ICESF
Hatfield Hertfordshire | UK | 10–11 September 2020

The Effect of Temperature Variation on Bridges - A Literature Review

Sushmita Borah[1], Amin Al-Habaibeh[2], Rolands Kromanis[3]

[1,2] *Product Innovation Centre, Nottingham Trent University, UK*
[3]*University of Twente, The Netherlands*

[1] sushmita.borah2018@my.ntu.ac.uk, [2] amin.al-habaibeh@ntu.ac.uk, [3] *r.kromanis@utwente.nl*

Abstract

Bridges are commonly subjected to complex load scenarios in their lifetime. Understanding the response of bridges under such load scenarios is important to ensure their safety. While static and dynamic loads from vehicles and pedestrians influence the instantaneous response of bridges, studies show that thermal load from diurnal and seasonal temperature variation influences its long-term response and durability. This study addresses the effects of thermal load variation on bridges and briefly reviews methods of measuring such effects. The findings show that thermally induced deformations in bridges are of magnitude equal or larger than that induced by vehicle induced load. This study highlights the significance of measuring temperature responses of bridges for their robust structural health monitoring.

Keywords: Bridges, Sensors, Structural health monitoring, Sustainable infrastructure, Thermal load.

1. Introduction

Bridges are a vital element of road infrastructure. The serviceability of bridges is sensitive to continuous traffic loads and environmental impact due to variations of ambient temperature and wind loads. A robust structural health monitoring (SHM) approach is essential to determine bridges' serviceability and thereby ensure traffic safety. Morandi bridge collapse in 2018, which took the lives of 43 people, in Italy is a recent reminder of the need for robust SHM for bridges [1]. Figure 1 illustrates a general framework of monitoring bridges under common loading scenarios such as traffic, temperature and wind load. Structural response data from the bridges are collected using suitable SHM approaches. Traditionally, in many countries general bridge inspection is carried out periodically that involves a visual survey of all accessible parts of the bridge. Such inspections are subjective and prone to human error. Contact and non-contact sensors are commonly used in SHM to eliminate the limitations of the general bridge inspection and conduct more frequent monitoring. The collected responses such as displacement, strain and accelerations are then analysed to provide feedback to bridge management authorities to undertake any required interventions.

The traffic load influences the instantaneous response of bridges, whereas, thermal load from diurnal and seasonal temperature variation influences its long-term response and durability. The magnitude of thermally induced response has been found in many cases to be equal or larger than the traffic-induced response [2]. This study aims to explore the literature on temperature-induced bridge responses and review key thermal response measurement techniques. The need for continuous SHM of bridges is emphasised to administer timely repair and replacement work. Early detection of damage can reduce the cost of bridge replacement and repair; and increase bridge life and traffic safety. Thus, SHM can aid sustainable infrastructure by ensuring public safety and reducing life-cycle maintenance cost of bridges.

