DOI: 10.3217/978-3-99161-057-1-114

Structural monitoring of Zeeland Bridge - improved structural identification by combining a modular model updating framework with a mobile measurement setup during load tests

F. Besseling[1,2, 0000−0003−4352−4536], C. Kortendijk[2], J. de Bruijn[2], E. Lourens[1, 0000−0002−7961−3672]
[1]Delft University of Technology, Stevinweg 1, Delft, The Netherlands
[2]Witteveen+Bos Consulting Engineers, Leeuwenbrug 8, Deventer, The Netherlands
email: f.besseling@tudelft.nl, coen.kortendijk@witteveenbos.com, janno.de.bruijn@witteveenbos.com, e.lourens@tudelft.nl

ABSTRACT: To reduce uncertainties associated with its structural re-assessment, the Zeeland Bridge in the Netherlands is currently the subject of a field lab, which will run for 2 years. In this contribution, the structural identification approach, the model updating concept and the first measurement campaign are presented, followed by some preliminary measurement results. The present stage focusses on load testing of the bridge to obtain insight into the possibly varying response in different spans of the bridge. Previously, parametric studies to expose input-output parameter dependencies were performed on a representative sub-system of the bridge, and the results are used to assist in the design of a measurement campaign and the development of a robust model updating strategy for the bridge. The results of the first measurements allow for evaluation of the actual performance of the bridge when subjected to heavy truck loads. This information will be used as a basis for further development of the updating approach.

KEY WORDS: Bridge monitoring; Structural identification; Concrete bridges.

1 INTRODUCTION

Bridges are vital infrastructure objects, with their availability critical for the operation of infrastructure networks. Many Western European bridges were built in the decades post WW-II, and therefore approach the end of their design lifetime. Depending on the function of a bridge and its location, loads may have substantially increased over the operational period due to increased traffic. Moreover, various time-dependent degradation processes may start to affect the state of a structure and therewith its safety. Examples of prestress loss related effects for prestressed concrete bridges are given in [1] and [2]. This necessitates structural reassessments of existing bridges in order to evaluate their structural reliability and remaining lifetime.

The models used for structural reassessments are developed based on design information, inspection results, and in some cases monitoring data. A key challenge in developing models for structural reassessments is uncertainty quantification. Bayesian techniques can be used to this end, combining data and expert knowledge to best estimate the actual state of a structure [7]-[10]. Where models are typically developed to predict the `normal' structural response in the governing load scenarios, their results may not represent reality in cases where local deviations of structural response occur. Examples include bridges where the level of damage in for instance orthrotropic steel decks varies significantly across spans, cable-stayed bridges suffering from damage concentrations in the deck structures at the location of specific cables, or concrete bridges showing regions with increased prestress losses. Response effects take place in such bridges, that seemingly result in load concentrations with locally increased damage potentials as a result. In such cases, tailored measurement campaigns might be needed to better understand the actual structural behavior.

In this contribution, the measurement strategy for the Zeeland bridge and a selection from the first measurement results are presented, followed by an outlook towards upcoming future measurements.

2 ZEELAND BRIDGE

The Zeeland bridge is a 5 km multi-span cantilever balanced prestressed concrete bridge, forming an important connection between the islands of Noord-Beveland and Schouwen-Duiveland in the Province of Zeeland in the Netherlands.

Figure 1. The Zeeland bridge in the local road network

The construction of the bridge was completed in 1964. The bridge spans are 95 m each, with a dowel connection at midspan connecting the two cantilever parts. Fig. 1 shows a picture of the bridge, with red ellipses indicating the locations of the dowel joints, the cantilevers, and

CC BY 4.0
https://creativecommons.org/licenses/by/4.0/deed.en
This CC license does not apply to third party material and content noted otherwise

DOI: 10.3217/978-3-99161-057-1-114

the foundations. These locations are related to the main sources of uncertainty in the bridge's load-response behavior, namely the forces transferred at the midspan joints (Fig. 2), shear stress levels in the cantilever, and foundation support stiffnesses.

Figure 2. The Zeeland bridge, showing the locations of main uncertainties.

