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ANYTWIN – standardizing monitoring-based safety assessments of bridges and the integration into Digital Twins

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ABSTRACT: Normative specifications and guidelines for the supplementary use of sensor-based monitoring in the assessment of road bridges are currently insufficient. This leads to heterogeneous approaches in measurement-based recalculations. In the research project ANYTWIN, standardized measurement and analysis concepts are being developed for selected structural safety verifications. Engineers will benefit from recommendations for actions that can be applied to structures with similar issues. To ensure sustainable and interoperable usage, concepts for integrating structural safety verifications into Digital Twins are created. This will enable information to be interoperably utilized across generations. The automated and standardized integration and analysis of measurement data prospectively establish a crucial core functionality of Digital Twins in infrastructure. The concepts are validated with extensive data from the model bridge of the research project IDA-KI and the Digital Twin of the Köhlbrand Bridge. The ANYTWIN research project commenced in September 2023 and is funded for three years by the Federal Ministry of Digital and Transport (BMDV). Approaches and initial results are presented in this paper.

1 INTRODUCTION

The transportation infrastructure is both a cornerstone and a vulnerability of Germany's economy. Due to the high age of structures and the significant increase in heavy traffic, in 2020 approximately 12% of bridge surfaces were in an insufficient condition (Bast 2023). Reinforced concrete, prestressed concrete and steel bridges account for approximately 83% of the total bridge stock in the federal highway network. Over 80% of the damages observed on these bridges can be attributed to cracks, deformations, and welding seam issues. (Schnellenbach-Held et al. 2015) (Bartels et al. 2022). These damages may result from deficient maintenance

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management or planning deficiencies in construction and structural analysis. Examples include the use of prestressing steels susceptible to stress corrosion cracking and the inadequate design of coupling joints in the sectional construction of prestressed concrete bridges.

Safety-relevant failure mechanisms that remain partly hidden and result in a sudden component failure pose a challenge. Therefore, a structural analysis is indispensable. However, the prevailing lack of information on existing bridges leads to conservative calculation assumptions. For the preservation of structures, especially those with high strategic importance in the infrastructure network, more innovative research approaches are required. Sensor-based monitoring can be utilized to conduct more realistic analyses and detect changes early on within the framework of continuous monitoring. The goal of the ANYTWIN project is to conceptualize a Digital Twin that enables a measurement-based structural safety assessment for road bridges. The project focuses on vulnerable areas of structures and typical deficiencies in structural analyses.

2 STANDARDIZATION OF MEASUREMENT-BASED VERIFICATIONS

Structures are based on the design calculations performed by structural engineers. These calculations are also conducted to assess the probability of specific failure mechanisms. The verifications are considered valid, and the structures are deemed structurally sound only as long as the initial computational assumptions remain applicable. Inadequacies in the original design approaches, changes in the structural condition, and variations in external influences, such as the increase in heavy traffic, often necessitate the reassessment of existing bridges. For German road bridges, there is a guideline for this purpose known as the recalculation guideline (BMVBS 2011). The procedure is structured in stages, with each stage increasing the computational effort and, consequently, the accuracy of the calculations (Figure 1).

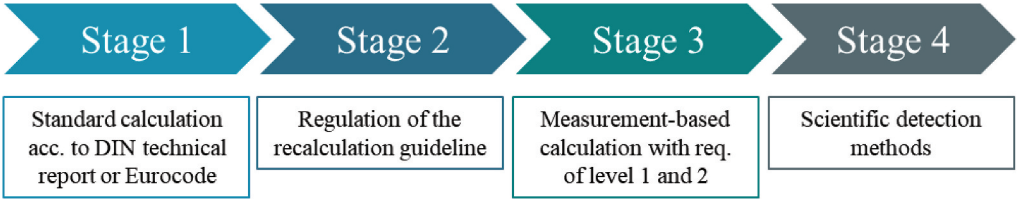

Figure 1. Stages of the recalculation guideline.

In Stage 3, additionally, sensor-based measurements of external influences or structural behavior can be integrated into a so-called monitoring- or measurement-based calculation. The verification result can extend the assessed lifespan of bridges without necessitating restrictions through traffic compensatory measures or costly reinforcement interventions (DBV 2018). While there are numerous practical examples for Stage 3, the recalculation guideline does not provide sufficient information on procedures. ANYTWIN aims to standardize these procedures.

