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Short-term monitoring of an in-service bridge to determine boundary conditions

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ABSTRACT: In Structure Health Monitoring (SHM), it is commonplace to model a structure to predict how it will behave. However, creating realistic models can be a challenging endeavour due to the information required about the structure. Support conditions are one of the most important structural properties affecting a model. Even if construction drawings are available, these boundary conditions can be hard to identify as the supporting properties can change over time with the deterioration of the bearing structures. This study presents a short-term monitoring regime to monitor the bearing movement of an in-service bridge to determine the boundary conditions of the bridge. The SHM system consists of optical displacement and temperature sensors with remote logging capabilities. The data shows how the fixed and movable bearings respond to changing temperatures and the differences between the north and south side of the bridge. The work undertaken in this study gives a method for a short-term monitoring scheme that can reduce the uncertainty in the structural modelling process.

1. INTRODUCTION

In civil engineering, the modelling of structures is a common occurrence. One of the major hurdles in this process is the realistic modelling of support conditions as the idealistic properties that are used when designing a structure do not always translate to reality. This paper presents a study designed to measure the supports of a structure and use the results to reduce the uncertainty in the modelling process.

The long-term goal of this study is to provide a blueprint for a monitoring campaign that can be used to aid in structural modelling and more specifically to more accurately model support conditions. This goal will be achieved by way of a case study in which the properties of the supports for an in-service bridge are measured and analysed.

The monitoring campaign presented in this paper spans a relatively short 4-month period. The information that was gathered can be used to create a structural model for the bridge such as a Finite Element (FE) model. This model will hopefully be more accurate to the realities of the bridge and so can be used in future bridge works such as designing other SHM systems or validating observations made regarding the bridge.

The use of representing structures as numerical models is nothing new and is used on a daily basis throughout civil/structural engineering practices. Probably the most well know is the Finite Element (FE) model with Jagota et al., (2013) stating that thousands of papers and hundreds of conferences have been dedicated to the subject. However, many methods can be used for the modelling of a structure such as regressions and statistical techniques.

With all of these methods, there is an associated amount of uncertainty. In the case of FE modelling, there are two main sources of uncertainty one from measurement noise and the other from modelling errors (Astroza and Alessandri 2019). Astroza & Alessandri, (2019) also claim that it is the latter that represents the main source of uncertainty in FE models. These modelling errors can take many forms from inaccurate reference material such as drawings or estimations of material properties. One of the most notoriously difficult aspects of an FE model is to accurately represent is the support conditions of the structure. The properties of the support condition can have a considerable impact on the model. Song et al., (2002) showed how taking into consideration the degradation of the support conditions can significantly impact the load carrying capacity of the model. Hester et al., (2019) found that the support conditions of the bridge were not behaving as designed and that to match their observation this real-life behaviour of the supports needed to be taken into consideration.

As modelling errors are not a new problem there have been many studies with the aim to reduce the uncertainties. Papadimitriou et al., (2018) used a Bayesian framework to input information into a structural model, using this method the uncertainties are accounted for and can be used to select the best model. Astroza et al., (2015) used a nonlinear stochastic filtering technique to estimate the properties of the model that are unknown.

Both of the above methods try and incorporate the uncertainty into the model. In this paper a method is presented that can be used to reduce the uncertainty in the structural modelling process by utilizing a short-term monitoring campaign.

2. SHORT-TERM MONITORING CAMPAIGN

This section gives an overview of the short-term monitoring campaign. The campaign is broken down into 2 phases. The first was to verify that the east end of the bridge was the location of the roller bearing. The second phase was to determine the behaviour of the roller bearing under normal loading conditions.