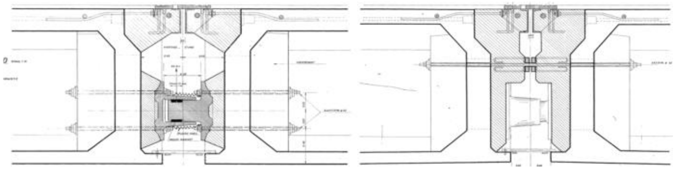

Figure 3. Longitudinal cross section of the Zeeland bridge sliding (left) and fixed (right) mid span joints.

In essence, the outcome of a structural reassessment is determined by both structural resistance and internal forces. For specifically balanced cantilever prestress concrete bridges, prestress loss and concrete time-dependent effects (e.g. creep) may occur, resulting in ongoing deformations with a potential effect on resistance as well as on internal force distributions. The potential development of extreme load concentrations in cantilevers depend on the relative stiffness of the cantilevers and midspan joints, and foundation support stiffnesses. Prestress loss in these type of bridges materializes as deformations increasing over time and reductions in shear capacity. According to Borges [1], the level of ongoing deformations can vary substantially per bridge, and is a function of concrete properties, the construction process, and environmental effects. For the Zeeland bridge specifically, potential long-term differential behavior between cantilevers in combination with additional deformations in the foundation or subsoil may contribute to internal loads in the cantilevers as well. Visual inspection of the mid-span joints of the bridge revealed signs of ongoing deformation and permanent load transfer between cantilevers. On the resistance side, the reduction of shear capacity due to time-dependent effects has been estimated in the range 1-5% [1]. Internal force variations due to variable loads, however, can reach levels up to 20%. Adding to these variations the additional internal loads due to possible long-term differential behavior between cantilevers and additional deformation in the foundation or subsoil, it can be concluded that for the Zeeland bridge the uncertainty associated with extreme internal loads is larger than the uncertainty associated with the loss of resistance. As such, we first focus on the identification of the actual load-deformation behavior of the bridge. Estimation of the actual degree of prestress loss per span will not be possible based on measured deformations under operational loads [2]. For specific spans of concern, localized destructive or non-destructive measurements may at a later stage be considered to further investigate the actual degree of prestress loss.

3 MODEL UPDATING FRAMEWORK

In our project we intend to develop a Bayesian Network (BN) based model updating strategy. The BN forms the statistical model covering the dependency structures between model parameters of interest and measurable response quantities. The BN will be developed based on both finite element simulation results and measurement data. Finite element simulation results are used as a basis for parameter dependency evaluation of structural properties (parameters) and load-response characteristics (measurands), for which one is referred to [3]. Measurement data is used to check and optimize the BN structure.

Challenges and limitations that are associated with increasing numbers of model updating parameters in Bayesian inference are known as the curse of dimensionality [4]. In order to deal with this we follow the concept presented in [6], by defining a sub-system as a basis for our structural identification problem. This approach allows us to limit the number of parameters in the identification problem and focus on local measurements for the updating of local sub-system models. The sub-system includes one full span, existing of two connected cantilevers and their two supports, and the balancing cantilevers of this span. The sub-system, including parameters of interest and possible measurement variables, is shown in Fig. 3. The sub-system parameters are the concrete effective stiffness in bending ($E_{c,i}$), the mid-span joint vertical stiffness ($k_{d,23}$), and the support rotational stiffnesses ($k_{s,ij}$). The sub-system boundaries are set at the mid-span joints of the two outer cantilevers, and the load transfer at these locations is accounted for using a vertical model boundary spring ($k_{bc,ij}$). The total sub-system length is 190 m. In Fig. 3, the system parameters are shown in (a), and the possible measurement quantities in (b).