2.1 *Examined failure mechanisms*

In (Fischer et al. 2016) and (Neumann & Brauer 2018), verification results of concrete, steel, and composite bridges were analyzed, evaluating the cause and effect of significant deficiencies. These analyses in ANYTWIN are used to determine the failure mechanisms to be investigated.

To verify and update these analyses and capture the impact of the optimized verification formats introduced since the implementation of the recalculation guideline, ANYTWIN will conduct a survey of infrastructure operators in December 2023. This survey will gather the experiences and challenges of operators with existing regulations and frequently encountered verification deficiencies. Furthermore, infrastructure operators will be surveyed regarding their current handling of Stage 3 and potential support in the application of measurement technology in the context of bridge reassessment.

Initial results of the analyses indicate that the most common deficiencies in verifications arise from the following five failure mechanisms:

- Failure of Couplings in Coupling Joints (Fischer et al. 2016)
- Stress Corrosion Cracking (Fischer et al. 2016)
- Shear Cracking (Fischer et al. 2016)
- Plate Buckling (Neumann & Brauer 2018)
- Fatigue (Neumann & Brauer 2018)

These five failure mechanisms will be further examined in the ANYTWIN project.

2.2 *Investigation of optimization opportunities through sensor-based monitoring*

The failure mechanisms can be described by limit state equations. The parameters included in the equations are examined regarding their impact on the results (sensitivity analysis) and their measurability through sensor-based methods. In the development of standardized measurement concepts, reference is made to the sensitive parameters that have a significant impact on the failure mechanism.

As an example, the limit state equation for fatigue verification at coupling joints is formulated as follows, see Equation (2.1).

$$g(x) = D_{limit} - D \tag{2.1}$$

This is based on the Palmgren-Miner rule, which requires the stress amplitudes $\Delta\sigma$ of all crossings to determine the damage sum D and is described by Equation (2.2).

$$D = \sum_i D_i = \sum_i \frac{n_i}{N_i} = \sum_i \frac{n_i}{\frac{\Delta\sigma_{Rsk}^m \cdot N^*}{\Delta\sigma_i^m}} = \frac{1}{\Delta\sigma_{Rsk}^m \cdot N^*} \cdot \sum_i n_i \cdot \Delta\sigma_i^m \tag{2.2}$$

If strains are directly measured on the prestressing steel, they can be converted into stresses and directly integrated into Equation (2.2). However, this approach requires exposing the tendons, which is not always desired due to the additional damage it causes (Steffens 2019). As an alternative, it is possible to determine the damage sum according to (Zilch et al. 2001) using Equation (2.3), where the prestressing steel stress is calculated, for example, using a finite element model. It should be noted that the basic moment (M_0) in a prestressed concrete cross-section influences the stress range due to the non-linear structural behavior of prestressed concrete according to Figure 2.

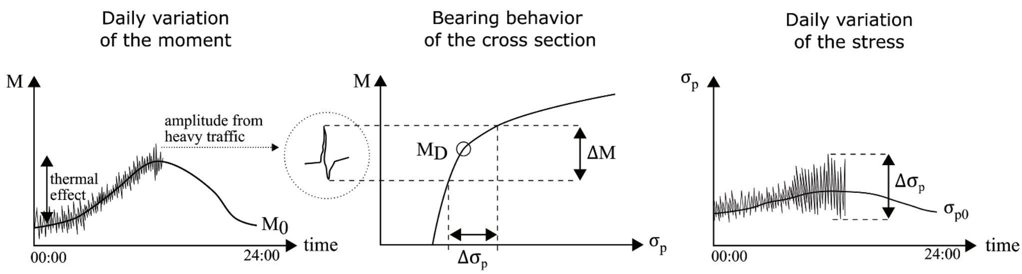

Figure 2. Stress amplitude ranges depending on the daily variations in temperature and vehicle loading.

As a result, the moment-stress relationship must be correctly recorded in the finite element model. Additionally, the actual basic moment is required to determine the stress range according to Equation (2.4).

The basic moment includes effects from dead loads, prestressing, settlements, and temperature. Whereby these can be assumed to act as constants, except for the cyclic temperature loading.

