Temperature-Based SHM of a Steel Tied-Arch Bridge

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ABSTRACT:

A temperature-based (TB) structural health monitoring (SHM) system was implemented along a long span steel tied-arch bridge. The underlying TB concept is based on the notion that temperature variations can be treated as measureable loading for bridges and thus can be used to obtain a complete input-output relationship. From this unique behavior a novel signature (or baseline) was defined using the three dimensional relationship between temperature changes, local mechanical strains, and global displacements [1]. This numerical and graphical baseline was then used within an SHM framework to identify unusual structural behaviors and proactively maintain the structure.

Test Structure and Measured Data

The TB SHM system was installed along a 168m (550ft) steel tied-arch bridge, designed and constructed in 1929 (Figure 1). The instrumentation for the arch was installed in 2010 and included the following equipment [2].

- 56 vibrating wire (VW) strain gages
- 2 VW displacement gages
- 58 thermistors
- 2 data acquisition systems located at each end of the arch (Campbell Scientific, model CR1000)
- 1 weather station (Columbia, Orion Weather Station)

Figure 1: Steel Tied-Arch Bridge

The full installation was completed in eight days with two people and no traffic disruption. All sensors were installed by climbing the structure with standard fall protection equipment. Figure 2 illustrates a displacement gage installed at the expansion bearing and strain gages installed along the lower chord of the arch. The data acquisition systems at each end of the span included cellular modems for remote connectivity. The sampling rate was set to three minutes to allow for minimal data storage requirements and easy data transmission.

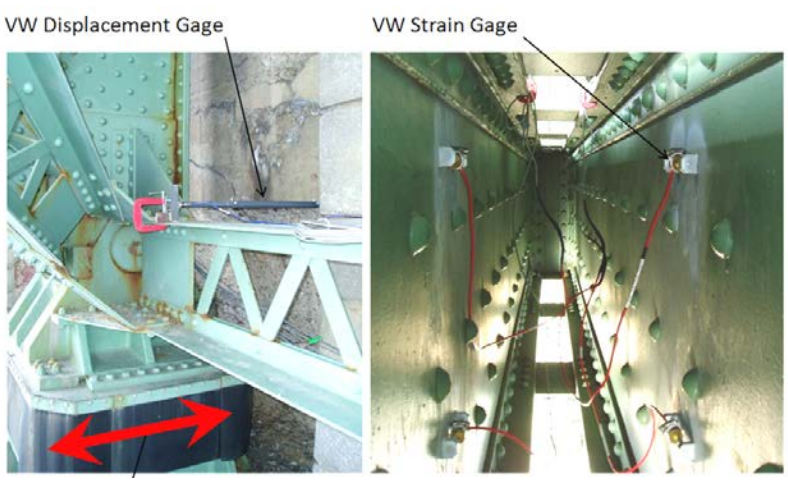

Figure 2: Example Installed Sensors along the Arch

Yarnold [3] presents a detailed direct analysis of the obtained data (i.e. prior to any model-experiment correlation). The primary conclusions from the analysis include:

- <u>Bearing Behavior</u>: A nonlinear "stick-slip" movement mechanism was characterized using both displacement measurements of the expansion bearings as well as strain measurements of the members framing into the bearing.

- Slotted Connection Behavior: Negligible axial strains were measured at the middle chord slotted connections, which indicated they were functioning well.
- Response Magnitudes: Typical daily and seasonal strain and displacement magnitudes were directly obtained. Daily mechanical strains ranged from 20με to 250με with displacements ranging from 5mm to 20mm.
- Equilibrium: The intrinsic force variations along the global load path were verified with equilibrium through free body slices of the structure during near steady-state conditions.

The measured data also illustrated that the nonlinear relationship between temperature, local mechanical strains, and global displacements results in a near-flat surface when plotted in 3D space (Figure 3). The bounds and the orientation (angle) of these surfaces are unique for each location and insensitive to normal operational changes in behavior. More importantly, a numerical sensitivity study was performed which indicated the surfaces are sensitive to a series of realistic scenarios which would result in meaningful changes in the performance of the structure. In addition, a comparison with a vibration-based SHM approach was also carried out, and the results indicated that the temperature-based approach was more sensitive for the scenarios examined.