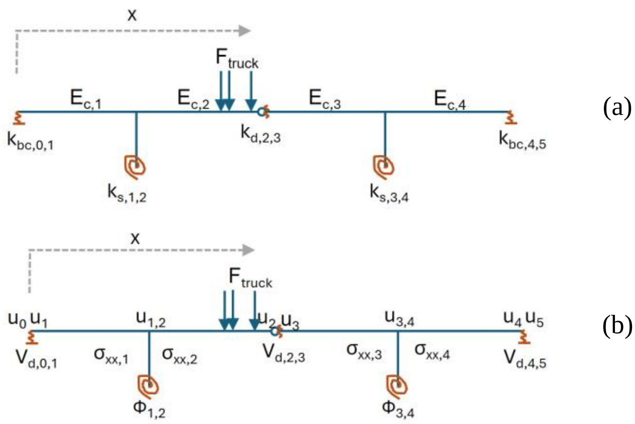

Figure 4. Sub-system schematization

The data used for model updating of the sub-systems is load-response measurement data from load tests on the bridge. Displacement response of the bridge is measured in various ways, from which displacement influence lines are constructed. The combined information of the known load, known load

CC BY 4.0
https://creativecommons.org/licenses/by/4.0/deed.en
This CC license does not apply to third party material and content noted otherwise

 DOI: 10.3217/978-3-99161-057-1-114

position and measured response quantities serves as input for the updating problem, and overcomes typical issues associated with operational variability.

4 MEASUREMENT CAMPAIGN

As a first test to identify the structural behavior of the bridge, a load test with two 50 tonnes 6-axle trucks and a mobile measurement setup is performed. The objective of this test is to obtain insight in the possibly varying response in different spans of the bridge. The measurement setup during the load test consists of measurements of the displacements at midspan relative to the supports, and the relative displacements of both cantilever ends at mid-span.

Absolute displacements are measured during the load test using Koherent's radio- based displacement measurement technology [12] and laser displacement measurements using GeoLaser L72 systems [13], verified by tachymeter measurements at some of the test locations. The results of the Koherent measurements are not yet included in this paper, because of time limitations and challenges associated with cleaning this data from radio wave reflections caused by the test vehicles.

Midspan joint relative displacements are measured by custom built joint displacement measurement devices (Figure 6). These systems provide high precision relative displacement monitoring of the joints, aiming to identify the load position where the direction of force transfer in the joints reverses. This is an indicator of permanent load transfer across a joint.

Figure 5. Laser receiver at midspan joint location

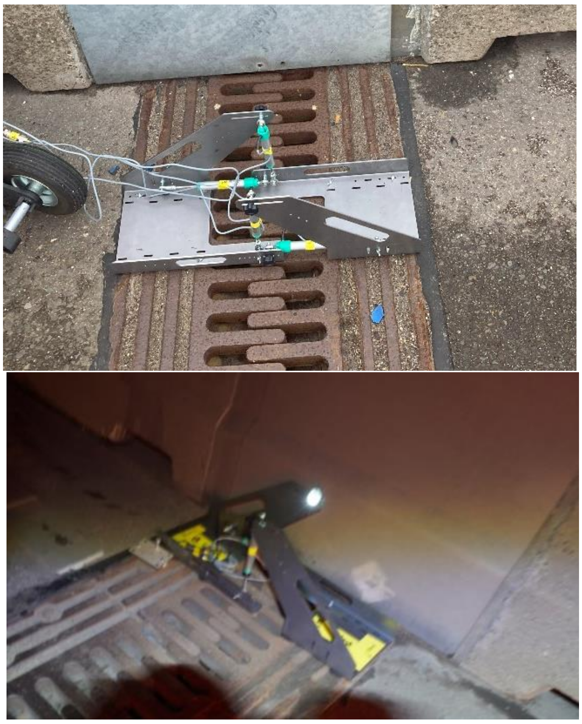

Figure 6. Midspan joint custom displacement sensor

The monitoring systems are applied in a mobile setup during the first phase load-test campaign, repositioning the systems repetitively across multiple spans of the bridge during a bridge closure by night (Figure 7).

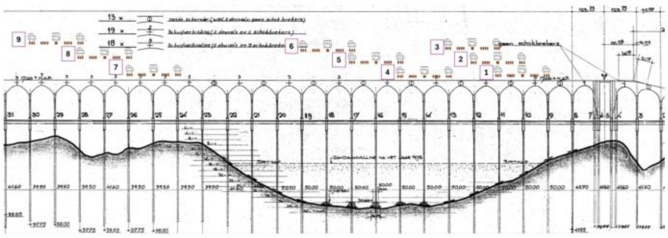

Figure 7. Multiple measurement locations in mobile load test setup

The load test is conducted by driving 1 and 2 trucks over a distance of 4 span lengths over the bridge at a speed of approximately 5 km/h. The setup with a load by both 1 and 2 trucks allows to evaluate the load level effect on the response. The 2 middle spans are equipped with the monitoring systems. By this means we generate influence lines of displacement response parameters for 2 spans.. This concept is illustrated by Figure 8. During 1 night a dataset consisting of load-response data for loads applied to 14 spans was obtained.