The influence of the basic moment on the stress range requires different temperature conditions to be considered when calculating partial damage from traffic-related alternating stresses (Krohn 2014).

$$g(x) = D_{limit} - N_{tot} \cdot \sum_{\Delta T = \min \Delta T}^{\Delta T = \max \Delta T} \left(\sum_{i=1}^{j} \left(\sum_{h=1}^{24} \lambda_{V,h} \cdot \lambda_{T,\Delta T,h} \cdot p_i \cdot D_{\Delta T,i} \right) \right) \tag{2.3}$$

$$\Delta\sigma(M_i) = \sigma(M_{perm} + M_{\Delta T} + M_{Q,max,i}) - \sigma(M_{perm} + M_{\Delta T} + M_{Q,min,i}) \tag{2.4}$$

where D_{limit} = limit of the total damage sum; N_{tot} = number of heavy vehicles in the period of use; $\lambda_{V,h}$ = share of heavy traffic during hour h in the total daily traffic volume; $\lambda_{T,\Delta T,h}$ = probability of the temperature gradient ΔT occurring during hour h of the day; p_i = share of vehicle type i; $D_{\Delta T,i}$ = partial damage of vehicle type i with simultaneous temperature gradient ΔT analogous to (2.2) by determining the stress ranges $\Delta\sigma_i$ according to (2.4).

Sensor-based measurements are primarily related to variable loads or stresses, as these represent measurable quantities affected by changing conditions. Nevertheless, the measurement of constant residual stresses typically entails significant effort. In the fatigue failure mechanism of the couplings, variable influences such as heavy traffic and temperature changes affect the magnitude of the stress range. Through long-term monitoring, the actual temperature gradients and traffic loads influences can be recorded. Traffic influences can be subsequently converted to the service life period, with or without considering traffic developments, as outlined in (Steffens & Geißler 2021). Furthermore, through short- or long-term measurements, it is possible to measure the behavior of the real structure, evaluate the basic moment and adjust the moment-stress relationship used for recalculation, as shown in (Zilch & Penka 2014) and (Weiher et al. 2015).

2.3 *Development of standardized measurement and analysis concepts*

For the measurement-based verification of failure mechanisms, standardized measurement concepts are developed. These include information on the type, scope, and location of sensors, as well as the respective measurement periods, sampling rates, and requirements for data processing. The challenge of standardization is to separate the measurement requirements from the uniqueness of each structure. To ensure the cross-structure usability of the measurement concepts, parameterized finite element models are developed, and influences on the choice of concept parameters are examined.

Like the approach of the recalculation guideline (Figure 1), ANYTWIN follows a stagewise progression in the measurement concepts, in which the complexity of the measurement task gradually increases. For example, in the case of coupling fatigue, in the first stage, over a limited period in summer (high temperature gradients) and under real traffic conditions, only the crack width of the coupling joint and the concrete strain in the uninterrupted area immediately adjacent to the coupling joint are measured and compared. Significant differences would indicate "joint breathing" and thus a potential fatigue problem. In subsequent stages, the scope and duration of the measurements can be expanded to pursue more complex approaches for calibrating the basic moment and the occurring temperature gradients and traffic loads. Figure 3 shows an exemplary excerpt from a measurement report with the positions of temperature sensors and displacement transducers, as well as exemplary data trends.

Evaluation concepts are intended to establish processes and conditions for substituting the verification-relevant physical parameters with a value based on raw measurement data. In the

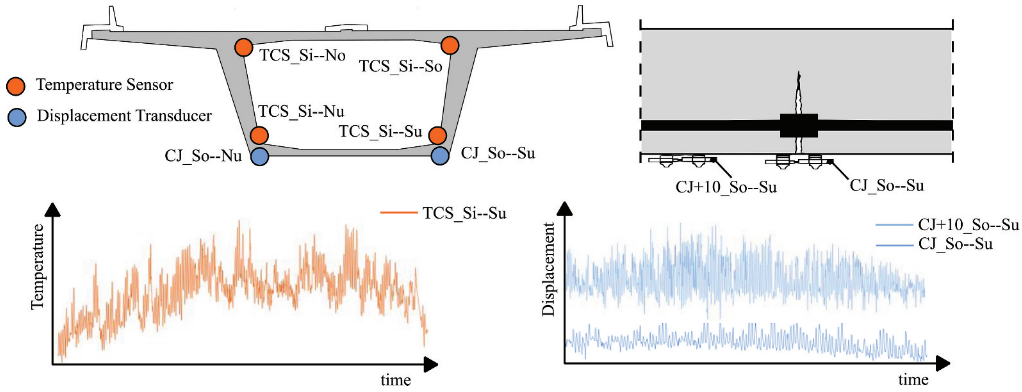

Figure 3. Exemplary measurement layout and corresponding data trends.

present example in Figure 3, this would involve converting the data from individual temperature sensors into a resulting vertical temperature gradient. Both the measurement and evaluation concepts need to be developed by the normative safety requirements of Eurocode 0.