2.1. Bridge used in the study

The bridge that was monitored in this study is a steel tied-arch bridge that spans 98 m and is 27.7 m wide. Figure 1 shows an elevation of the bridge. Each of the main arches supports 22 tie rod hangers with a diameter of 90 mm. These hangers support the main deck structure. The main longitudinal beams are a mix between welded plate girders (in the centre) and box sections (at the springings) with a depth of approximately 1650 mm. The 275 mm deep concrete deck acts compositely with the transverse crossbeams which are supported by the main longitudinal beams. The steel bridge structure is supported on two concrete abutments that are in turn supported by reinforced concrete driven piles.

Figure 1: Steel tied-arch bridge used in study

2.2. Experimental setup

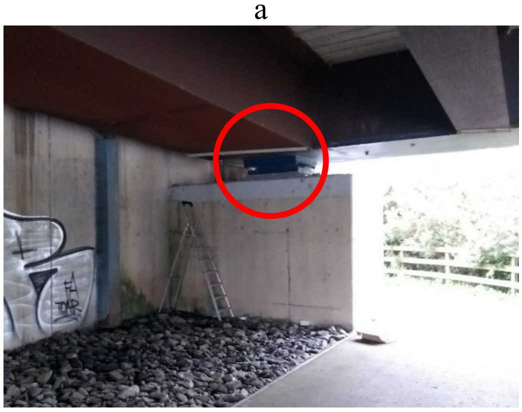
The sensor used to measure both the bearing movement and tilt of the beam was the Optical Displacement Sensor (ODS) Node from Senceive (Figure 2). The ODS node consists of an optical laser that can detect high-precision displacement measurements, and a triaxial tilt sensor. The dimensions of the ODS node are 90 x 90 x 60 mm, and it is powered by an integrated long-life battery. The optical sensor has a resolution of 0.1 mm and repeatability of ± 0.15 mm. The triaxial tilt sensor resolution of 0.0001° (0.0018mm/m) and repeatability of ±0.0005° (±0.009 mm/m). The ODS node also has an integrated temperature sensor.

Figure 2: Optical Displacement and Tilt Sensor Node

The measurements taken by the two ODS nodes are sent via Senceive Proprietary FlatMesh network to a gateway located on the west side of the bridge. The gateway is a 3G enabled unit (218 x 68 x 126 mm. After the gateway has acquired the data from the ODS sensors, it sends it to a server where the data can be remotely downloaded. The gateway has an internal battery that is charged via a solar panel.

The sensors were installed on the underside of the primary beam close to the end of the beam and measured the distance between the sensor and the bridge abutment. Figure 3(a) shows the bearing at the east end of the south girder with the location of the ODS indicated with a red circle. A zoomed-in view of the ODS is shown in Figure 3(b). During phase 1 of the campaign, the sensors were installed on both ends of the southern primary beam. During phase 2 of the campaign, both sensors were installed on the eastern side of the bridge on the north and south primary beams.

a



b

Figure 3: SHM equipment installation (a) location of ODS Node (b) close up of installed ODS Node

3. ANALYSIS OF COLLECTED DATA

3.1. Phase 1

The results of this initial trial can be seen in Figure 4. The red and blue plots show the movement of the east and west bearings, respectively. The range of longitudinal movement of the bearings is 1 mm for the west bearing and 14 mm for the east bearing. This result confirms that the roller bearings allowing longitudinal movement of the deck are located on the bridge's east side. After this confirmation trial was complete, the ODS node from the west end of the bridge was moved to its phase 2 location on the east end of the north girder.