CC BY 4.0
https://creativecommons.org/licenses/by/4.0/deed.en
This CC license does not apply to third party material and content noted otherwise

DOI: 10.3217/978-3-99161-057-1-114

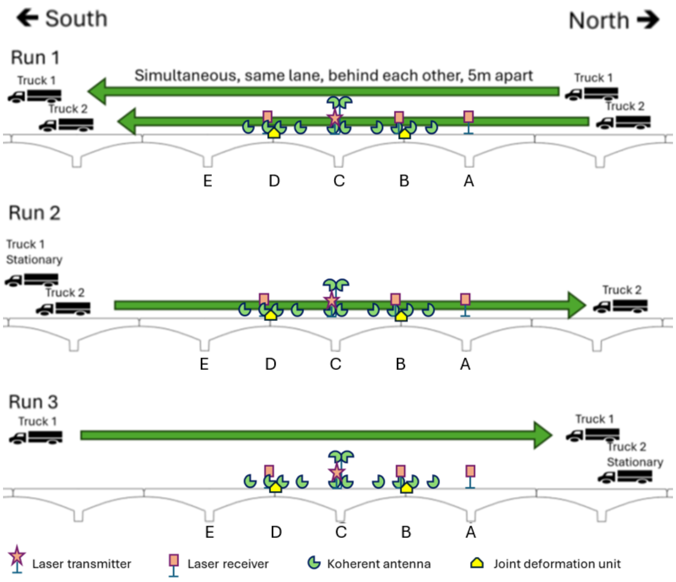

Figure 8. Mobile load test setup

5 PRELIMINARY MEASUREMENT RESULTS

5.1 Generation of response influence lines from measurement systems and GPS logging

The test trucks are equipped with the Witteveen+Bos GeoSaFence RTK-GPS tracking system. The GPS antennas are mounted on the outside top of the truck cabin, approximately above the first axle. Raw GPS measurement data comprises date and time and the location of the truck antenna in geographic coordinates (latitude and longitude in degrees). The positioning data are converted to geographic coordinates, and a coordinate transformation is applied to align the X-coordinate with the bridge's axis. Missing samples are filled by interpolation and the Rauch-Tung-Striebal Kalman Filter is applied to smoothen the positions and remove spurious jumps in the positions which occur during some of the runs. The result maps the bridge responses measured as function of time to the associated truck position on the bridge.

5.2 Laser based displacement influence lines

Laser measurements are performed to track the total displacements of the midspan joint relative to the adjacent pier at which the laser transmitter was positioned (see Figure 6). Figure 9 illustrates the laser measurement results for a single test run. The total displacement at midspan corresponded well with the model predictions. Displacements at the sliding joints are 10 to 30 % larger than the displacements at the fixed joints (Figure 3). Two trucks in convoy caused 10 to 20 % larger displacements than a single truck passage. It is interesting to note that displacements did not diminish to zero for trucks moving outside the test area: behavior was observed where the bridge deformations at some point do not seem to change with the truck position anymore, but rather some form of residual deformation remains. Possibly the trucks are not completely out of the zone where they influence the measurements, or time-dependent effects may be associated with the dampers present in some midspan joints or effects in the soil-structure interaction response of the piers. All such effects may contribute to the observed behavior where displacements at the end of a test run did not return to zero.

Laser receiver E, positioned 1 full span away from the transmitter, was meant as a reference receiver, allowing for correction of measured displacements for support rotations. Rotation of the pier where the laser transmitter is positioned is observed from this receiver. In Figure 9 the blue curve represents the reference receiver positioned at pier 17. A vertical displacement of +/- 1 mm are recorded by this receiver, for the truck moving backwards from pier 18 to pier 14. The data shows how the total midspan displacement consists of a bending component of the cantilever beam and a vertical displacement component associated with pier 'support' rotation, the latter being one order of magnitude smaller. The fact that the vertical displacement influence line for this reference receiver extends over a distance of 4 spans implies that the recorded vertical displacement in fact represents a rotation of the support where the laser transmitter is placed for this stage, and not an actual vertical deformation of the support where this receiver is positioned.