3 CONCEPT OF A DIGITAL TWIN

Germany's sustainability strategy (BMVI 2020) is aligned with the 17 Sustainable Development Goals of the UN Agenda 2030. Goal 9 includes the establishment of a "resilient transportation infrastructure." The strategy prioritizes "maintenance over expansion and new construction" and the optimization of traffic flow. The German "BIM Master Plan" for Federal Highways (BMVI 2021) envisions the future scenario of maintenance and operation based on Digital Twins. After Building Information Modelling (BIM) has been established in the planning and manufacturing phases, the development and testing of Digital Twins are intended to create a "Master Plan" for Digital Twins. This perspective also includes integrating verifications of failure mechanisms, conducted either as a one-time assessment or continuously through sensor-based monitoring, into a Digital Bridge Twin. In ANYTWIN, a concept is being developed as a basis for this. The focus lies on the operational phase, where Digital Twins enable real-time monitoring.

3.1 *Definition and characterization of the Digital Twin*

The term "Digital Twin" originated in 2002 and 2003 when Grieves and Vickers described it as a "conceptual ideal for the product lifecycle management" using the example of a motor vehicle (Grieves & Vickers 2017). Today, the user-specific definition of a Digital Twin varies across different industries:

In the wind energy industry, the Digital Twin is primarily understood as a three-dimensional finite element model calibrated with real-time information for structural assessment (Solman, et al., 2022). In mechanical engineering, the Twin is defined as a virtual assistance system in connection with Mixed Reality in plant operations, enabling remote monitoring and maintenance of critical machine components (Schweiger-Recksiek et al. 2020).

In the construction industry, despite the ongoing digitization and the introduction of BIM, there are no uniform standards for the terms and definitions of Digital Twins. Additionally, there are no standardized definitions for linking with BIM and utilizing it in maintenance management. In bridge construction, the combination of real-time data with a BIM model is increasingly used to create Digital Twins (Lazoglu et al. 2023) (Ye et al. 2019).

The common element of collecting and evaluating information about the actual structure is shared in all definitions. Publications related to construction, like the one by (Boje et al. 2020), offer a general overview of progress in this field.

For most applications in construction, it is not necessary to digitize the physical object with all its information. For example, the use of sensors in construction is currently mainly event-driven, focusing on critical areas and specific damage or failure mechanisms of an object and its surroundings. Abstraction can be achieved through the definition of maturity levels (ARUP 2019). The choice of the maturity level to be developed depends on the engineers' and operators' individual requirements, considering the complexity of the object and its specific safety and relevance to society and the environment. Thus, infrastructure with high operational importance for the transportation network is particularly suitable for developing Digital Twins with higher maturity levels.

The first use cases of the Digital Twin were elaborated in (Nieborowski et al. 2023), serving as a basis for identifying use cases in ANYTWIN.

3.2 *Data integration, management, and provision in the Digital Twin*

The definition of use cases for Digital Twins requires consideration of relevant structural and environmental data. In the context of verifying failure mechanisms, these include e. g. computational results from finite element analysis, primarily evaluated measurement data and sensor states. The quality of this data significantly influences valid structural safety information. It is also necessary to integrate existing conditions and state information (such as damages and material properties) as they have a direct impact on the failure mechanism.

The challenge in data integration lies in the diversity of the heterogeneous data sources, some of which are not digital, machine-readable, or decentralized. In the ANYTWIN project, the current state is being explored, and based on use cases, proposals for data formats, quality requirements, and metadata, especially for monitoring data, are being developed.

In ANYTWIN, the Digital Twin is considered a Single Source of Truth, functioning as a database system where all relevant data, including BIM model information, is digitally stored. To address the size limitation of IFC-files, alternative approaches for integrating extensive monitoring data into Digital Twins are being investigated. Linked and Embedded Data methods are often favored in practice, where BIM structural and domain models are updated in a Common Data Environment (CDE). Additional databases may exist to link dynamic data (Wedel et al. 2022).

Efficient storage, management, and processing require the development of a data structure model, especially at higher levels of automation. In ANYTWIN, a generalized data structure model is being designed based on use cases, serving as the foundation for the development of a flexible database system. The focus is on cross-structure applicability and scalability for potential future use cases.