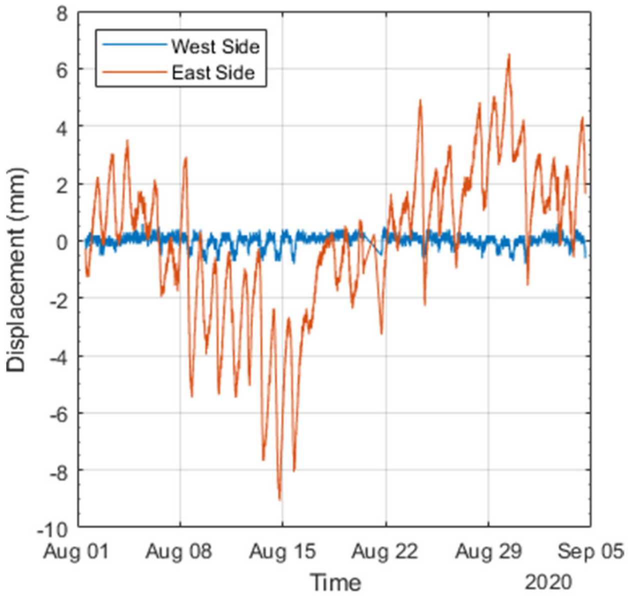


Figure 4: Displacement of the bearings during phase 1

3.2. Phase 2: Bearing movement data

Bearing movement data was collected from the two bearings located on the bridge's east side, with a displacement reading being taken every 10 minutes. Figure 5 shows the bearing movement over a period of 2 months, with the blue line representing the northeastern bearing and the red line representing the southeastern bearing. The temperature measurements are also shown in the figure by the green dashed line. The range of bearing movement over this monitoring period is 14.1 mm and, from the figure, it can be observed that the movement is approximately inversely proportional to the temperature. The northern and southern bearing move in tandem for the majority of the time, with the average difference between them being only 0.5 mm. However, on a limited number of occasions, the bearings' displacement diverges, with the northern bearing showing a higher level of movement. One of these periods occurs in January and is highlighted in the red box in Figure 5(a). A zoomed-in view is shown in Figure 5(b). The cause of this divergence is not known, but one possible explanation is a sticking behaviour at the bearing, similar to that observed in Hester et al. (2019) where there is a friction force that means the bearing exhibits a stick/slip behaviour.

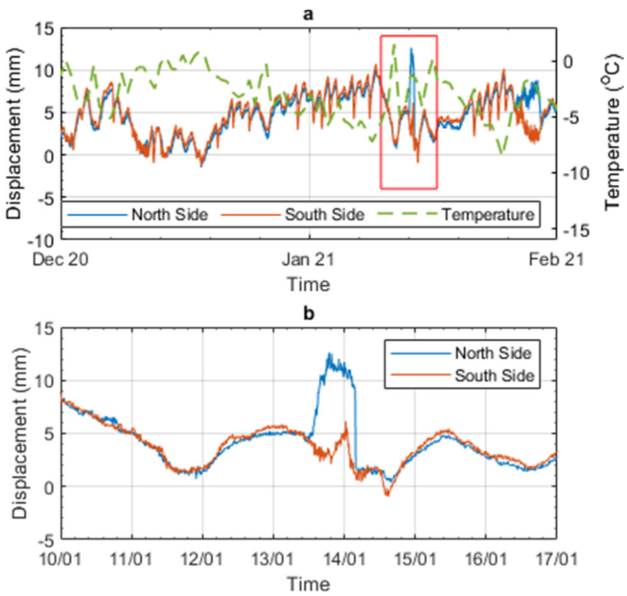


Figure 5: Displacement of the two eastern bearings (a) whole monitoring period (b) 7 day period

To ensure that the magnitude of the bearing movement is credible, equation (1) was used to calculate the expected expansion of the bridge.

$$\Delta L = a \times L \times \Delta T \qquad (1)$$

Where ΔL is the variation in bridge length, a is the linear expansion coefficient of steel (12e-6/°C), L is the bridge's original length (98.8 m) and ΔT is the temperature change.

From the temperature data, the temperature range is 11°C which means ΔL can be calculated as 13.04 mm. The range of the bearing movement measured using the ODS nodes was 14.1 mm. This 14.1 mm of measured movement is comparable to the calculated movement of 13.04 mm, which suggests the measurements are accurate/credible.

3.3. Phase 2: Tilt data

The ODS nodes contain a triaxial tilt sensor and, due to their placement on the lower flange of the primary beam, they measure the tilt of the beam. Tilt around the y axis represents the major-axis bending of the beam and tilt around the x axis represents the torsional moment of the beams. As the sensor uses the force of gravity as a reference, the rotation around the vertical axis (z) cannot be measured. This measurement convention is shown in a schematic in Figure 6 for both the major bending and the torsion.

