Comparative Analysis of Simulation Models for Digital Twins and Damage Identification on Bridges: A Steel Bridge Case Study Using Strain Measurements

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ABSTRACT

Structural Health Monitoring (SHM) and Digital Twin (DT) technologies are transforming the management of civil infrastructure by enabling real-time condition assessment and predictive maintenance. A key component of these advancements is the development of accurate simulation models that represent physical assets in virtual environments. This paper explores different simulation approaches for DTs and damage identification on bridges, using a steel bridge with an orthotropic deck as a case study. Various state-of-the-art modeling techniques, including truss models and finite element models, are developed based on the bridge's as-designed geometry. Their performance is evaluated in terms of computational efficiency, ease of parameterization, and accuracy in capturing structural behavior, with strain measurements from a load test serving as a reference. Statistical metrics assess the alignment between simulated and observed data. While all models involve certain simplifications, they demonstrate good agreement with experimental results. The findings highlight the importance of selecting an appropriate modeling approach based on specific SHM and DT objectives, such as real-time monitoring or detailed structural analysis. While truss models offer advantages in computational efficiency and straightforward parameterization, more detailed finite element models provide higher fidelity for local structural behavior. This study underscores the potential of even simplified models to achieve reliable predictions of global structural behavior when key geometric features are appropriately represented. Ongoing work further refines these approaches to enhance their applicability in damage identification, contributing to the advancement of DT-based predictive maintenance for bridges.

INTRODUCTION

Like other transportation infrastructure, steel bridges have been subjected to increasing loads in recent years, which can lead to deterioration and damage. To ensure their long-term structural integrity, Structural Health Monitoring (SHM) offers valuable insights and enables early damage detection [1]. This requires processing the collected monitoring data to accurately assess the bridge's current condition [2].

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Recently, data-driven, model-free approaches have shown great potential for damage detection and localization [3]. These methods extract patterns directly from measurements without requiring detailed physical models. However, while effective for rapid diagnostics, they often lack the predictive capabilities for simulating damage scenarios and interpretability needed for maintenance planning. For these advanced tasks physics-based models are more suitable. By incorporating structural mechanics and material behavior, these models enable deeper insights and form the basis for Digital Twins (DT) [4]. This raises the question of the advantages and disadvantages of different physics-based modeling approaches with regard to SHM-driven DTs.

Historically, model selection was limited mainly by computational resources. Simplified beam-based models, still widely used today, especially for truss or large-scale bridges, offer a practical balance of cost, speed, and acceptable accuracy [5]. With modern computing, detailed finite element (FE) models have become feasible, allowing for realistic geometry and boundary conditions. However, their higher accuracy comes at the cost of significant computation time, limiting their use in real-time applications. As a result, shell-based FE models are often applied only to selected regions using submodels or within multi-scale frameworks [6, 7]. Physics-based reduced-order methods offer a promising compromise between detailed geometries and computational performance [8]. These approaches retain essential physics from high-fidelity models while significantly lowering computational demands, enabling real-time updates and analytics even for complex steel structures [9].

Unlike concrete bridges, steel bridges make highly efficient use of material, with structural elements present only where strictly necessary. This often leads to complex geometries that require explicit modeling. This study compares three physics-based modeling approaches to explore the challenges and capabilities using real monitoring data: a simplified beam-based FE model, a detailed shell-based FE model, and a reduced-order model based on the shell model using the Static Condensation Reduced Basis Element (SCRBE) method [10].

MATERIALS AND METHODS

Case Study: Strain Monitoring on a Steel Tied Arch Bridge

Figure 1 shows the $91\,\mathrm{m}$ long tied arch bridge with an orthotropic steel deck considered in this study [11]. The bridge accommodates two traffic lanes with a combined width of $6.5\,\mathrm{m}$ and a footpath measuring $4.9\,\mathrm{m}$ in width. The main girders, the transverse girders and the hangers are designed as welded I-sections, with the orthotropic deck acting as the upper flange of the transverse girders. The arches are fabricated as welded, two-cell box sections. Transverse beams are spaced at $3.5\,\mathrm{m}$ intervals, supporting an orthotropic deck with different types of longitudinal stiffeners. Vertical hangers are located at every second transverse beam, resulting in twelve hangers per side.

