# Structural Monitoring of the Zeeland Bridge for Improved Load - Response Evaluation and Structural Lifetime Estimation

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**Abstract.** To reduce uncertainties associated with its structural reassessment, the Zeeland Bridge in the Netherlands is currently the subject of a field lab, which will run for 2 years. In this contribution, numerical investigations to study the dependencies between variables associated with uncertain structural properties of the bridge and various response/measurement quantities are presented. Initial focus is on load testing of the bridge to obtain insight into the possibly varying response in different spans of the bridge. Parametric studies to expose input-output parameter dependencies are performed on a representative subsystem 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.

**Keywords:** Bridge monitoring · Structural identification · Bayesian networks

## 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. 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


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knowledge to best estimate the actual state of a structure [1–3]. 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 multi-span bridges where the level of damage in for instance orthrotropic steel decks greatly varies 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. In such cases, tailored measurement campaigns might be needed to better understand the actual structural behaviour.

In this contribution, initial investigations to define a measurement strategy for the Zeeland bridge are presented. To identify the most promising types of measurements to perform, analyses capable of exposing the dependence structures between specific types of measurement quantities and the model parameters of interest are performed. The presented parametric studies are performed on a representative subsystem of the Zeeland bridge, and are focussed specifically on load tests, where the quasi-static response of the bridge to a known mass placed at different locations is recorded.

## 2 The Zeeland Bridge

The Zeeland bridge is a 5 km multi-span balanced cantilever prestressed concrete bridge, connecting the islands of Noord-Beveland and Schouwen-Duiveland in the Province of Zeeland in the Netherlands. 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. Figure 1 shows a picture of the bridge, with red ellipses indicating the locations of the dowel joints, the cantilevers, and the foundations. These locations are related to the main sources of uncertainty in the bridge's load-response behaviour, namely the forces transferred at the midspan joints (Fig. 2), shear stress levels in the cantilever, and foundation support stiffnesses.

**Fig. 1.** The Zeeland bridge, showing the locations of main uncertainties.

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

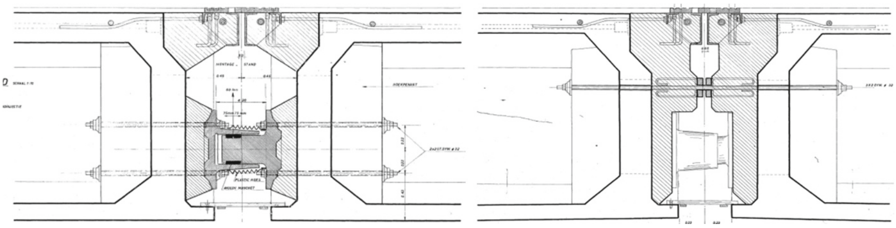


**Fig. 2.** Longitudinal cross section of the Zeeland bridge dowel (left) and fixed hinge (right) mid span joints.

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, 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 [4], 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% [4]. 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 behaviour 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 deformation behavior of the bridge. Estimation of the actual degree of prestress loss per span will not be possible based on measured deformations [5]. For specific spans of concern, localized destructive or non-destructive measurements may at a later stage be considered to further investigate prestress loss.

## 3 Towards a Robust Model Updating Strategy for the Zeeland Bridge

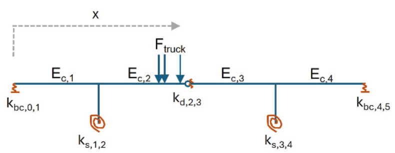
In our project we intend to develop a Bayesian network based model updating strategy, where the dependency structures between model parameters of interest and measurable response quantities are properly accounted for. This is especially interesting in cases where these dependency structures are complex, and where large numbers of spatially varying parameters are to be estimated.

### 3.1 Bayesian Networks

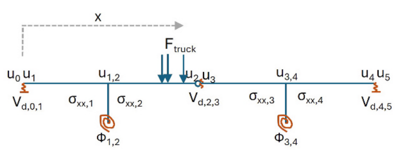
Bayesian networks (BN's) are widely used in modeling statistical dependencies in complex problems. For the assessment of existing bridges, applications of BN's include integrity assessment and damage detection [6], prediction of crack growth [7], integration of inspection data and expert judgment [8,9], forensic assessment of bridge collapse [10], and bridge structural model updating [2]. In the work by Calvert et al. [9], relations are implemented between defect mechanisms to improve damage state estimation based on limited data. The same concept might be applicable to account for relations between locally varying structural properties, construction stage effects, local defects, internal force (re)distributions, and damage potential for future load scenarios. Some research on structural model updating focuses specifically on the spatial variability of structural properties [12], which is particularly interesting for structures where local variations of structural properties determine internal force concentrations in weak components or structural joints. Successful case studies in which Bayesian networks are used for the identification of spatially varying parameters in real bridges, in order to evaluate bridge load-response behavior, are to the authors' best knowledge not available.