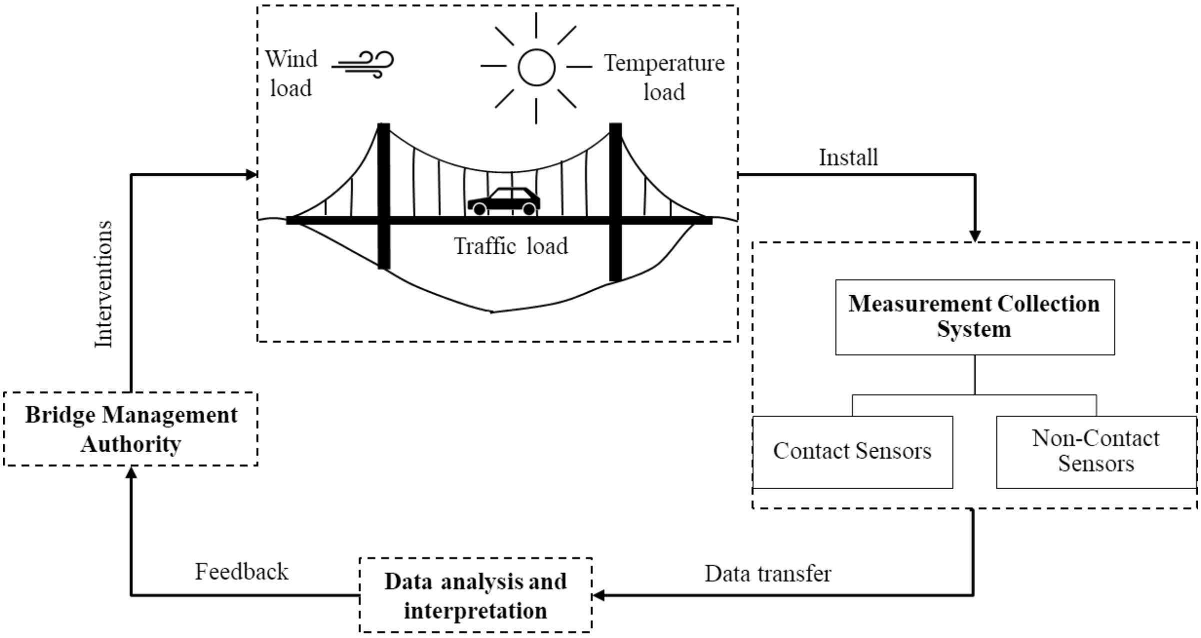

Figure 1: A general framework of Bridge health monitoring

2. Thermal response of bridges

2.1 Temperature distribution pattern in Bridges

Distribution of ambient temperature in bridges in most cases is non-linear. The temperature distribution is influenced by material type, bridge orientation, shading from neighbouring structures, etc. Kromanis and Kripakaran [3] recorded maximum temperatures from 26.8°C to 35.4°C at different locations along the length of the National Physical Laboratory footbridge in Exeter, UK. In Shanghai Yangtze River Bridge, Zhou and Sun [4] observed a negligible temperature gradient in the steel girder along the longitudinal and transverse direction and a significant vertical temperature gradient between the top and bottom girder plates up to 17°C on a hot summer day. Lawson et al. [5] computed temperature profiles along the depth of two hypothetical concrete and composite girders based on weather data of Nevada, USA. Daily temperature variation was maximum in the top surface of concrete superstructure followed by bottom and internal layers in decreasing order. In the composite superstructure, the temperature varied only in the concrete layer whereas the steel layer experienced almost uniform temperature. The temperature difference between any two points along the depth of both superstructures was found usually to be more than 30°C; as maximum temperature difference exceeded 40°C in the concrete superstructure and 36°C in the composite superstructure. Thus, a significant temperature gradient is observed in the bridge due to ambient temperature and solar radiation, especially along its depth.

2.2 Temperature effects on the static response of bridges

Temperature gradients can induce static responses in bridges such as displacement and strain. Long term monitoring of Cleddau Bridge in Wales showed that bearing displacements closely follow diurnal and seasonal temperature variations [3]. Xia et al. [2] recorded daily temperature-induced strains of magnitude equal or larger than that due to traffic and static load in the Yangtze River in Jiangsu, China. Measured temperature-induced strain in the bridge exceeded 150 με in the lower deck and 100 με in the upper deck. In comparison, the traffic-induced strain in the bridge did not exceed 100 με, while strain under a point load of 17680 kN was found to be 156 με. Likewise, range of variation of thermal and vehicle induced stress in the lower deck were found to be of similar magnitude.

Zhou and Sun [6] monitored the Shanghai Yangtze River Bridge to evaluate temperature effects on several bridge response parameters. Temperature dependencies of these response parameters showed two modes: (i) amplitude of variations due to annual temperature cycles was significantly larger than those due to diurnal temperature cycles. Girder length, the distance between the two-tower tops and structural total strains at mid-span exhibited this mode and their temperature-induced change was governed by and directly proportional to average girder temperature. (ii) the amplitude of variation due to annual temperature cycles was approximately equal to those due to diurnal temperature cycles. The vertical deflection and elastic strains at mid-span, and average cable tensions of the longest centre-span cables exhibited this mode. The temperature-induced changes in mid-span vertical deflection and average cable tension were simultaneously governed by average cable temperature and average girder temperature. The elastic strain within the top and bottom plates of the girder was mainly caused by the temperature gradient between the plates.

