once the parameters are identified different simulations will be performed to establish the implications and potential long-term performance of the structure.

Another focus of the future research will involve long-term structural health monitoring technique utilizing the temperature-driven signature. Algorithms will be developed that take advantage of the sensitivity of this signature to identify future structural changes (potentially as a result of damage). Threshold criteria will be established and automated software will be developed for an alert and reporting system.

A framework for temperature-driven structural identification and health monitoring will be developed as a result of this study. Associated guidelines will be distributed for future applications. The goal is to improve evaluation and monitoring of long-span bridges.

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