Approaches are being developed in ANYTWIN for the intuitive provision of relevant condition information in the Digital Twin. These approaches aim to deliver data based on user needs, providing maximum flexibility and efficiency. This supports engineers in making informed decisions about repair measures. It also enables rapid responses to change in structural conditions, with visualizations tailored to various user groups such as infrastructure operators, structural engineers, and the public.

4 VALIDATION OF THE CONCEPTS

4.1 *SmartBRIDGE Hamburg – monitoring system of the Köhlbrand bridge*

In the "smartBRIDGE Hamburg" project, a Digital Twin of the Köhlbrand bridge has been developed with continuous update through data from an extensive monitoring system with approximately 800 sensors (Grabe et al. 2020) (Wenner et al. 2021). The structure comprises a cable-stayed bridge with a steel superstructure and adjacent bridges with prestressed concrete superstructures. Verifications for failure mechanisms such as shear failure, coupling fatigue, steel fatigue, and buckling have been successfully conducted in higher verification stages (including Stages 3 and 4). For the piloting of the Digital Bridge Twin these failure mechanisms have been monitored through measurements for nearly 2.5 years.

For example, strain gauges distributed on the steel box girder capture the stresses within the steel plates. These stresses contribute to an automated, probabilistically guided buckling verification, analogous to (Herbrand et al. 2021). The evaluation is automated by determining a failure probability expressed as a reliability index with a reference period of 50 years (β_{50Y}). This index, along with other condition indicators, is imported into the database of the Digital Twin and made available through the "Condition Control" platform (Herbrand et al. 2022).

The extensive dataset in the Digital Twin of the Köhlbrand bridge allows for the validation of concepts developed in ANYTWIN. Due to the collaboration of some authors in the conception and testing of fundamental concepts in smartBRIDGE Hamburg, synergies can be leveraged across projects.

4.2 *OpenLAB – research bridge in Bautzen, Germany*

As part of the research project IDA-KI, a research bridge, the "openLAB," was constructed as an open research structure (see Figure 4). It is approximately 45 meters long, 4.5 meters wide, and consists of three spans, made of prestressed concrete with tendons in immediate composite action. Additionally, post-tensioning strands were incorporated to enable the replication of a coupling joint issue. Specific structural vulnerabilities, such as damaged tendons, gravel nests, voids, and areas with reduced shear capacity, were deliberately included. To capture changes in condition, measurement technology was installed during the production of the components. A significant portion of the monitoring is conducted using distributed fiber optic sensors (DFOS).

Along the coupling joint, the arrangement of DFOS was carried out in a way that allows the capture of joint opening profiles and strain profiles across the entire cross-section. The extensive measurement equipment of the openLAB, the existing IT infrastructure, and the implementation of a Digital Twin enable the validation of concepts in ANYTWIN. For this purpose, the existing measurement and loading concept from IDA-KI is expanded to meet the requirements of ANYTWIN. Finally, there is the possibility of integrating the measurement data into the existing BIM-based Digital Twin of the openLAB. Further information on the research project IDA-KI and the openLAB can be found in (Herbers et al., in press).

Figure 4. Virtual representation of the research bridge IDA-KI (Hentschke Bau GmbH).

5 SUMMARY AND OUTLOOK

In the research project ANYTWIN, which commenced in September 2023, holistic measurement and evaluation concepts are being developed for the structural assessment of bridge structures and their integration into Digital Twins. Following initial research, the focus for standardizing measurement-based verification is placed on failure mechanisms such as buckling and fatigue in steel bridges, as well as stress corrosion cracking, coupling- and shear failure in prestressed concrete bridges. Standards are being developed for the entire verification process, ranging from sensor requirements (including necessary metadata) to data cleansing and integration into failure equations. The conceptual development for the verification of coupling fatigue is the starting point.

This article presents the results of an initial investigation into the definition and existing concepts and implementations of cross-industry Digital Twins. Subsequently, ANYTWIN aims to develop a data structure model for the Digital Twin, based on which the collected and analyzed data can be stored in a flexible database system and visualized appropriately for different user groups. This approach ensures the full utilization of the benefits of the Digital Twin, providing effective support for infrastructure operation. Standardization requires a comprehensive systematic compilation of ideas and concepts, as well as the implementation of numerous Digital Twins that must be carefully evaluated through pilot projects. ANYTWIN will play a crucial role in this process.

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