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TEMPERATURE VARIATIONS AS LOAD CASES FOR STRUCTURAL IDENTIFICATION

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ABSTRACT

This paper presents a strategy for structural identification that takes advantage of temperature variations. The identification task is performed by considering temperature variations as load cases and comparing predicted thermal behaviour using physics-based models with measured thermal behaviour from continuous monitoring of structures. The Tamar suspension bridge in United Kingdom is presented as a case study to demonstrate the applicability of the strategy. Longitudinal movements of the bridge deck are used to evaluate the potential candidate models. The evaluation is performed using the model-falsification methodology taking into account model and measurement uncertainties. Results show that temperature variations have much potential for enhancing structural identification task.

KEYWORDS

Structural health monitoring (SHM), temperature variations, structural identification, model falsification.

INTRODUCTION

Monitoring the structural health of key infrastructures (i.e., bridges, tunnels, and buildings) is crucial to the public safety and economic efficiency. Furthermore, it allows engineers to better understand the usage profile and failure mechanisms of structures. Although the number of structures that are continuously monitored is increasing, interpreting measurement data remains as a challenge. Studies have been conducted and many methodologies have been proposed. The state of the art report provided by the American Society of Civil Engineers (ASCE 2013) presents an overview of nearly 20 years of research in this field. In some cases, uncertainties may lead to wrong identification (Goulet 2012; Goulet et al. 2010). This task is even more difficult when measurement data are influenced by environmental variations, such as temperature, wind and humidity.

Temperature is an important factor influencing the performance and serviceability of bridges. Solar radiation, air temperature and other metrological elements produce significant nonlinear temperature variations and consequent thermal stresses within bridges. The magnitude of thermal stresses, especially within a concrete box-girder, can be comparable to live and dead load stresses (Peng and Qiang 2007). Furthermore, other studies have shown that temperature variations predominately influence the measured structural responses and live loading was found to be less significant in comparison to the thermal effects (Bell et al. 2008; Catbas and Aktan 2002). Catbas et al. (2008) and many others have observed that the peak-to-peak strain differential due to temperature over a one-year period is more than ten times higher than the strain due to observed maximum daily traffic. Temperature variations also affect the dynamic characteristic of the structure. Xu and Wu (2007) showed that changes in natural frequencies of a cable-stayed bridge due to damage in girders or cables may be smaller than changes due to temperature variations.

Temperature-dependent behaviour was also observed in the SHM activities on the Tamar Bridge located in the south west of the United Kingdom. This bridge has been continuously monitored using a range of technologies that have been applied by Vibration Engineering Section researchers and collaborators since 2000. Dynamic characteristic and static behaviour of the bridge have been investigated and the results showed that structural responses have a strong correlation with temperature variations (Brownjohn et al. 2009; Koo and Brownjohn 2010; Koo et al. 2010). Cross et al. (2010) found that temperature has more of a seasonal than daily effect, whilst traffic loading was found to be the most dominant driver of daily frequency fluctuation. A detailed finite element model (FEM) of the bridge has been created for better understanding of environmental effects on the structural behaviour (Westgate and Brownjohn 2010) and de Battista et al. (2011) showed that the temperature-dependent behaviour of Tamar Bridge is complex.

In general, influence of temperature variation on structural behaviour has been acknowledged many times in this field. However, only few have accounted for this variation in their methods for structural-performance evaluation. Most of these studies have only examined the effects of temperature on modal variations such as natural frequency and mode shape (Balmès et al. 2009; Liu and DeWolf 2007; Moser and Moaveni 2011; Ni et al. 2005). The most common strategy with regards to temperature variations in SHM is to attempt to remove the effects. However, Laory et al. (2011) found that removing temperature-effects is not always advantageous. Instead of cancelling out temperature variations, the study presented in this paper aims to utilise these variations explicitly for identifying parameters of the physics-based behavioural models.