After approximately 40 years in service, the bridge shows signs of deterioration, particularly at the welded connections between the hangers and the stiffening girders. As part of a structural reassessment, uniaxial strain measurements were performed to assess the current condition and to support the numerical recalculation [11]. To determine the structural stresses at critical weld details at two exemplary locations, strain gauges were

Figure 1. Sideview of the investigated steel arch bridge

positioned on the bottom flange (SG1 and SG2) and top flange (SG3 and SG4) of the stiffening girder in longitudinal direction, as well as in the vertical direction on one hanger (SG5) (Figure 2 b) and d)). In contrast to their original purpose, the existing sensors are used here to examine the quality of the various models.

A load test was conducted using a weighted truck with a total weight of $40.2\,\mathrm{t}$. The truck was positioned at five predefined locations in each traffic lane. Exact wheel loads and load positions are shown in Figure 2 a) and c). Prior to data evaluation, temperature compensation and zero-offset calibration were performed. For each load case, strain values were smoothed and averaged for the stationary response time.

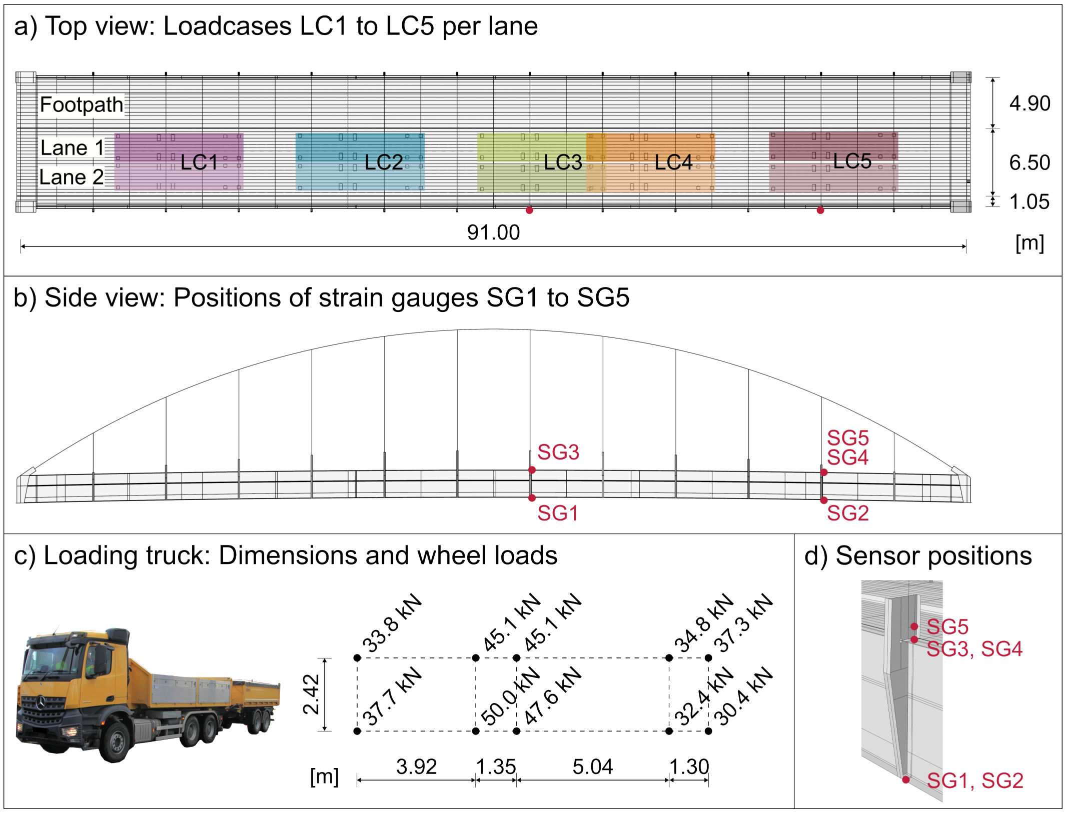

Figure 2. a) Top view with load positions, b) Side view with global sensor positions, c) dimensions and wheel loads of the loading truck, d) detailed sensor positions