2.3 Temperature effects on the dynamic response of bridges

Temperature gradient significantly influences the dynamic properties of bridges such as natural frequency. Cornwell et al., [7] reported about 5% variation of the first three natural frequencies of the Alamosa Canyon Bridge during daily temperature cycle. Liu and DeWolf [8] reported a maximum of 6% change in natural frequency of a concrete bridge in Connecticut, USA in a 21.11 °C peak to peak temperature change during one-year and found that changes in girder temperature affect the bending modes more easily than the torsional modes. Peeters & De Roeck [9] found a bilinear relationship between natural frequency and temperature change in Z24 Bridge. Natural frequency fluctuated between 1.7% to 6.7% over one-year in Ting Kau Bridge when temperature ranged between 3°C and 53°C [10]. The frequency of the first and fourth bending modes of the Tianjin Yonghe Bridge varied by 3.155% and 1.470% with a corresponding change in the ambient temperature of -11.5 °C to 3.7 °C over 16-days

[11]. In Dowling Hall Footbridge, the first six modal frequencies varied by 4 to 8% within a temperature range of -14 °C to 39 °C over 16-weeks of data [12].

Several lab-based investigations also confirmed the dependency of the natural frequency of bridges with temperature variation. In a two-year dynamic test on a reinforced concrete slab in a laboratory, Xia et al. [13] observed a decrease of 0.13 to 0.23% in bending modes of natural frequency per one degree Celsius increase in temperature. Balmes et al. [14] observed an increase of 16%, 8%, 5%, and 3% in first four natural frequencies of a clamped beam when ambient temperature decreased by 17 °C. Kim et al., [15] found a decrease of 0.64%, 0.33%, 0.44% and 0.22% in first four natural frequencies of a small-scale laboratory bridge model per °C increase in temperature.

2.4 Health Monitoring Technology

The majority of the bridge monitoring events to measure thermal response used contact sensors that require the physical deployment of hardware. The Yangtze River in Jiangsu, China was monitored with an SHM system of 170 sensors including accelerometers, Fibre Bragg grating (FBG) sensors to measure deck strain and temperature, displacement sensors, global positioning system (GPS) receivers, shear pins and ultrasonic anemometer, etc [2]. Shanghai Yangtze River Bridge was mounted with 227 sensors including FBG and GPS [4]. Liu and DeWolf [8] studied thermally induced changes in natural frequency of a concrete bridge in Connecticut, USA that was equipped with 12 temperature sensors, 16 accelerometers, and six tiltmeters.

These contact sensors provide accurate measurement collection. However, their advantages are limited due to cumbersome and expensive installations and requirements of a dense sensor network [16]. Vision-based monitoring is an emerging non-contact measurement collection technique using cameras and image processing algorithms. Vision-based monitoring exhibited promising results in measuring traffic-induced responses [17]; however, limited studies are available measuring temperature-induced response [18]. Feasibility of such vision-based sensors in measuring thermal response can be explored in future.

3. Conclusions

This paper has presented a literature review of temperature variation effects in bridge responses such as displacement, strain and natural frequency and methods of measuring such responses. It concludes that temperature variations could have a slow but very significant effect on the long-term response of bridges, and it should be taken into consideration when addressing the design and monitoring of bridges. Contact sensors are commonly used in previous researches while emerging vision-based monitoring system can be explored in future for thermal response measurement. Future work will include developing a vision-based thermal response measurement collection technique and validating through finite element analysis and laboratory experiments.

References

[1] G. J. O'Reilly *et al.*, "Once upon a Time in Italy: The Tale of the Morandi Bridge," *Struct. Eng. Int.*, vol. 0, no. 0, pp. 1–20, 2018.