METHODOLOGY

The methodology aims to take advantage of the thermal behavior of monitored structures. The idea is to perform structural identification by applying temperature variations as load to physics-based models and comparing the predicted thermal behavior with the thermal behavior that is extracted from continuous monitoring. In this approach, thermal variations are considered to be similar to load tests. Structural identification using load tests requires a good knowledge of the load. Therefore information with regards to temperature distribution is required. Temperature sensors are cheap and by employing sufficient number of temperature sensors on the structure, a good approximation of the temperature distribution within the structure could be feasible. However, thermal variation is a complex phenomenon that includes solar radiation, rain, snow, humidity and other factors that contribute to uncertainty. Furthermore, structural responses that are measured using monitoring systems are dependent on the excitation sources such as traffic, humidity, wind and temperature variations. A signal decomposition strategy is thus required in order to extract thermal responses from measured signals. In this study, regression analysis is used to extract temperature-dependent responses from continuous monitoring data.

To account for uncertainties, error-domain model-falsification is employed for the identification task. It involves (physics-based) model generation, uncertainty quantification, model falsification and evaluation. First, an initial model set is generated based on the model parameters to be identified. Then, a falsification process is performed based on threshold bounds that are defined using combined uncertainties associated with both the model and measurements. The measured and predicted measurement values are compared for every generated model. If the predicted value is outside an interval defined by the threshold bounds, the model is falsified. All models that are not falsified are part of the candidate model set. Candidate models serve as baseline for evaluating the structural performance.

In this study, to reduce the uncertainty of thermal modelling, only uniformly distributed temperature variation is considered. This is performed through data grouping based on measurement time. Only data in the time span from 12:00 pm to 5:00 am is used for analysis. This period is congenially used for structural geometric surveys since no solar radiation is present during this time period and the temperature distribution is most likely to be uniform. In addition, vehicle traffic is a minimum so the bridge is in a quiescent state with minimised time varying of load and response.

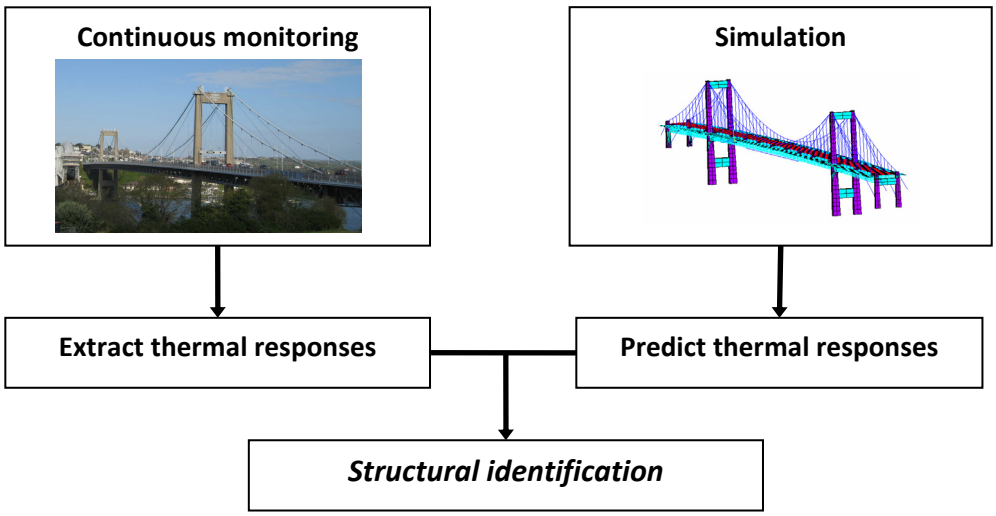

Figure 1. Flowchart of a structural identification strategy using thermal variations