### 3.2 Analyzed Sub-system

We follow the concept presented in [13], 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. 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.




(a) Sub-system parameters




(b) Measurement quantities

**Fig. 3.** Sub-system schematization

The sub-system parameters are the concrete effective stiffness in bending ($E_{\mathrm{c},i}$), the mid-span joint vertical stiffness ($k_{\mathrm{d},23}$), and the support rotational stiffnesses ($k_{\mathrm{s},ij}$). The sub-system boundaries are set at the 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 ($k_{\mathrm{bc},ij}$). 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).

### 3.3 First Test Campaign

As a first test to identify the structural behavior of the bridge, a load test with 50 tonnes 3-axle trucks will be 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 will include measurements of the displacements at midspan relative to the supports, and the relative displacements of both cantilever ends at mid-span.

Displacements are measured during the load test using Koherent's radio-based displacement measurement technology [16]. The stresses $\sigma_{\mathrm{xx},i}$ indicated in Fig. 3(b) are measured using smart aggregate technology developed at the TU Delft. Measuring the shear forces $\mathrm{V}_{\mathrm{d},ij}$ in the cast iron dowels with reasonable uncertainty is concluded to be complicated, especially in a mobile setup covering a load test on multiple spans. Dowel forces will therefore not be considered as outputs. Instead, during load testing the differential displacement $u_i - u_j$ over the midspan joints will be measured 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.

### 3.4 Parametric Study to Expose Dependency Structures

In this initial study we focus only on the forward modelling, with the aim of exposing input-output parameter dependencies that might have an influence on the design of an optimal measurement set-up for the bridge. The static response of the sub-system described in Sect. 3.2 is calculated through simplified DIANA FEA simulations for 20 truck positions, where the bridge superstructure is modeled as a 2D beam model using CLASS-III Mindlin-Reissner beam elements, with quadratic mesh order. In the model, at this stage, time-dependent effects and effects related to prestress loss are accounted for by varying the cantilever's effective bending stiffness. To identify the input-output dependencies, a parametric study is performed in which the input (i.e. sub-system model) parameters are sampled from normal distributions having mean $\mu$ and standard deviations $\sigma$ indicated in Table 1. DIANA FEA simulations were run in batch mode, stacking the model output of all sampled parameters sets and all truck load positions.

**Table 1.** Sub-system parameters distributions

| Parameter | $E_{1-4}$ | $k_{\mathrm{d},2,3}$ | $k_{\varphi,1,2}$ and $k_{\varphi,1,2}$ | $k_{\mathrm{bc},0,1}$ and $k_{\mathrm{bc},4,5}$ |
|---|---|---|---|---|
| Units | N/m$^2$ | N/m | Nm/rad | N/m |
| $\mu$ | 2.30E+10 | 2.00E+08 | 2.00E+10 | 1.00E+07 |
| $\sigma$ | 2.30E+09 | 2.00E+07 | 5.00E+09 | 2.50E+06 |

Analyses on model input-output dependencies are performed both in the actual variables' space and in copula space, using the PyBanshee Python package [14]. Transformation to copula space is calculated using the empirical copula transform [15]. The actual parameter space gives insight into the expected amplitudes of the output variables. An evaluation of dependencies in copula space allows for an assessment of the dependency between variables, without being biased by their individual marginal distributions. Also, the observed dependencies in copula space are used as a basis to evaluate the assumption of Gaussian copulas for input-output relations, based on a Cramer Von Mises (CVM) statistic calculated on the synthetic data and on the measured data once available.