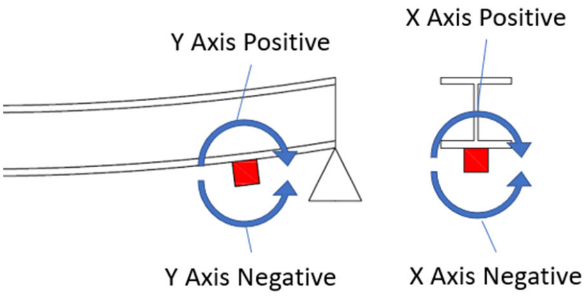


Figure 6: Schematic diagram showing tilt measurements convention

Figure 7 shows the tilt data for both the x and y axis, with the blue line representing the northeastern bearing and the red line representing the southeastern bearing. Figure 7(a) shows the tilt around x axis over the entire monitoring period. The magnitudes of the rotations are very small, with the rotation caused by the torsional moment (x axis) ranging from approximately -0.0049° to 0.0042°. Figure 7(a) shows that the rotation caused by the torsional moment has an inverse correlation between the two primary beams. This inverse correlation can be clearly seen in Figure 7(c), which shows the tilt data over the period of 2 days. In Figure 7(c) the temperature is shown by the green dashed line; it can be seen that the south sensor is correlated with the temperature readings and the north sensor is inversely correlated with temperature. What this means in practice is that when the temperature increases, both bottom flanges move outward.

The rotation caused by the major-axis bending of the primary beams (y axis) can be seen in Figure 7(b). The magnitude of the rotation ranges from approximately -0.0211° to 0.0349°. In contrast to the torsional rotation, the major-axis bending rotation is correlated between the two primary beams. This can clearly be seen in Figure 7(d), which shows the tilt data over the period of 2 days. Like before, the temperature is shown in Figure 7(d) by the green dashed line. Both the north and south tilt measurements are correlated with the temperature measurement. When the temperature increases, the beams are rotating in the positive y direction shown in Figure 6.

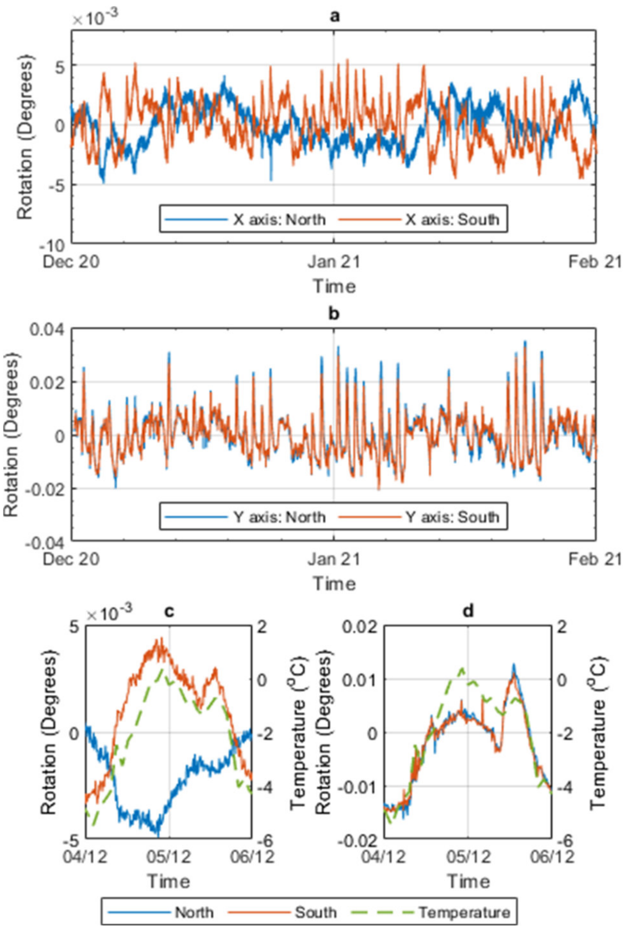


Figure 7: Rotation measurements (a) x axis rotation over the whole monitoring period (b) y axis rotation and temperature over a 3-day period (c) x axis rotation over the whole monitoring period (d) y axis rotation and temperature over a 3-day period