[2] Q. Xia, L. Zhou, and J. Zhang, "Thermal performance analysis of a long-span suspension bridge with long-term monitoring data," *J. Civ. Struct. Heal. Monit.*, vol. 8, no. 4, pp. 543–553, Sep. 2018.

[3] R. Kromanis and P. Kripakaran, "Predicting thermal response of bridges using regression models derived from measurement histories," *Comput. Struct.*, vol. 136, pp. 64–77, 2014.

[4] Y. Zhou and L. Sun, "Insights into temperature effects on structural deformation of a cable-stayed bridge based on structural health monitoring," *Struct. Heal. Monit.*, vol. 18, no. 3, pp. 778–791, 2019.

[5] L. Lawson, K. L. Ryan, and I. G. Buckle, "Bridge Temperature Profiles Revisited: Thermal Analyses Based on Recent Meteorological Data from Nevada," *J. Bridg. Eng.*, vol. 25, no. 1, pp. 1–11, 2020.

[6] Y. Zhou and L. Sun, "A comprehensive study of the thermal response of a long-span cable-stayed bridge: From monitoring phenomena to underlying mechanisms," *Mech. Syst. Signal Process.*, vol. 124, pp. 330–348, 2019.

[7] P. Cornwell, C. R. Farrar, S. W. Doebling, and H. Sohn, "Environmental variability of modal properties," *Exp. Tech.*, vol. 23, no. 6, pp. 45–48, 1999.

[8] C. Liu and J. T. DeWolf, "Effect of temperature on modal variability for a curved concrete bridge," *J. Struct. Eng.*, vol. 133, no. 12, pp. 1742–1751, 2007.

[9] B. Peeters and G. De Roeck, "One-year monitoring of the Z24-bridge: Environmental effectsversus damage events," *Earthq. Eng. Struct. Dyn.*, vol. 30, pp. 149–171, 2001.

[10] H. F. Zhou, Y. Q. Ni, and J. M. Ko, "Constructing input to neural networks for modeling temperature-caused modal variability: Mean temperatures, effective temperatures, and principal components of temperatures," *Eng. Struct.*, vol. 32, no. 6, pp. 1747–1759, 2010.

[11] H. Li, S. Li, J. Ou, and H. Li, "Modal identification of bridges under varying environmental conditions: Temperature and wind effects," *Struct. Control Heal. Monit.*, vol. 17, pp. 495–512, 2010.

[12] P. Moser and B. Moaveni, "Environmental effects on the identified natural frequencies of the Dowling Hall Footbridge," *Mech. Syst. Signal Process.*, vol. 25, no. 7, pp. 2336–2357, 2011.

[13] Y. Xia, H. Hao, G. Zanardo, and A. Deeks, "Long term vibration monitoring of an RC slab: Temperature and humidity effect," *Eng. Struct.*, vol. 28, no. 3, pp. 441–452, 2006.

[14] E. Balmes, M. Corus, and D. Siegert, "Modeling thermal effects on bridge dynamic responses," in *In: Proceedings of the 24th International Modal Analysis Conference (IMAC-XXIV)*, 2006.

[15] J. T. Kim, J. H. Park, and B. J. Lee, "Vibration-based damage monitoring in model plate-girder bridges under uncertain temperature conditions," *Eng. Struct.*, vol. 29, no. 7, pp. 1354–1365, 2007.

[16] D. Feng and M. Q. Feng, "Computer vision for SHM of civil infrastructure: From dynamic response measurement to damage detection – A review," *Eng. Struct.*, vol. 156, no. May 2017, pp. 105–117, 2018.

[17] Y. Xu and J. M. W. Brownjohn, "Review of machine-vision based methodologies for displacement measurement in civil structures," *J. Civ. Struct. Heal. Monit.*, vol. 8, no. 1, pp. 91–110, 2018.

[18] R. Kromanis, Y. Xu, D. Lydon, J. Martinez del Rincon, and A. Al-Habaibeh, "Measuring structural deformations in the laboratory environment using smartphones," *Front. Built Environ.*, vol. 5, no. April, 2019.