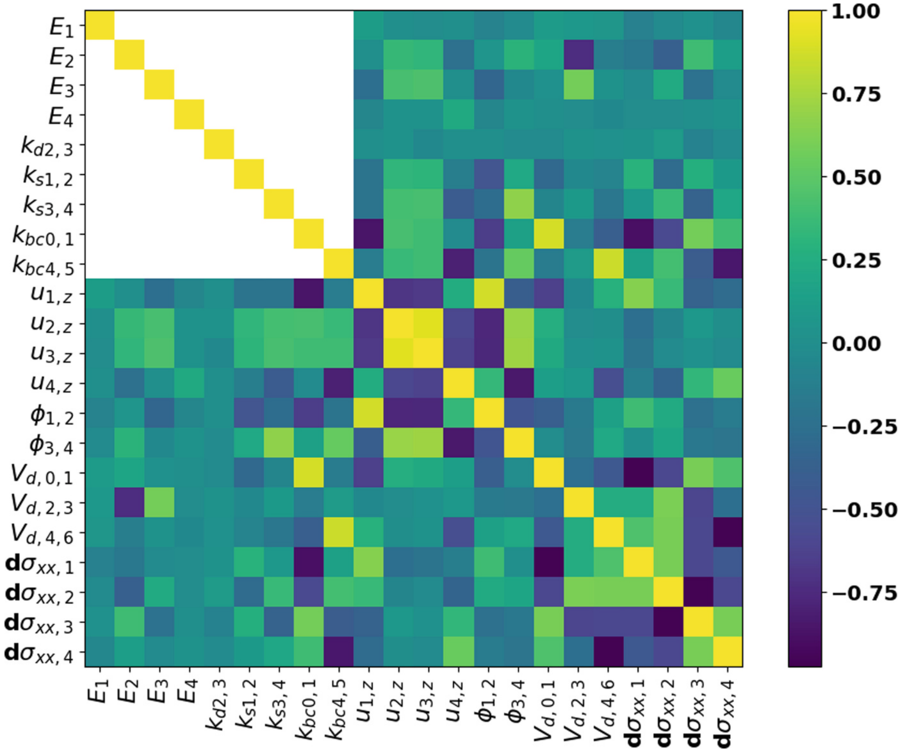



**Fig. 4.** Simulated load test variable dependencies

The input and output variable dependencies are indicated in Fig. ref-fig:variablespsdependencies in copula space by their Pearson correlation coefficients $\rho$ for the simulations with parameters sampled in accordance with Table 1. For the results presented here, the sub-system model parameters were considered to be uncorrelated. At mid-span location, the vertical displacements $u_2$ and $u_3$ are correlated most with $E_2$ and $E_3$ (i.e. with the bending stiffness of the two cantilevers that form the center span), and with the two rotational support stiffnesses $k_{s,12}$ and $k_{s,34}$. Since the actual rotational stiffness of the supports $k_{\varphi,ij}$ is uncertain at this stage, an additional analysis was conducted where the mean of the rotational stiffness was increased by a factor 10. In this case, it was found that only $E_2$ and $E_3$ correlate significantly with the mid-span displacements.

The load in the mid-span dowel is correlated most with the difference between $E_1$ and $E_2$. This observation remains valid also when the support rotational stiffness is increased substantially. Higher correlation coefficients are obtained for measurement quantities that are locally directly linked to certain sub-system parameters, like $E_2$ and $E_3$ to $u_2$ and $u_3$, or $u_1$ and $u_4$ to $k_{bc,0,1}$ and $k_{bc,4,5}$, respectively. This supports the concept of [13] that the "best" models are those which are locally the most probable based on the available data. However, Fig. 4 also indicates that there are numerous 'non-local' dependencies, implying that this specific identification problem is complex in terms of both displacement and internal force variables being dependent on many considered system parameters. A Bayesian network implementation strategy will need to be tailored to this complex dependency structure in order to be effective for structural identification and to allow for reasonably accurate estimations of extreme internal forces in the structure.

### 3.5 Load Test Response Predictions

Figure 5 shows the calculated bridge deformation response influence lines across the sub-system parameter distributions described in Table 1. The mean and +/− 1 standard deviation intervals are indicated in blue. The total displacement at mid-span due to the 50-tonne truck is estimated to be around 0.02 - 0.03 m. When the mean of the rotational stiffness of the supports is increased by a factor of 10, this deflection could reduce to 0.01 to 0.015 m.

Varying stiffness over the multi-span bridge results in vertical load transfer at the mid-span joints. Figure 6 shows the influence line of the load transferred at the mid-span dowel connection for the sub-system parameter distributions described in Table 1. The line colors vary with the difference between sampled $E_2$ and $E_3$ and the mean and +/− 1 standard deviation intervals are indicated in blue. For the analysis with an increased mean support stiffness, this becomes as shown in Fig. 7. The transferred load is the result of the bridge's dead weight and an additional position-dependent contribution from the truck load.

It is interesting to observe that the permanent load being transferred through the joints can differ substantially due to variations in stiffness parameters. In reality, a differential effective stiffness across spans can be the result of different prestress losses, concrete properties or creep effects. Effects due to differential support settlements will add to the load transfer. Load levels of ±100 kN or ±250 kN are calculated for the simulation runs in Figs. 6 and 7, respectively. The ultimate load transferred through the mid-span connection during the load test is calculated to range from −500 kN to +500 kN. These analyses underline