Physics-based Modeling Approaches

The first modeling approach reflects the current state of art in structural engineering using the commercial structural analysis software *RFEM* (version 5.35) of Dlubal Software GmbH. All structural components except the steel deck are modeled using beam elements (Figure 3 a)). Shear deformation in wide flanges is considered via effective widths and eccentric connections are captured with idealized rigid or hinged coupling links. The orthotropic deck is modeled using shell elements with orthotropic stiffness without explicitly modeling longitudinal stiffeners. Vehicle loads are applied as point loads directly onto the deck, neglecting load distribution as no local strains in the area of the roadway are examined. Structural strains are derived by segmenting beam elements, calculating internal forces, and applying linear-elastic post-processing.

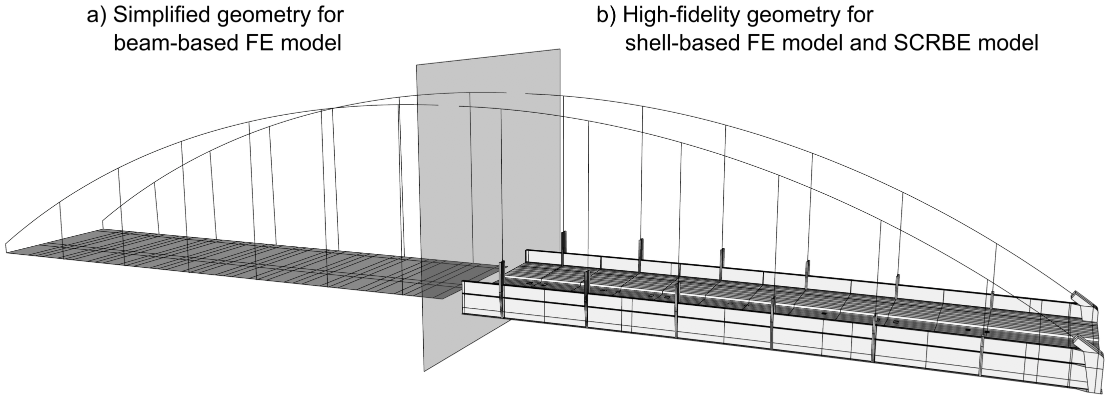

Figure 3. a) simplified line-based geometry for the beam-based FE model, b) high-fidelity surface-based geometry for the shell-based FE model and the SCRBE model

The second approach bridges practice and advanced research by explicitly modeling nearly all steel plates, stiffeners, cut-outs, and connection details as isotropic shell elements while the upper parts of hangers and arches are simplified with beam elements (Figure 3 b)). Simulations are carried out using *Abaqus* (version 2023). The model includes over 2.5 million elements, incorporating superelevation and longitudinal slope, but omitting transverse slope. The vehicle loads are applied as pressure loads over wheel contact areas. In a post-processing step, strains are interpolated from shell integration points to match experimental measurement locations.

The third approach uses physics-based reduced order modeling via the SCRBE method [10], implemented in *Akselos Modeler* (version 2025) by Askelos SA. Based on the detailed shell model, it improves computational efficiency while maintaining geometric and structural fidelity. The SCRBE method includes two phases:

- Offline phase: The structure is subdivided into components using Static Condensation; each component is precomputed over a parameter space using the Reduced Basis method. The outcome is a library of pre-solved components.

- Online phase: For a specific load case, the model assembles the precomputed components and solves the global structural problem efficiently.

The shell structure is subdivided here into 81 components, reducing degrees of freedom to about 7,000 in the online phase. Load application, post-processing, and superstructure modeling follow the shell-based approach, with minor differences in hanger cross-sections and boundary conditions.

