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Temperature-based structural health monitoring baseline for long-span bridges

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ABSTRACT

A core prerequisite of an effective structural health monitoring (SHM) system is the development and characterization of a baseline response that is sensitive to meaningful changes in the structural system, and insensitive to normal operational changes. Such a baseline allows the use of detected changes to drive proactive maintenance and preservation interventions, or more refined assessment approaches, to ensure the on-going safety, serviceability, and durability of the structure. The approach developed as part of this research utilizes the relationship between temperature changes and the resulting strains and displacements of the structure to create a unique numerical and graphical baseline within an SHM framework. Evaluation of the method was performed through benchmark studies along with long-term monitoring data from a long-span steel tied arch bridge. The benchmark studies and field measurements illustrate that the nonlinear relationship between temperature, local mechanical strains, and global displacements results in a near-flat surface when plotted in 3D space. 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.

1. Introduction

Long-span bridges support vital arteries for national transportation systems, serve as lifelines across waterways and otherwise impassable terrain, and play a substantial environmental, social, and economic role in their respective regions. The majority of the long-span bridges within the U.S. were constructed during the first half of the 20th Century and thus are approaching their initially envisioned service lives. However, due to political, historical, and financial constraints, such structures have proven difficult to replace, and thus proactive approaches to preserve and renew these critical assets are becoming more relevant.

The state-of-the-art in long-span bridge assessment (to inform preservation activities) is continually being advanced with new developments in sensor technologies, information/communication technologies, and various data processing, visualization, and mining algorithms to aid in data interpretation. In recent years, utilizing field measurements within the paradigm of structural identification [1] has become commonplace when assessing the vulnerability or diagnosing performance problems of signature bridges [2–7]. Although not yet as common, utilizing field measurements to track longer-term performances through structural health monitoring (SHM) applications is beginning to enter the practice (as evidenced by on-going signature bridge projects including the Tappan Zee, Geothals, and Bayonne Bridges, among others) – delayed no doubt by a series of early applications that failed to live up to their billing.

One of the most common methods for SHM of long-span bridges is an ambient vibration-based approach (VBSHM) [8–15]. This method provides an overall characterization through tracking the modal parameters of the structure, and while it has enjoyed significant attention over the last several decades, it has many widely recognized drawbacks [16]. First, readily tracing changes in modal parameters to their root causes is difficult. Second, the relative insensitivity of modal parameters to local structural changes is challenging as such changes may be masked by varying environmental conditions [17]. Additional weaknesses include the

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unknown nature of the inputs that are assumed as wide banded white noise, predication on modal theory assumptions (linearity, stationary, etc.), and significant data processing and storage requirements. Some of these shortcomings are gradually being mitigated by advances in technology; however, others will persist as they are associated with fundamental assumptions that are implicit within the method itself.

As an alternative to vibration-based techniques, there is increasing attention being paid to the direct use of temperature and temperature induced responses for both structural identification [18,19] and SHM of long-span bridges [20–22]. Logistical advantages of temperature-based SHM (TBSHM) include large signal-to-noise ratios, low required sampling rates, and inexpensive sensing, data acquisition, data storage, and data transmission costs. As a result, TBSHM appears to have potential to overcome the current challenge of demonstrating attractive benefit-to-cost ratios to owners of long-span bridges.

The overarching goal of the research presented herein is to evaluate a novel three dimensional (3D) numerical and graphical TBSHM baseline for its potential to provide a reliable signature that is (a) insensitive to normal operational changes, and (b) highly sensitive to relevant and realistic damage scenarios. To accomplish this, simple benchmark numerical models were examined under several scenarios culminating in an application on a long-span tied-arch bridge. To place TBSHM in proper context, a comparison with VBSHM was carried out on a calibrated FE model of the tied-arch bridge in which several realistic damage scenarios were examined.

2. Concept and approach

TBSHM aims to track, characterize and ultimately identify and interpret changes to the relationship between responses (strains, displacements, and tilts) and the variations in temperature that induce them. The primary technical advantage of this approach over vibration-based methods is that the forcing function (i.e. temperature fluctuations) can be measured and thus a full transfer function (or input–output relationship) can be obtained (the underpinning assumptions of this transfer function are discussed below). In addition, TBSHM has several practical advantages such as (1) large signal to noise ratios, (2) extremely low power consumption due to relatively low sampling rates, and (3) relatively inexpensive sensing, data acquisition, and communication requirements.

