A Reduced-Order Digital Twin for Structural Health Monitoring of Steel Bridges

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ABSTRACT

Conventional simulation methods, such as the Finite Element method, are less suitable for efficient and adaptive digital twins of large-scale structures needed for structural health monitoring (SHM). The complexity and scale of such structures require new simulation techniques that can handle the increasing computational demands and provide accurate results in real-time. This paper presents a novel approach for the implementation of a digital twin for SHM of steel bridges using reduced order modelling. For this purpose, the commercial software Akselos originally developed for digital twining in the aerospace industry is herein adapted to a structural engineering context. The parametric and component-based approach allows a modular structure of the digital twin with the possibility for quick adaptions according to the SHM data. The method is applied to a steel arch bridge as a case study. The example bridge was monitored over the period of a month using strain gauges at five critical locations together with temperature sensors. In addition, a targeted loading test with a truck was performed. The collected monitoring sensor data is processed and merged into the digital twin. This integration enables precise predictions about the bridge's structural integrity, maintenance and repair planning as well as possible future damage locations. The proposed approach demonstrates the potential of the digital twin for real-time monitoring and prediction of changes in the structural integrity of large-scale structures, providing a promising solution for efficient and effective SHM of steel bridges.

INTRODUCTION

Structural Health Monitoring (SHM) on bridge structures aims to determine critical details on the basis of deterministic or probabilistic considerations. Measurements are mainly made with strain gauges, displacement transducers and accelerometers. The main difficulty in developing suitable models to describe the state of the structure is that structures are highly variable in terms of building materials, construction method, load-bearing structure, stress, age and condition, and are subject to ongoing change. There-

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fore, the information is scattering, uncertain, and/or also highly time-varying. However, the progression of damage to a critical condition can take several decades [1, 2]. In SHM, adaptive models are fundamentally different from conventional prediction models, which are always intended to provide a statement at an initial point in time over a relatively long period of time. This inevitably leads to an increased complexity. On the other hand, adaptive models have the ability to continuously adjust to the new state. Adaptive models offer the opportunity to link in-situ damage detection and global SHM to provide adaptive lifetime prediction or predictive maintenance [2]. However, a requirement is digital linkage of information/data as well as models for damage prediction. This can be done via a Digital Twin (DT).

The DT technology has been used to predict and analyze the maintenance and structural behaviour of bridges [3–5]. In order to capture the current state of a structure, the DT is continuously updated with data from the structure, such as in-situ inspections [3], laser scans, drone and photo images [6], SHM and non-destructive testing [4, 5]. The data of the DT is used to predict the structural behaviour via Finite Element (FE) models. The focus of research to date has been on the description of global load-bearing behaviour [3, 5, 7] or dynamic behaviour [4, 5, 8] of bridge structures, while local effects are often only recorded in qualitative terms.

The techniques used for bridge structures are mainly experience-based measurement calibration [4] or single domain FE update approaches [5]. With experience-based calibration, the result may be subject to bias. Single domain approaches require a high numerical effort [5] and are therefore inefficient for a continuous update process of measured data from SHM. More efficient approaches for identifying structural models for bridges are available [9], but these approaches have only been validated for academic examples.

Kapteyn, et al. developed the concept of a DT consisting of reduced order components for an aircraft and linked SHM data with predicted damage states via optimal classification trees with hyperplane splits [10]. This allows to determine the current damage state and perform flight decisions based on it. The advantage of this concept is the high flexibility in the description of the structural system, as well as the easy later integration of additional damage states. Compared to global FE update, the "divide and conquer" paradigm of the component base is numerically advantageous. So far, the concept has only been validated with numerical models and synthetic measurement data [11]. The performance in real world application cases from bridge engineering still needs to be investigated. A challenge for further development is the appropriate decomposition of the bridge structure into components in order to describe the global and local load-bearing behaviour. So far, the choice of the component is based on numerical performance, e.g. mesh size and port surface. Questions arising from structural analysis point of view, e.g. influence of material differences, variations in thickness and stress concentrations have not been in the focus of research so far. Therefore, the objective of this paper is to assess the current state of art for reduced-order component modeling of steel bridge structures and to identify challenges, especially with regard to digital twining for SHM.

Figure 1. Sideview of the investigated steel arch bridge

MATERIALS AND METHODS

The efficiency of methods for creating digital twins of structures depends in particular on the size and complexity of the investigated structure. Therefore, a large-scale tied arch bridge with orthotropic steel deck and a span of $91\,\mathrm{m}$ is considered in this work. The bridge consists of two vehicle lanes with a total width of $6.5\,\mathrm{m}$ as well as a footpath with a width of $4.9\,\mathrm{m}$. Figure 1 shows a side view of the bridge.