Comparison criteria

The evaluation of the models is possible using a variety of criteria. The focus here is on the evaluation of accuracy based on real measurement data. Therefore, only the following criteria are considered here:

1. Computational effort: computational resources required for simulations,
2. Modeling effort: manual work and expertise for model creation,
3. Parametrization complexity: definition and variation of model parameters,
4. Model accuracy: local consistency with strain measurement data.

RESULTS

To independently evaluate model accuracy on a real steel bridge, actual strain measurements are used for comparison. Exact matches between measured and calculated strains are not expected, as all models are based on design specifications and do not reflect the as-built structure or its current condition

Figure 4 (left) shows the simulation results from all three models plotted against the corresponding measured strain values. A qualitative evaluation indicates that all three models are generally capable of reproducing the measured strains, with most data points clustering near the identity line. However, closer inspection of the residuals (Figure 4, right) reveals subtle differences in predictive accuracy. In the residual plots, the boxes represent the median and interquartile range (IQR), while the whiskers extend to 1.5 times the IQR. Outliers are indicated by crosses. Both the shell-based FE model and the SCRBE model exhibit relatively consistent residuals across most strain gauges, with comparable median values. For SG4 and SG5 in particular, nearly all residuals remain below $10\,\mu\mathrm{m/m}$. Notably, the SCRBE model shows a wider spread than the shell-based FE model for SG1, whereas the reverse is true for SG3. In contrast, the beam-based FE model generally exhibits greater variability in the residuals, especially for SG4 and SG5, where both the median and the spread are significantly higher compared to the other two models. For SG2 and SG3, the residuals from all models are similar.

Three common statistical measures are considered to quantitatively evaluate the accuracy of the strain predictions. The root mean squared error (RMSE) quantifies the average magnitude of the prediction errors, with a stronger emphasis on larger deviations. In contrast, the mean absolute error (MAE) reflects the average absolute error, treating all deviations equally. The coefficient of determination R^2 indicates how well the model explains the variability of the measured data, with values closer to 1 suggesting a better fit. Table I summarizes the results for all three models, including an estimated solve time magnitude on a standard workstation.

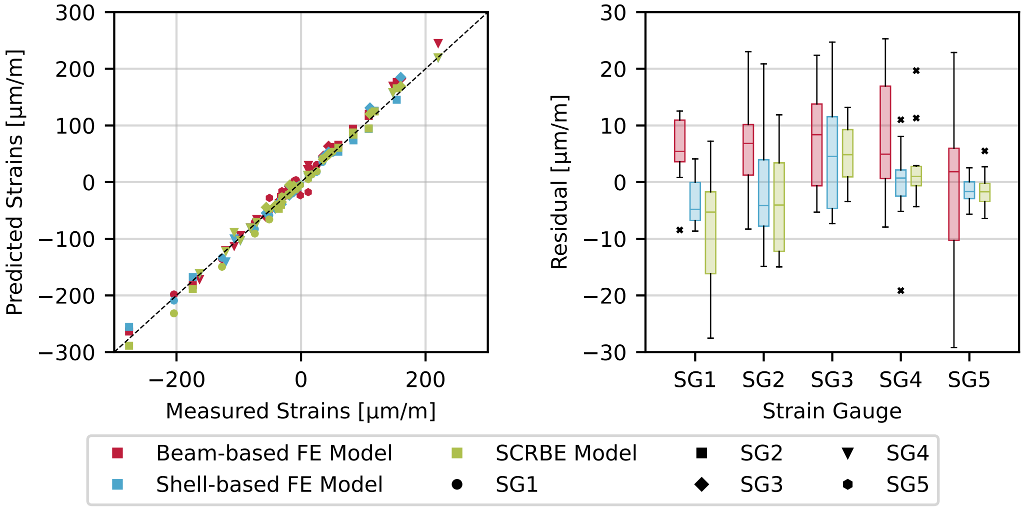

Figure 4. Comparison of the measured and calculated strains as well as the residuals for the beam-based FE model, the shell-based FE model and the SCRBE model