The tilt data served to ensure the bearing displacement was not significantly affected by the rotation of the beams. Bearing displacement readings are taken relative to the abutment wall; any rotation of the beam will change the angle of the measurement, which will increase the horizontal distance measured. The increase in distance does not represent any true movement in the longitudinal direction and should not be considered in the bearing movement measurement. However, the average bending tilt of the beam is only 0.0061° and because the cosine of such a small angle can be approximated as 1, the error in the measurement will be negligible.

4. ANALYSIS OF BOUNDARY CONDITIONS

To give context to this section, this study was used to inform two further pieces of work. The first was to produce a finite element (FE) model of the bridge and the second was to improve a data model that had been developed to predict the natural frequency of the bridge based on various environmental measurements.

For the FE model of this bridge and FE models in general one of the most challenging aspects is modelling the boundary conditions accurately. The data that was collected during this monitoring campaign allowed the following information to be gained regarding the boundary conditions of the bridge:

- The location of the roller bearings. This was in doubt as no drawings of the bridge were available, and due to the construction of the bridge, a visual inspection was inconclusive.
- The behaviour of the roller bearings was not consistent. Although for most of the time the bearing moved relative to the temperature conditions there were times when one bearing would freeze/stick compared to the other. This had the effect of essentially becoming a pin joint for that time period.

5. CONCLUSIONS

The aim of this paper was to outline a procedure to reduce the uncertainty in support conditions in the structural modelling process by utilizing a short-term monitoring campaign.

Analysing the data from the SHM system allowed information to be gained about the construction of the structure namely the location of the roller bearings. The location of the bearings could have been identified with a few days of data, however, because the system was left on for a longer period more operational information was acquired.

The sticking behaviour of the bearings could be used to fine-tune a structural modal, it gives the modeller real-life bearing movements that can be used to update a model while constructing the updated parameters to a range of real-life values.

Overall this case study presented an easy to deploy SHM system that can very quickly provide data that can reduce the uncertainty in structural models.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Astroza, R., and A. Alessandri. 2019. "Effects of model uncertainty in nonlinear structural finite element model updating by numerical simulation of building structures." *Struct Control Health Monit*, 26 (3): e2297. https://doi.org/10.1002/stc.2297.

Astroza, R., H. Ebrahimian, and J. P. Conte. 2015. "Material Parameter Identification in Distributed Plasticity FE Models of Frame-Type Structures Using Nonlinear Stochastic

Filtering." *J Eng Mech*, 141 (5). https://doi.org/10.1061/(ASCE)EM.1943-7889.0000851.

Hester, D., K. Koo, Y. Xu, J. Brownjohn, and M. Bocian. 2019. "Boundary condition focused finite element model updating for bridges." *Eng Struct*, 198 (September 2018): 109514. Elsevier. https://doi.org/10.1016/j.engstruct.2019.109514.

Jagota, V., A. P. S. Sethi, and K. Kumar. 2013. "Finite Element Method: An Overview." *Walailak Journal of Science and Technology (WJST)*, 10 (1): 1–8.

Papadimitriou, C., C. Argyris, and P. Panetsos. 2018. "Information-Driven Modeling of Structures Using a Bayesian Framework." 38–61.

Song, H.-W., D.-W. You, K.-J. Byun, and K. Maekawa. 2002. "Finite element failure analysis of reinforced concrete T-girder bridges." *Eng Struct*, 24 (2): 151–162. https://doi.org/10.1016/S0141-0296(01)00107-9.