After about 40 years of use, the bridge shows various damages, especially at the welds at the hanger connections to the stiffening girders. As part of a recalculation, strain measurements were carried out to determine the actual condition of the bridge using a Gantner measurement system with uniaxial strain gauges of type HBM 1-KY11-2/120 and Techni Measure FLA-3-350-11 with a sampling rate of $100\,\mathrm{Hz}$. The sensors were located in the region of two hanger connections on the bottom flange (MP 1/2) and on the top flange of the stiffening girder (MP 3/4). In addition, the strain was determined on one hanger in the vertical direction (MP 5). The exact measurement positions are shown in Figure 2. For the calibration of the simulation model, a defined load was applied with a weighted truck at five load positions in each of the two vehicle lanes.

Numerical Method

The structural behaviour of bridges is usually investigated using the FE method. In this paper, the Static-Condensation Reduced Basis Element (SCRBE) method is used which combines the Reduced Basis Element (RBE) method with static condensation (SC) [12]. The RBE method approach involves creating a low-dimensional parametric subspace which is subsequently used to approximate the full solution [13]. Typically, a small number of basis functions is used compared to the large number of degrees of freedom (DOF) in the FE method. The procedure divides into offline and online computations: In the offline step, basis functions are generated by solving a discrete set of FE models, called snapshots. These snapshots are carefully selected to represent the system's behaviour. The basis functions are constructed using algorithms like the standard Greedy algorithm [14]. In the online step, the reduced basis functions are used to approximate the solution of the full problem by projecting the governing equations onto

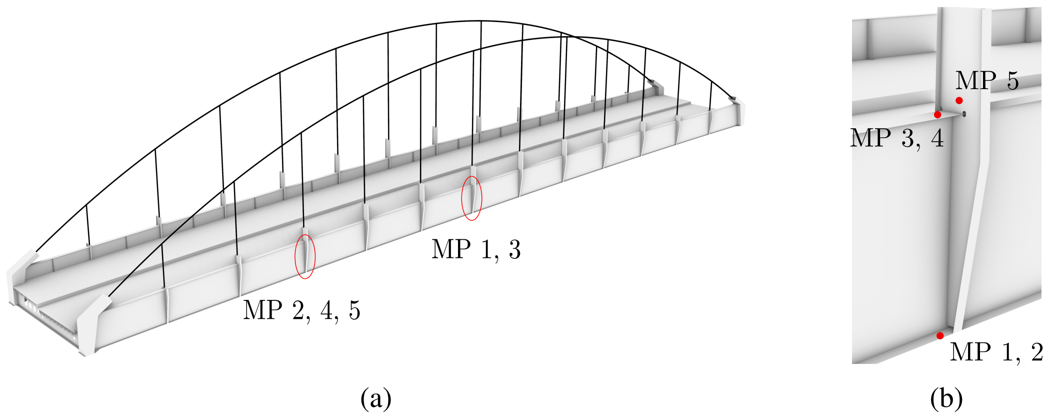

Figure 2. (a) Rendered geometric model with sensor locations, (b) detailed sensor position on hanger connection

the reduced basis space. This results in a smaller set of equations that can be solved more efficiently. The RBE solution's accuracy depends on the number of basis functions employed, with increased accuracy achieved by incorporating more basis functions. However, the computational cost also increases with the number of basis functions.

In SC, the model and the associated DOF are divided into different domains, hereafter called components, and their interfaces, the ports. The internal DOF within the components are eliminated by solving for them in terms of the external DOF on the ports, using the equations that relate them. The condensed system of equations has a much smaller size than the original system, and can be solved more efficiently.

While SC is effective in reducing the size of the system of equations, the required matrix inversions can be computationally expensive, especially for large-scale structures. However, the SCRBE method overcomes this issue by combining the benefits of the SC and the RBE method. The method has been intensively studied in recent years and extended in research projects [15, 16]. In this paper, the commercial software *Akselos RB-FEA* of Akselos SA. in the version of 2021 is used as a proprietary implementation of the SCRBE method.