To illustrate the concept, consider a simply supported beam with a longitudinal spring subjected to a uniform temperature change (Fig. 1). The mechanical strain (defined as the restrained portion of the strain (resulting from restrained displacement) that produces mechanical stress), ε_M, and unrestrained displacement (defined as the measured movement that does not produce mechanical strain), δ_U, as a function of the spring stiffness, k_S, coefficient of thermal expansion, α, uniform temperature change, ΔT, beam length, L, cross sectional area, A, and modulus of elasticity, E, is provided by Eqs. (1) and (2), respectively [23]. If the beam and the longitudinal spring are assumed to be linear, then a straight line results when ε_M, δ_U, and ΔT are plotted in 3D space. However, if an external elastic-perfectly plastic nonlinearity exists (e.g. k_s) or an internal elastic-perfectly plastic nonlinearity exists (e.g. EA), then the 3D plot becomes a surface.

$$\varepsilon_M = \frac{-k_S\alpha(\Delta T)L}{AE\left(1+\frac{k_S L}{AE}\right)} \tag{1}$$

$$\delta_U = \frac{\alpha(\Delta T)L}{1+\frac{k_S L}{AE}} \tag{2}$$

To illustrate the 3D surface behavior consider the simple beam model with a nonlinear k_s stiffness that is elastic-perfectly plastic (Fig. 2) with all other parameters (E, A, L, and α) linear. For this illustration the model is subjected to four uniform temperature changes (ΔT), with the initial condition of 0 °C. The first ΔT is an increase of 20 °C, which is the temperature change where the spring force reaches the bifurcation point (F_{slip}) and the ε_M, δ_U, and ΔT relationship becomes nonlinear. This is illustrated with point (a) in Fig. 3. A second ΔT increase equal to 20 °C is then applied to the model as shown by point (b). It is seen from Fig. 3 that the further expansion of the beam is not restrained (no increase of mechanical strain) by the spring since it is in the plastic range. The remaining two ΔT values applied were both decreases equal to −20 °C, which unloads the system and returns the overall temperature to 0 °C. These results are represented with points (c) and (d). As expected the behavior is nonlinear, but more importantly the ε_M, δ_U, and ΔT relationship maps a flat 3D surface as shown in the lower right plot of Fig. 3. To further illustrate this point a larger temperature time-history, consisting of 120 temperature cycles, was applied to the model following a typical seasonal temperature trend and the corresponding 3D surface plot was generated (Fig. 4).

The feasible limits (or bounds) of the 3D surface can also be illustrated from this model. Consider the limiting case of a rigid beam (i.e. infinite EA) and a nonlinear external spring (simulated by considering a range of stiffnesses). The resulting surface resides entirely in the temperature–displacement plane (Fig. 5) since no mechanical strain can develop. In the other limiting case of a rigid external spring and a nonlinear beam, the resulting surface resides entirely in the temperature-mechanical strain plane (Fig. 5) since all external displacement is restrained. The final case shown in Fig. 5 represents the surface for a beam with a finite elastic stiffness and a nonlinear external spring, which creates a surface that cuts across all three planes (Fig. 5).

The research reported herein, adopts these surfaces as a structural baseline and aims to establish their characteristics and sensitivities to various common damage scenarios. As illustrated through the simple example above, these surfaces are obtained

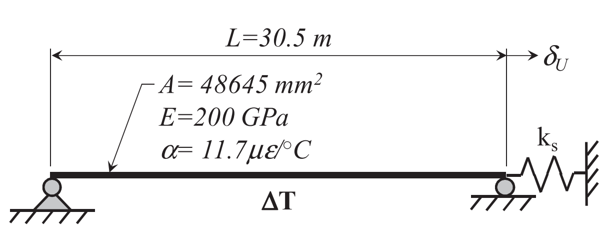

Fig. 1. Simple beam model.

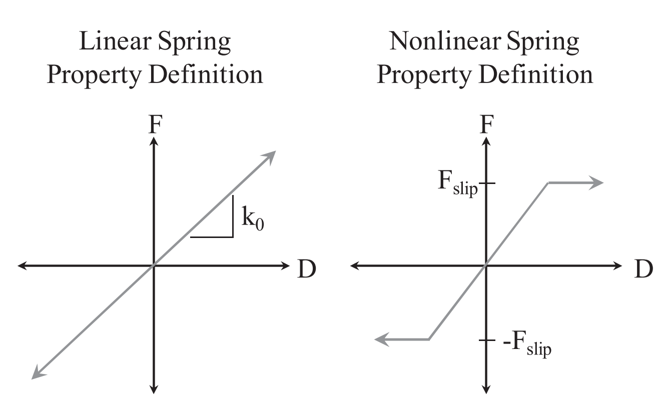

Fig. 2. Linear and nonlinear spring definitions.