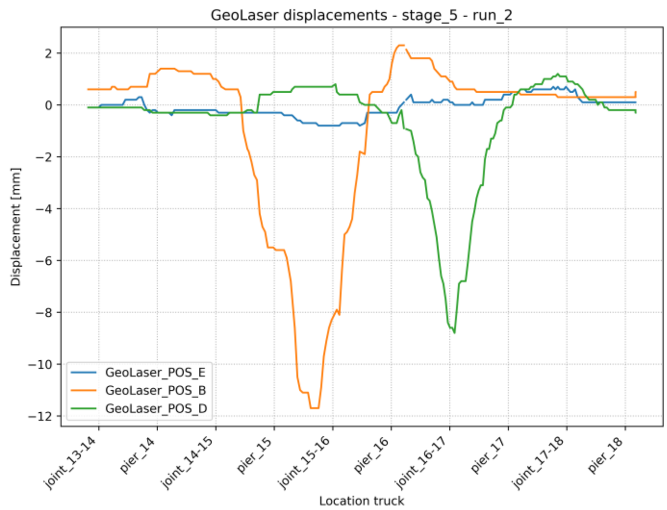

Figure 9. Total vertical displacements of midspan joints 15-16 and 16-17, and reference pier 17, measured by GeoLaser with transmitter positioned at pier 16

Evaluating the performance of the GeoLaser system, we conclude that the technology did perform quite well. The lasers' distance range was specified to be 100 m maximum. The 50 m measurements at the nearest midspan joints did generally perform well. The laser transmitter and receivers' glass screens however suffered from foggy circumstances during some measurement stages and runs, causing the reference receiver measurement to not be successful. For the adverse foggy conditions encountered during the test night the 100 m is concluded to be very much at the limit.

CC BY 4.0
https://creativecommons.org/licenses/by/4.0/deed.en
This CC license does not apply to third party material and content noted otherwise

DOI: 10.3217/978-3-99161-057-1-114

5.3 Joint deformation influence lines

The sliding and fixed joints depicted in Figure 2 are used in the Zeeland bridge in different configurations.. Going from North to South for pier 8 to 23 there are alternating sliding and fixed joints. This implies that this part of the bridge consists of sets of 2 coupled piers with balanced cantilevers forming a frame, having in the center a fixed dowel connection, and connected to the next part at the midspans of the outer cantilevers by sliding dowel connections. From pier 23 to 33 the pattern is different and all midspan joints are sliding joints. Figure 10 and Figure 11 show the joint relative displacements for joints 11-12 and 12-13 and for joints 15-16 and 16-17. Joints 11-12 and 15-16 are both sliding joints and 12-13 and 16-17 are fixed joints. In these figures the joint relative displacements at measurement location B and D (Figure 8), on both the East and West side of the bridge are presented.