Geometric and Numerical Modeling

As the investigated bridge is not symmetrical in either longitudinal or transverse direction, a complete model of the entire structure was necessary. The geometric model incorporates the cross slope of the footpath and roadway, as well as the longitudinal superelevation of the bridge. Considering the later integration of measurement data into the digital twin, the superstructure is primarily represented by the middle surfaces of the metal sheets based on available 2D plans. Simpler line models are sufficient for the hangers and the two arches, since high-resolution geometry is not required. The CAD program *Rhino 7* and its *Grasshopper* plugin were used for generating parametric regular sections. Figure 2 depicts an isometric view of the rendered geometric model, showing the global sensor positions in (a) and detailed sensor positions in (b).

For the simulation of a bridge's structural behaviour, simplified truss models with consideration of the effective bridge deck width are commonly employed. The SCRBE

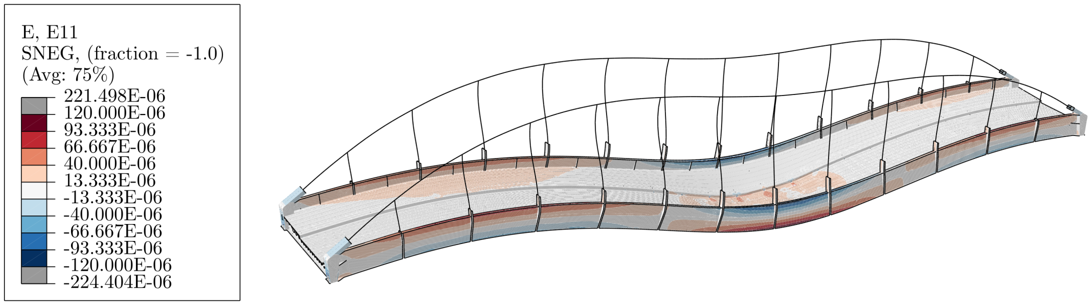

Figure 3. Strains in longitudinal direction under the described load case for the ideal model, calculated with *Abaqus 2023*; the deformation is exaggerated by a factor of 300

method enables the use of shell element models for large-scale structures, employing an efficient offline/online decomposition approach. Consequently, shell elements are utilized for the primary sections of the superstructure, while beam elements are used for the arches and hangers. Meshing, material assignment, and cross-section properties are accomplished using the FE software *Abaqus 2023*.

The SCRBE method requires appropriate component definition, considering factors such as numerics (number of DOF, port sizes and compatibility, singularities), damage state and sensor locations as well as the modularity and reusability of components. The bridge under investigation is divided longitudinally into $3.5\,\mathrm{m}$ long components, with ports located midway between the cross girders. In transverse direction, the outer sections with stiffening girders and hanger connections are separated from the middle sections. The component choice is based primarily on numerics, for example, singularities are avoided by ensuring geometric continuity in port placement. Each of the 81 components has a parameterized stiffness behaviour, allowing calibration against measurement data. The component's Young's moduli are adjusted using stiffness calibration factors χ_i. The calibration is limited to discrete increments between $0.5 \leq \chi \leq 1.5$.

RESULTS

Using the SCRBE method and training the model offline, the number of DOF is reduced from $\approx 550,000$ in the FE model to $\approx 2,000$ during online application. This leads to a significant decrease in computation time, with over 100 times faster acceleration compared to the FE solution. The short computation time is beneficial due to the large number of solutions required for different damage states. However, it is impossible to fully investigate all possible damage states, even with the limitation of one damage parameter per component. Therefore, only selected components will be subjected to discrete gradation steps.

In a first step, one load case is examined, in which the truck is located approximately in the middle of the bridge. To evaluate the SCRBE model, a simulation is perfomed in *Abaqus 2023* with a comparable FE model for selected damage states. Initially, the measured strains are compared with an ideal model, where the stiffness calibration factor χ equals 1.0 everywhere. The resulting strains in the longitudinal direction of the bridge