A CASE STUDY

Tamar Bridge connects Saltash to Plymouth in southwest England (Figure 2). It was designed as a conventional suspension bridge with symmetrical geometry and was first opened in 1961. The total length is 642 m with a main span of 335 m and side spans of 114 m and the tower height is 73 m. Trusses are 4.9 m deep with chords of welded hollow box structures. To meet the requirement that bridge should be capable of carrying trucks up to 40 tons, the Tamar Bridge was strengthened and widened in March 1999 and the upgrading was completed in December 2001. The upgrading included replacing the original composite main deck by a three-lane orthotropic steel-deck, adding single lane cantilevers at each side of the truss and installing sixteen new cables acting as additional stays to carry the additional dead load of new cantilever lanes and associated temporary works. This bridge is continuously monitored to measure environmental variations and structural behaviour (dynamic and static responses). The measurements collected from the monitoring system of Tamar Bridge show variations in static and dynamic behaviour of the bridge. These variations are most likely to be the result of environmental and traffic loading effects.

Many types of sensors were installed during and subsequent to the strengthening and widening to monitor the behaviour of the bridge. They included anemometers, displacement sensors, thermometers, load cells and accelerometers. Four pairs of accelerometers have been clamped onto the stay cables, oriented vertically and axially to the cable. Another three accelerometers have been installed on the deck. A total positioning station (TPS) has been installed for monitoring the movement of the bridge. TPS is an electronic theodolite integrated with an electronic distance meter (EDM) to read distances from the instrument to a particular point. The coordinates of the surveyed points relative to the TPS are easily computed. As shown in Figure 3, the TPS was installed on top of the Tamar Bridge Office located near the bridge. 15 reflectors were placed on the bridge deck, on top and wall of towers and on top of side towers (Figure 4). Displacement measurements in longitudinal, lateral and vertical directions were recorded every 30 minutes.