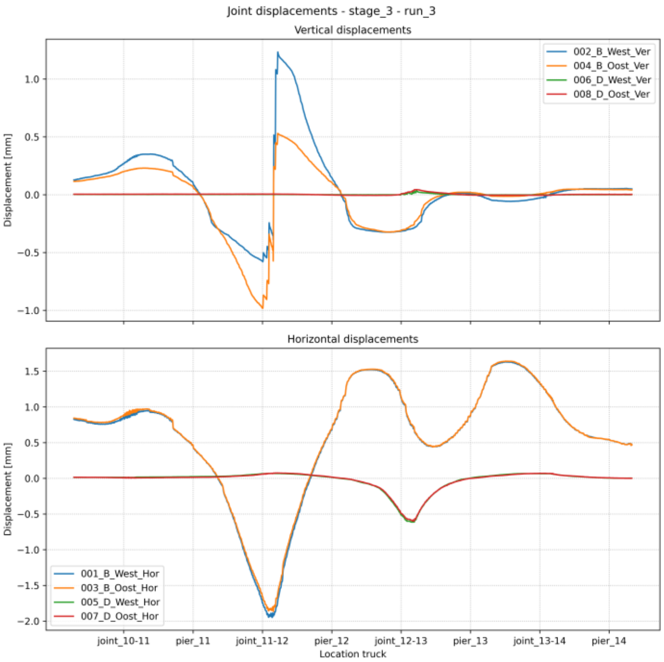

Figure 10. Joint displacements of joint 11-12 and joint 12-13

The different joint configuration affects both the total vertical displacements measured by the laser receivers and the joint relative displacements. Clearly, very different vertical relative displacement response is observed. Where in the first figure a more gradual increase of vertical joint displacements is recorded, the second figure shows more abrupt displacements when the truck is approaching and when the axles are passing the sliding joint. Also it is clear that the joint relative displacement sensors at joint 15-16 (B_West and B_East) do already record substantial negative vertical displacement when the test truck is still at joint 16-17, i.e. one span away from the sliding joint. This behavior deviates from the typical behavior observed at all the other measured spans (e.g. Figure 10). Apparently some displacement allowance is present in this joint which is mobilized by the test truck when it is on the center of the next span. Further research is ongoing to explain the locally deviating behavior around piers 14 to 16.

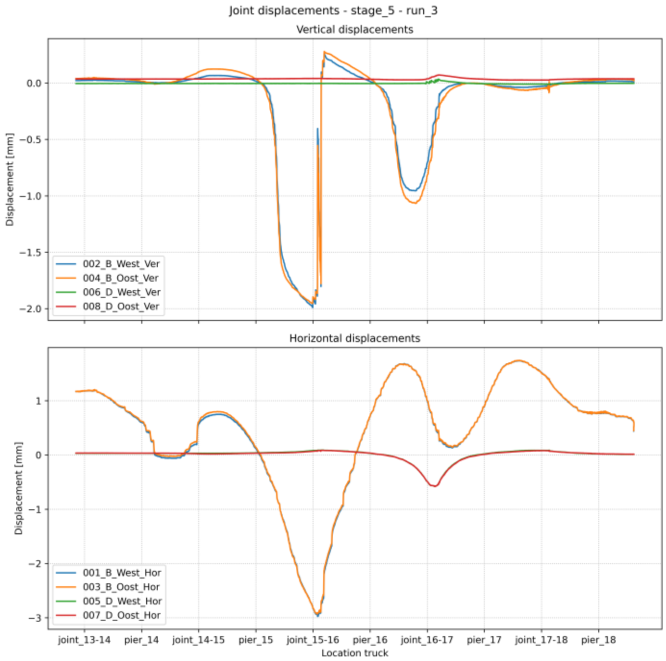

Figure 11. Joint displacements of joint 15-16 and joint 16-17

It is interesting to note that, as observed for the total displacements measured by the laser, residual displacements are present in the joints at the end of test runs. A certain degree of 'memory' seems to be present in the bridge system when it is subjected to heavy truck loads. It could not be established from the data which physical mechanisms causes this typical behavior. This will be further investigated in the upcoming phase.

From the figures is can also be observed that the fixed joint, where the two cantilevers are tied together with prestressed 32 mm steel bars, still show some vertical horizontal displacement allowance of approximately 0.5 mm. Vertical displacements for this joint configuration are limited to tens of millimeters. This is interesting because the same cast iron dowels are present at all joints, also the sliding joints where larger displacements are measured. This implies that the fixation point seems to take over the load transfer from the dowel at the fixed joints, which is an important insight from the perspective of load introduction in the concrete structure.

The part of the bridge with a joint configuration consisting of only sliding joints shows different behavior (Figure 12). The total vertical joint relative displacements are somewhat larger compared to the bridge part with alternating fixed-sliding joints. Horizontal joint relative displacements are much larger as well, up to 10 mm relative displacement amplitude, and shows, for both measured joints, a more or less symmetric response for the truck positioned at either side of the joint. The distance over which the joint relative displacement influence lines show substantial displacement is longer for the part of the bridge with only sliding joints. Especially the vertical joint displacement influence lines show comparable levels of relative joint displacement when the truck axles are passing the measured joint and when the truck is at midspan of adjacent spans.