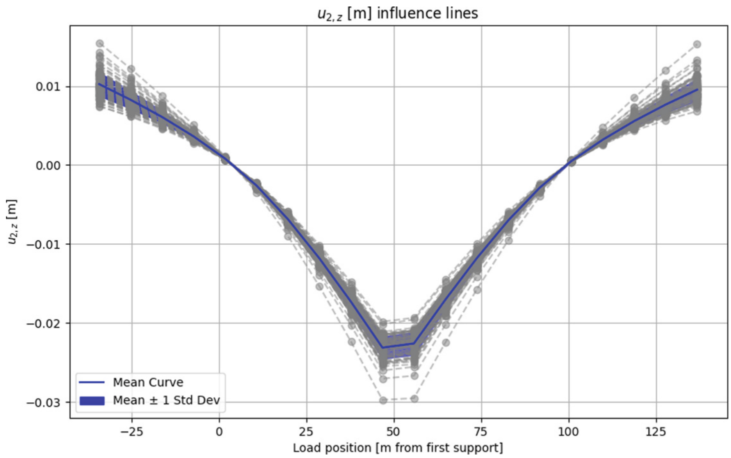



**Fig. 5.** Vertical displacement influence lines for parameter distributions described in Table 1.

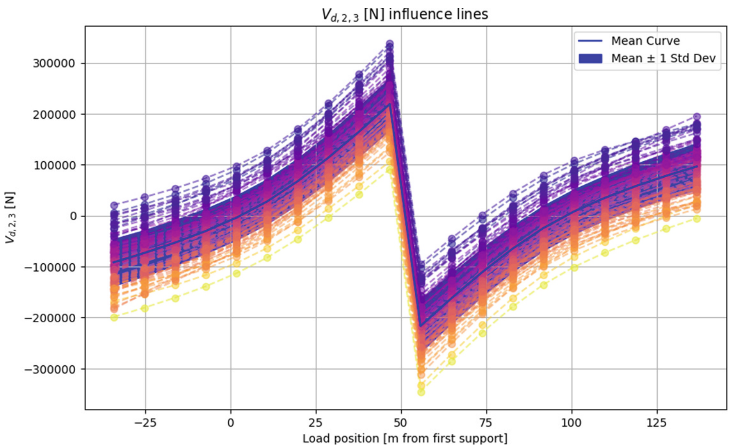



**Fig. 6.** Mid-span load transfer influence lines for parameter distributions described in Table 1.

the value of measuring the dowel forces, but as mentioned earlier this is very challenging and these forces are considered unavailable in the initial load testing. Recognizing, however, that the dowel connections have approximately up to 3 mm vertical displacement allowance, the onset at which contact in the dowels is lost and again established in the other direction, can be used to estimate the permanent load transfer. The consistent shape of the load transfer influence lines across the different parameter distributions benefits this approach.

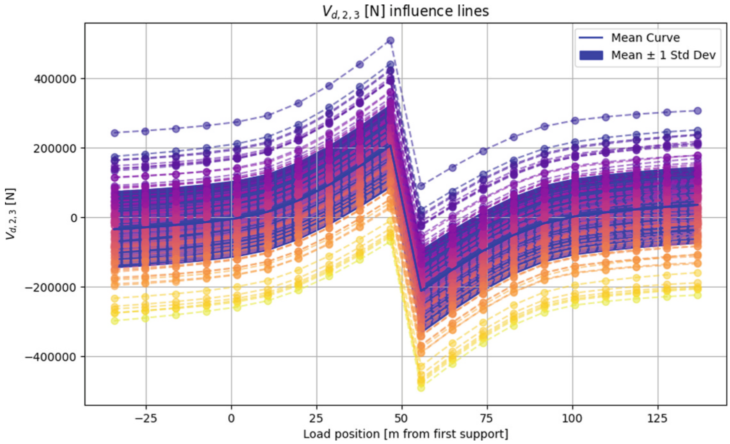



**Fig. 7.** Mid-span load transfer influence lines for an increase in the mean support stiffness

## 4 Conclusions

This paper presented a number of initial numerical investigations performed within the framework of an ongoing project on structural monitoring of the Zeeland bridge. To generate insight into the bridge's behaviour, dependencies between variables associated with uncertain structural properties of the bridge and various response/measurement quantities were investigated. The investigations were performed for a foreseen load test, and were based on simulations of a representive sub-system of the bridge. Results indicate a complex dependency structure between the properties that are to be identified (the inputs) and the deformations and internal forces occurring in the bridge (the outputs). Only a few strong dependencies between specific input and output parameters were found, implying a challenging identification task. The last observation supports the use of a Bayesian network for structural identification, in order to quantify and subsequently account for the statistical dependence between various variables of interest. Based on the results, it is furthermore concluded that structural parameter identification based solely on deformation measurements will be inadequate for this bridge. Future work, following the planned load tests in March 2025, will focus on the development of a Bayesian network based model updating strategy to identify the load-response behaviour of the bridge.

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