Figure 2. Tamar Bridge

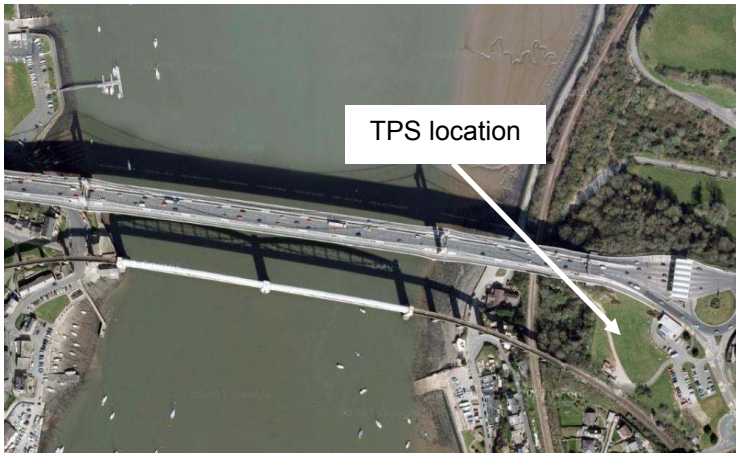

Figure 3. Tamar Bridge with TPS location

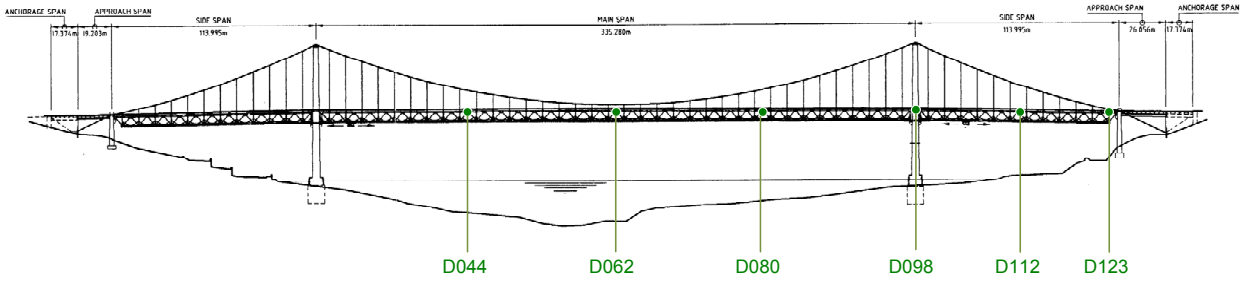

Figure 4 Reflector locations and their abbreviation

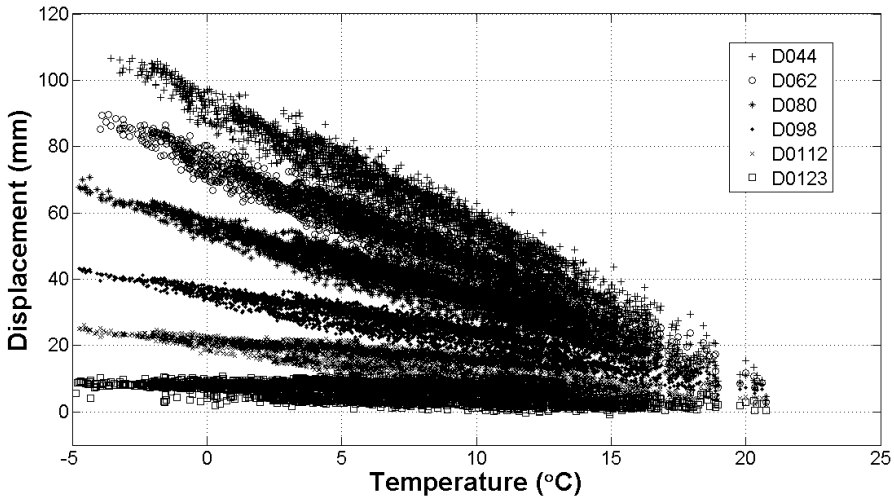

Figure 5. Longitudinal thermal displacements of the bridge deck

Figure 5 shows the relationship between longitudinal deck displacements and temperature (the reflector abbreviations are shown in Figure 4). For longitudinal movements, displacement magnitudes are shown to be dependent on temperature changes. The relationship is linear with some scatter. Displacements at D044 are shown to be the most sensitive to temperature with approximately 80 mm of displacement over a 20°C temperature change. The main span and the Plymouth side-span are continuous at the Plymouth Tower and the bridge deck has a fixed end at the Plymouth abutment and a free end at the Saltash Tower. This explains the gradually decreasing thermal displacement as the sensor locations are closer to the fixed end. This dependency of thermal movement on locations is also shown in the relationships within the longitudinal displacements (Figure 5).

Structural identification is performed through comparing measured with predicted thermal responses. An initial model set that represents the solution space is generated using a template model. Initial strain of the main and hanger cables, boundary conditions (longitudinal stiffness) of the Plymouth side, Saltash side and deck expansion joints are the five parameters to be identified. Combinations of these parameters define the solution space. For each interval, the parameter value is discretized into five values. Having five values for each parameter, this generation process lead to 5^5 (3125) models. Model falsification incorporates uncertainties by introducing threshold bounds that are computed using the combined uncertainties. Uniformly distributed temperature (20°C) is applied to the models as a load. The predicted thermal displacements are compared with thermal displacements computed from the regression functions that are developed using measurement data. Figure 6 illustrates the falsification process using longitudinal displacements where measured and predicted values are compared for location D044. The horizontal axis represents the models while the vertical axis represents the predicted value of each model. The threshold bounds are shown as solid lines. Models having predicted values outside the threshold bounds are then falsified.

The number of the possible parameter combinations is significantly reduced after falsification. 2875 models out of 3125 are falsified, leading to a much smaller number of candidate models (250). These candidate models could serve as a baseline for subsequent monitoring and maintenance activities. The ranges of parameter values that are found for the candidate models are shown in the radar plot (Figure 7). The plot shows that the parameter ranges for the longitudinal stiffness of deck expansion joint and boundary conditions at Plymouth side are reduced (the dots represent plausible value of the parameter). While high values for deck stiffness are discarded, only the highest stiffness value for the boundary conditions at Plymouth side is accepted through the falsification process.