TABLE I. Comparison of statistical and computational measures for assessing the accuracy of the strain prediction of different simulation models

Criterion	**Beam-based FE model**	**Shell-based FE model**	**SCRBE model**
RMSE	$11.29\,\mu\mathrm{m/m}$	$8.00\,\mu\mathrm{m/m}$	$8.50\,\mu\mathrm{m/m}$
MAE	$9.46\,\mu\mathrm{m/m}$	$6.19\,\mu\mathrm{m/m}$	$6.59\,\mu\mathrm{m/m}$
R^2	0.966	0.987	0.980
Solve time magnitude	seconds	minutes – hours	seconds (online phase)

The comparison of the models shows that the shell-based FE model achieves the best overall performance across all criteria. It yields the lowest RMSE and MAE, indicating both small typical errors and a low sensitivity to outliers. Furthermore, its R^2 value suggests an excellent correlation between the predicted and measured strains. The SCRBE model also performs well, slightly below the shell-based FE model for all statistical measures. The beam-based FE model shows comparatively larger deviations, though still demonstrating an overall good agreement with the experimental data.

DISCUSSION

The results in Figure 4 and Table I show that all three models achieve high accuracy in predicting local strains. The shell-based FE model performs best, with the lowest RMSE and MAE and an R^2 of 0.987, indicating excellent agreement with measured data. The SCRBE model delivers similarly strong results, with slightly lower accuracy due to minor modeling differences. While the beam-based FE model ranks last in accuracy, it still achieves a solid correlation with an R^2 of 0.966, though it differs more across other evaluation metrics.

In terms of computational efficiency, the beam-based FE and SCRBE models are the fastest, with solve times of just a few seconds. The SCRBE model is slightly quicker, as the beam-based model includes shell elements that increase the computational effort. The shell-based FE model, by contrast, requires a fine mesh for convergence, leading to significantly longer solve times ranging from several minutes to hours depending on mesh density. Due to the use of different commercial software, quantitative timing comparisons are not provided.

Regarding the modeling effort, the beam-based FE model is the simplest to set up and requires only moderate engineering expertise, such as for defining effective beam widths. The shell-based FE model is more complex, involving detailed geometry and physical properties. The SCRBE model is the most demanding, building on the shell-based FE model and requiring additional decomposition of the structure into components.

Parameterization complexity differs as well. The beam-based FE model allows straightforward adjustments via element stiffness. In contrast, the shell-based FE model requires changes to material properties and stiffness, which can lead to unrealistic behavior at parameter boundaries. For both model types, parameter adjustments always require re-solving the full model. The SCRBE model includes parameterization through the Reduced Basis method. In the online phase, it benefits from the use of pre-trained components, enabling rapid parameter adjustments.

CONCLUDING REMARKS

The comparative evaluation of the three modeling approaches shows that all methods can deliver highly accurate strain predictions under defined loading conditions. Thus, for many practical applications in strain-based SHM of steel bridges, highly detailed, computationally expensive models are not always necessary. The beam-based FE model is notable for its simplicity, low computational cost, and adaptability through spring-based connection adjustments, making it ideal for long-span bridges focused on global behavior. However, additional shell-based submodels are required to capture localized phenomena like stress concentrations or predict strains within the orthotropic steel deck if structural elements such as stiffeners are only modeled implicitly. The shell-based FE model provides higher geometric and mechanical fidelity, making it preferable for local stress distributions, detailed damage analysis, and component-level behavior such as fatigue cracking. Its high computational demand and complex parametrization, however, restrict its use to offline simulations or limited configuration studies. The SCRBE model combines the advantages of both previous approaches. Though it requires significant initial effort to develop, it achieves high operational efficiency with fast, accurate, and low-cost computations in the online phase. Furthermore, the use of the Reduced Basis method enables an efficient parametrization in the online phase. However, its application remains mostly within research contexts. Ultimately, model choice depends on the specific application goals, available computational resources, and the required balance between accuracy, efficiency, and detail.

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