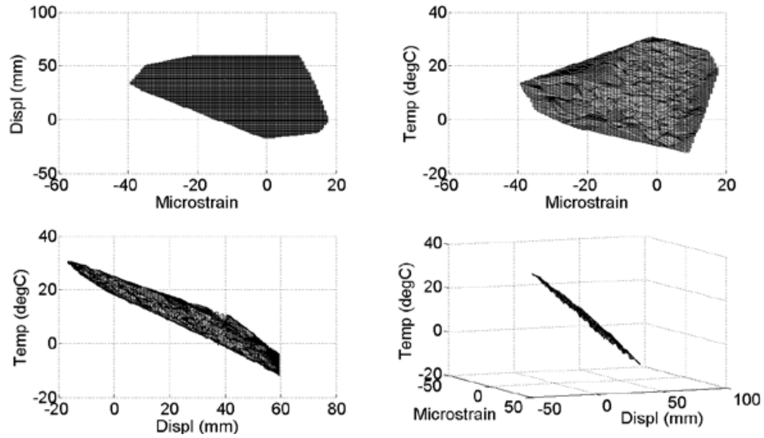

Figure 3: 3D Surface Plot from the Lower Chord Data (1 Year)

SHM Methodology and Results

The TB methodology utilized for this SHM application is based on the notion that temperature variations can be treated as a measureable forcing function and thus be used to obtain a complete input-output relationship (or transfer function). This is achieved through instrumentation of both the critical members and movement mechanisms (expansion bearings, joints, etc.). Each instrumentation location includes sensing for temperature measurement (input) along with measurement of mechanical strains, displacements, and/or rotations (output). These measured relationships associated with member forces and movement mechanisms can identify a unique signature (or baseline) of the structure. This signature can be utilized within the structural identification (St-Id) framework to determine various structural parameters and evaluate the structural performance under different scenarios [4]. This signature may also be leveraged for identification of unusual structural behaviors within a structural health monitoring (SHM) framework [1]. Figure 4 shows a graphical depiction of the TB framework.

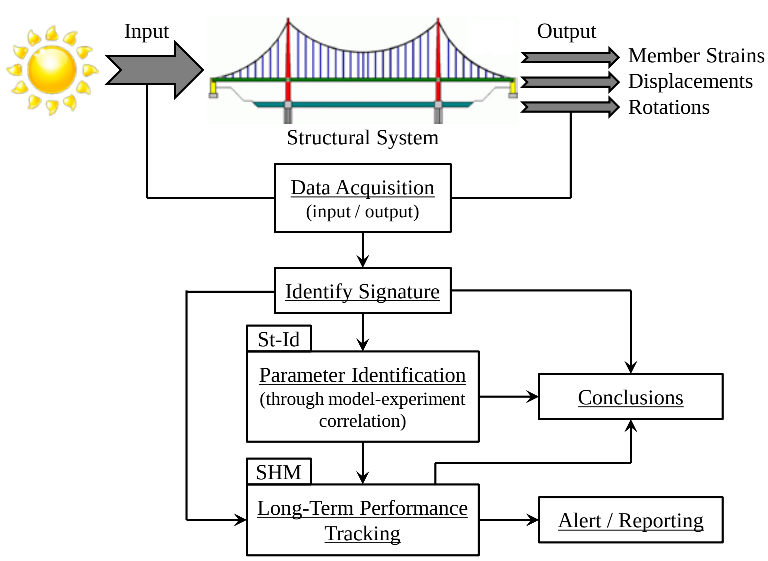

Figure 4: TB Framework

A long-term SHM system is in place along the arch span and utilizes the TB 3D baseline (illustrated in the prior section) to identify anomalies (potentially indicating structural damage). An automated system was developed that includes daily checks of the established performance metrics. In addition, email alert capabilities are include with automated reporting functionality.

Lessons Learned

Logistically some of the lessons learned from the TB SHM application include:

- easily measurable input and output relationship with high signal-to-noise ratio;
- sensors need to be protected from direct solar radiation to ensure data quality;
- relatively inexpensive equipment to capture the input-output relationship;
- negligible data storage requirements;
- minimal time synchronization requirements (only static data is needed);
- many structural parameters are highly sensitive to temperature variations increasing the potential for structural identification and the benefit for structural health monitoring.

The specific lessons learned from the comparison of a TB SHM system baseline to a vibration-based baseline illustrated the following.

- The vibration-based SHM baseline was relatively insensitive to local and global damage scenarios. Changes to the natural frequencies and modes shapes were negligible (less than 5% for nearly all scenarios). This indicated a vibration-based baseline to have limited potential to identify structural changes.
- The TB SHM baseline was sensitive to localized effects, but this was dependent on the resolution of the instrumentation. Sensors realistically need to be placed within one bay of the damage to be reliably identified.
- The TB SHM baseline was highly sensitive to global changes of the structure (over a hundred percent change for most scenarios). The 3D baseline is able to readily identify damage scenarios that involve the primary structural members.

Acknowledgements

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