CC BY 4.0
https://creativecommons.org/licenses/by/4.0/deed.en
This CC license does not apply to third party material and content noted otherwise

DOI: 10.3217/978-3-99161-057-1-114

The system of balanced cantilevers coupled by only sliding joints behaves much more like a continuous chain of rigid rotating elements. Relatively large horizontal compared to vertical displacements indicate the relevance of global rotation of the bridge superstructure and the need for modelling of the degrees of freedom at the supports. These need to be properly accounted for in models. The freestanding height of the foundation piles is around 15 m, which means that the characteristic of the substructure supporting the superstructure is determined by bending of foundation piles and soil-structure interaction of the bridge substructure and foundations. Both need to be integrated into lumped support springs in the model. The data of combined horizontal and vertical measured displacement allows to calibrate the model support characteristics.

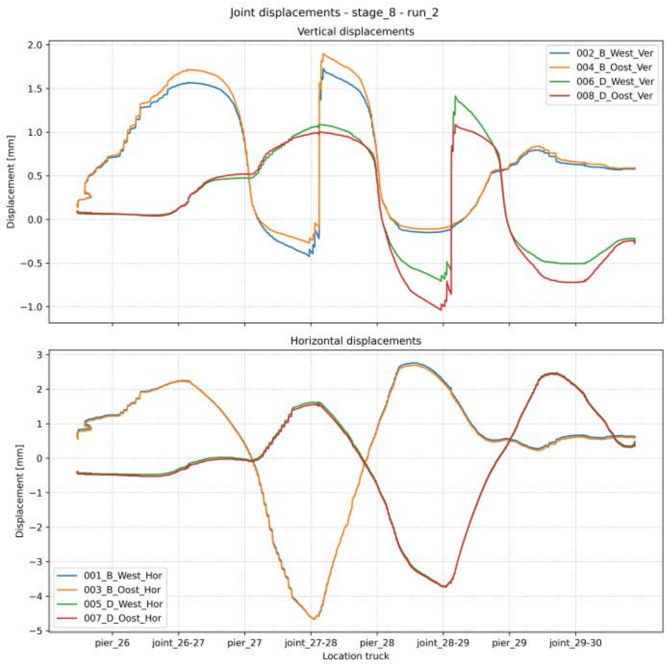

Figure 12. Joint displacements of joint 27-28 and joint 28-29

6 OUTLOOK TO UPCOMING MEASUREMENTS

The measurement results from the first tests have revealed interesting variations in the deformation response of certain cantilevers and spans, relative to others. These can be indicators for load concentrations in specific spans. In the next measurement campaign we will measure concrete stresses in the bridge indirectly by means of smart aggregates technology developed by TU Delft. These are installed in the box girder floor near 2 supports (locations indicated by $\sigma_{xx,I}$ in Figure 4), which is in the compression zone of the cantilever gross cross section. Moreover, the mobile displacement measurements with laser and the custom joint sensors will be repeated at more spans to obtain a larger dataset and obtain insight in the response of more spans.

7 DISCUSSION

Load-deformation response is investigated for the Zeeland bridge to form a basis for full structural identification of the bridge.This paper builds on the previous paper [3] that introduced the model updating strategy for bridge structural identification. In the previous paper parameter dependencies between structural properties (parameters) and load-response characteristics (measurands) were investigated. The first phase measurement results that are now available form a basis for model updating of the sub-system models. However, given the quite different behaviour observed for the different spans one could question whether the model updating parameters set beforehand suffice to cover this spread in the observed behaviour. The measurement data indicates different ‘states’ of the sub-systems in terms of their neutral state, affecting their load-response behaviour when loaded by heavy test vehicles. It needs to be evaluated further how dependencies between input and output variables can contribute to the identification of the root cause or underlying mechanism that causes different behaviour of the spans. This will be one of the main topics considered in the upcoming phase of the project. Additional parameters that represent such different states might need to be added to the problem. In the upcoming phase it will be investigated how and through which parameters we can best represent the actual state in the updating problem formulation.