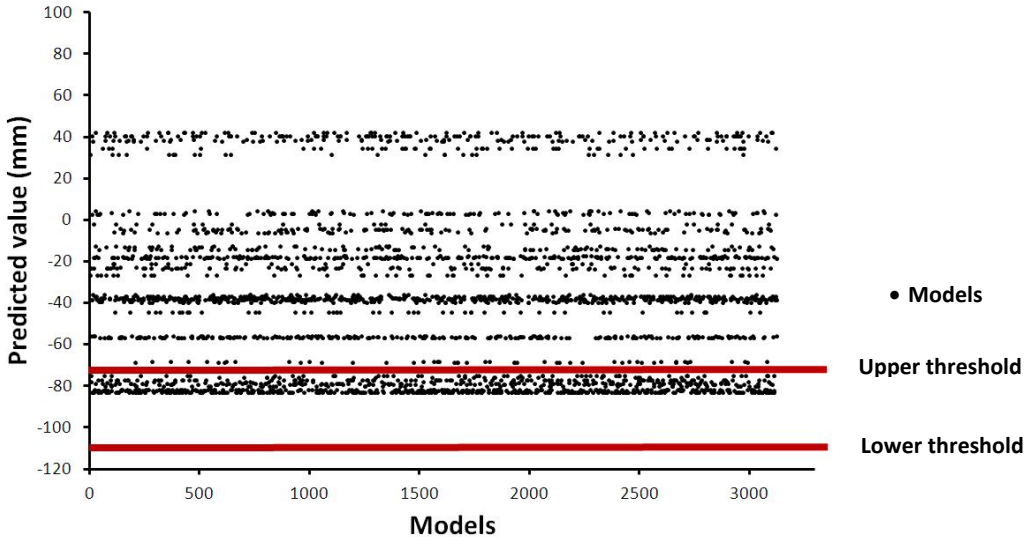

Figure 6. Model falsification using longitudinal displacements at D044

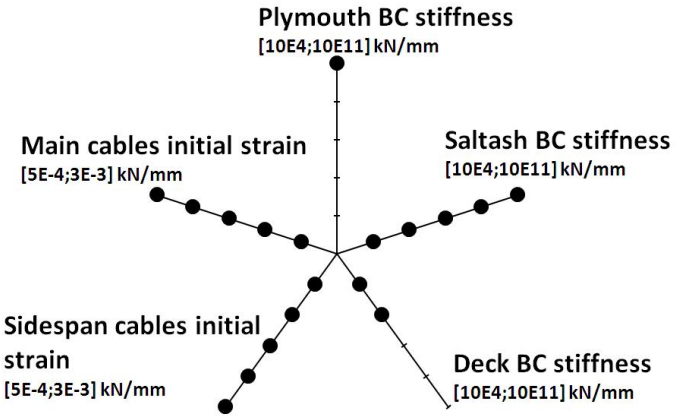

Figure 7. Radar plot of parameters identified in the candidate model set for Tamar Bridge

CONCLUSION

A structural identification strategy that takes into account thermal variations is proposed. The strategy utilizes thermal variations as load cases to evaluate candidate models. This study shows that temperature variations can be considered as load cases. Despite the complexity of the phenomena, thermal variations have been shown to be advantageous for structural identification and have a promising potential for enhancing data interpretation in structural health monitoring.

However, a good knowledge of structural thermal behaviour is necessary for this strategy. This includes a monitoring system that is able to capture thermal distribution within the structure and methodologies to extract thermal responses from measurement data as well as thermal modelling. Uncertainties which arise due to the complex nature of thermal variations may eventually decrease the reliability of the identification task. This trade-off requires further study.

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REFERENCES

ASCE (2013). *Structural Identification of Constructed Systems: Approaches, Methods, and Technologies for Effective Practice of St-Id*, ASCE, Virginia, USA.