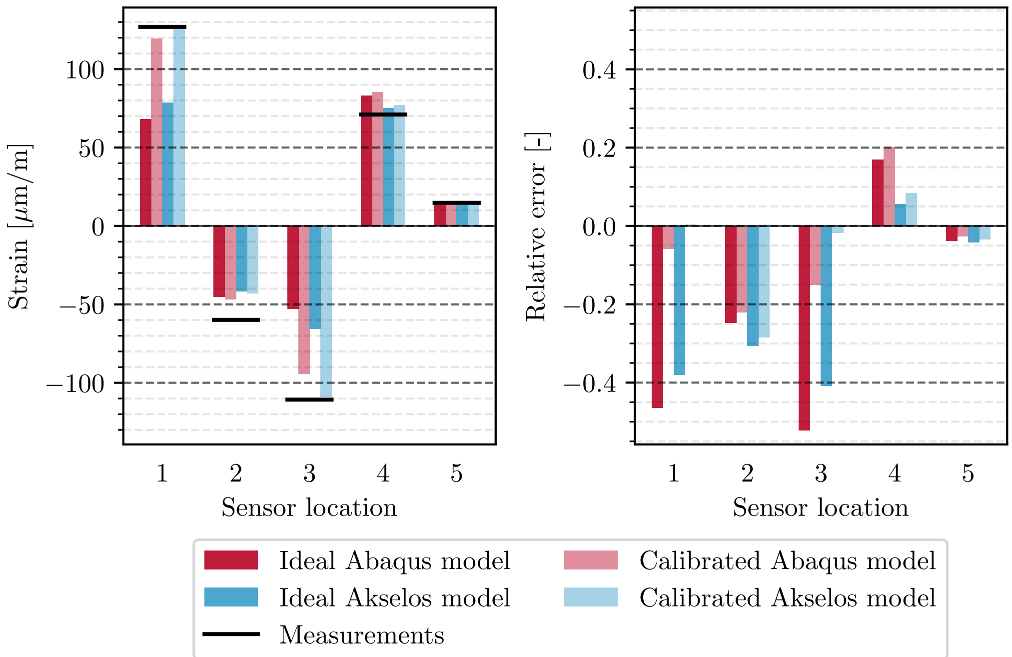

Figure 4. Comparison of the absolute strains and the relative errors for the measurements, the FE models and the SCRBE models

between $+120\,\mu\mathrm{m/m}$ and $-120\,\mu\mathrm{m/m}$ calculated with *Abaqus* are shown in Figure 3. In the following, the measured strains are compared with the calculated strains from both numerical models and the models are calibrated using the factors χ_i for each component. The results are given in Figure 4 for the absolute strain values as well as for the relative errors for the investigated load case.

Even with ideal simulation models, the strains for the investigated load case are accurately predicted, especially the absolute vertical strains (MP 5) on the hanger. Adjusting the model within the specified range $0.5 \leq \chi_i \leq 1.5$ improves the accuracy for the first and third sensor (see Figure 2). However, the other measurement points do not show any significant improvement and may even exhibit slightly worse results. Comparing the two numerical methods, the FE model in *Abaqus* and the SCRBE model in *Akselos*, generally yield consistent results. Although there are minor differences in absolute strain values, the SCRBE results are even slightly better than the FE results.

DISCUSSION AND COMPARISON

For the selected load case used to calibrate the numerical models, good agreement with the measured data is observed even at $\chi = 1.0$, with an average percentage error of $\approx 29\,\%$. Generally, the numerical models appear suitable for predicting the structure's actual behaviour. Deviations may be attributed to factors such as differences between the real structure and the 2D plans, as well as geometric simplifications in the structural model. 3D-scanning the entire structure or parts of it can help minimize this error [6].

When comparing the different numerical methods, the observed differences exceed the expected error between the SCRBE method and the FE method [15]. One possible explanation is the distinct treatment of the coupling between shell and beam elements for the arch and the hangers. Interestingly, the SCRBE method seems to be more accurate than the FE method for the considered load case in this comparison.

Although the models fit well for the measured data of the investigated load case, they do not adequately describe the behaviour for other load cases. For example, when the truck is positioned near one end of the bridge, the numerical models predict different tension and compression ranges in the stiffening girder at MP 1/3 and MP 2/4, whereas the measured data shows no change. The utilization of a single damage parameter χ per component provides a simple and computationally efficient damage model, but also exhibits significant limitations, as noted by Kapteyn [11]. The initial results on the present steel bridge indicate that employing a single parameter per component may suffice for describing the global structural behaviour. However, in addition to the influencing factors mentioned above, the mechanical behaviour needs to be taken into account for the component selection, which has not yet been considered in previous research. Consequently, it is important to develop strategies for identifying efficient components that can universally capture the behaviour of the structure, especially for large-scale bridge structures.

CONCLUDING REMARKS

The Static-Condensation Reduced Basis Element method represents a promising approach for creating digital twins of steel bridges. Its numerical efficiency makes it a suitable candidate for modeling large and complex structures. However, further research is required to improve the selection of components, taking into account the mechanical behaviour of the structure, and to calibrate the model using actual measurement data. These challenges must be addressed to ensure the accuracy and reliability of the digital twin model, which can ultimately be used to improve the structural integrity and maintenance of steel bridges.

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