8 CONCLUSIONS

The present paper introduced the Zeeland bridge field lab and research project as well as an initial measurement campaign and the obtained load testing results. Structural re-assessment of the bridge requires a reduction of the uncertainty associated with internal forces in the bridge structure The research project involves the development of a modular model updating approach for structural identification, based on load-response evaluation of sub-systems. Load-response influence lines constructed from measurement data are collected during the load tests with a mobile measurement setup . The developed mobile measurement setup performed well for the purpose of structural identification of the load-response behaviour. The total vertical displacements measured with lasers and the joint relative displacements measured with custom joint deformation monitoring systems were successful. It is concluded from the first phase measurement results that different spans exhibit different load-response behaviour. Differences in observed behavior can partially be assigned to different joint configurations across the bridge, but could possibly also be associated with a different ‘neutral’ state of the spans of this 5 km long multi-span bridge. In the upcoming phase of the project, this will be further investigated from both a theoretical (finite element model based) and experimental perspective (additional, more expensive measurements).

CC BY 4.0
https://creativecommons.org/licenses/by/4.0/deed.en
This CC license does not apply to third party material and content noted otherwise

DOI: 10.3217/978-3-99161-057-1-114

ACKNOWLEDGEMENTS

The authors acknowledge the Dutch Ministry of Water and Infrastructure and the Dutch Provinces for their support to the ongoing research project on improvement of model updating strategies for structural reassessment. Especially we would like to acknowledge the Province of Zeeland for their contribution to this research for the Zeeland bridge and the commitment of their team when performing the first phase measurement campaigns.

REFERENCES

[1] Andrade Borges, E.A.: Long term effects of creep and shrinkage on the structural behaviour of balanced cantilever prestressed concrete bridges. (2023)
[2] Chavez, A.A. and Gonzalez-Libreros, J. and Wang, C. and Capacci, L. and Biondini, F. and Elfgren, L. and Sas, G. : Assessment of residual prestress in existing concrete bridges: The Kalix bridge (2024)
[3] Besseling, F., Lourens, E., Structural monitoring of the Zeeland Bridge for improved load - response evaluation and structural lifetime estimation, Proc. EVACES 2025, (2025)
[4] Dashti M, Stuart AM. The Bayesian approach to inverse problems. In: Handbook of uncertainty quantification. Cham: Springer International Publishing; 2017, p. 311–428, [Chapter 10].
[5] Zhou Y, Lu Z, Hu J, Hu Y. Surrogate modeling of high-dimensional problems via data-driven polynomial chaos expansions and sparse partial least square. Comput Methods Appl Mech Engrg 2020;364:112906.
[6] Beck, J.L.: System identification methods applied to measured seismic response, Proc. 11th World Conference on Earthquake Engineering (1996)
[7] Mendoza-Lugo, M.A. and Delgado-Hernandez, D.J. and Morales-Napoles, O.: Reliability analysis of reinforced concrete vehicle bridges columns us-ing non-parametric Bayesian networks, Engineering Structures 188 (2019) https://doi.org/10.1016/j.engstruct.2019.03.011
[8] Jesus, A. and Brommer, P. and Westgate, R. and Koo, K. and Brownjohn, J. and Laory, I.: Bayesian structural identification of a long suspension bridge considering temperature and traffic load effects, Structural Health Monitoring (18-4), pp 1310-1323, (2019), https://doi.org/10.1177/1475921718794299
[9] Koune, I-C. : Bayesian system identification for structures considering spatial and temporal dependencies, http://repository.tudelft.nl., (2021)
[10] Arangio, S. and Beck, J. L.: Bayesian neural networks for bridge integrity assessment, Structural Control and Health Monitoring 19-1, pp 3-12 (2012) https://doi.org/10.1002/stc.420
[11] Barros, B. and Conde, B. and Riveiro, B. and Morales-Napoles, O., Gaussian Copula-based Bayesian network approach for characterizing spatial variability in aging steel bridges, Structural Safety(106) (2024), https://doi.org/10.1016/j.strusafe.2023.102403
[12] Koherent Homepage, http://koherent.io/. Last accessed 3 March 2025.
[13] Geolaser Homepare, https://geo-laser.de/ Last accessed 7 April 2025.

CC BY 4.0
https://creativecommons.org/licenses/by/4.0/deed.en
This CC license does not apply to third party material and content noted otherwise