Balmès, É., Basseville, M., Mevel, L., and Nasser, H. (2009). "Handling the temperature effect in vibration monitoring of civil structures: A combined subspace-based and nuisance rejection approach", *Control Engineering Practice*, 17(1), 80-87.

Battista, N.D., Westgate, R., Koo, K.Y., and Brownjohn, J.M.W. "Wireless monitoring of the longitudinal displacement of the Tamar Suspension Bridge deck under changing environmental conditions", *Proceedings of SPIE*, San Diego, CA, USA.

Bell, E.S., Sipple, J., and Yost, J. "Long-Term Thermal Performance of a CFRP-Reinforced Bridge Deck." *ASCE*, 242-242.

Brownjohn, J.M.W., Worden, K., Cross, E., List, D., Cole, R., and Wood, T. "Thermal effects on performance on Tamar Bridge." *Proceding of The Fourth International Conference on Structural Health Monitoring of Intelligent Infrastructure*, Zurich, Switzerland, 152.

Catbas, F. N., and Aktan, A. E. (2002). "Condition and Damage Assessment: Issues and Some Promising Indices", *Journal of Structural Engineering*, 128(8), 1026-1036.

Catbas, F.N., Susoy, M., and Frangopol, D.M. (2008). "Structural health monitoring and reliability estimation: Long span truss bridge application with environmental monitoring data", *Engineering Structures*, 30(9), 2347-2359.

Cross, E., Worden, K., Koo, K. Y., and Brownjohn, J. M. W. *Modelling environmental effects on the dynamic characteristics of the Tamar Suspension Bridge*, IMAC XXVIII, Florida USA.

Goulet, J.-A. (2012). *Probabilistic Model Falsification for Infrastructure Diagnosis*, PhD Thesis No. 5417, Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland.

Goulet, J.-A., Kripakaran, P., and Smith, I.F.C. (2010). "Multimodel Structural Performance Monitoring", *Journal of Structural Engineering*, 136(10), 1309-1318.

Koo, K.Y., and Brownjohn, J.M.W. (2010). "Innovative structural health monitoring for Tamar Suspension Bridge by automated total positioning system", *Proceedings of the Fifth International IABMAS Conference*, Philadelphia, USA, July.

Koo, K.Y., Brownjohn, J.M.W., Carden, P., List, D. I., Cole, R., and Wood, T. (2010). "Long-term structural health monitoring for Tamar Suspension Bridge", *Proceedings of the Fifth International IABMAS Conference*, Philadelphia, USA, July, 336-343.

Laory, I., Trinh, T. N., and Smith, I.F.C. (2011). "Evaluating two model-free data interpretation methods for measurements that are influenced by temperature", *Advanced Engineering Informatics*, 25(3), 495-506.

Liu, C., and DeWolf, J.T. (2007). "Effect of Temperature on Modal Variability of a Curved Concrete Bridge under Ambient Loads", *Journal of Structural Engineering*, 133(12), 1742-1751.

Moser, P., and Moaveni, B. (2011). "Environmental effects on the identified natural frequencies of the Dowling Hall Footbridge", *Mechanical Systems and Signal Processing*, 25(7), 2336-2357.

Ni, Y.Q., Hua, X.G., Fan, K.Q., and Ko, J.M. (2005). "Correlating modal properties with temperature using long-term monitoring data and support vector machine technique", *Engineering Structures*, 27(12), 1762-1773.

Peng, Y., and Qiang, S. "Analytical Solution to Temperature Variations in Highway Concrete Bridges Due to Solar Radiation." *ASCE*, 252-252.

Westgate, R.J., and Brownjohn, J.M.W. *Development of a Tamar Bridge finite element model*, IMAC XXVIII, Jacksonville, Florida, USA.

Xu, Z.-D., and Wu, Z.S. (2007). "Simulation of the Effect of Temperature Variation on Damage Detection in a Long-span Cable-stayed Bridge", *Structural Health Monitoring*, 6(3), 177-189.