

Damage Identification Strategies for the Preservation of an Existing PC-Bridge

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ABSTRACT

This paper explores the application of Structural Health Monitoring (SHM) as a decision-making tool for the preservation of the Nibelungen Bridge in Worms (NBW), a prestressed concrete (PC) bridge completed in 1953. The NBW exhibits damage mechanisms that are characteristic of PC-structures of that era, including corrosion of tendons and inadequate shear load-bearing capacity. To address these issues, an initial SHM system was installed in May 2023. The present study proposes damage identification strategies aimed at preserving the NBW. By leveraging SHM data, the study explores both model-based and data-based approaches to ensure the long-term safety and functionality of this historic structure.

INTRODUCTION

In recent years, Structural Health Monitoring (SHM) has emerged as a vital non-destructive assessment method for civil engineering structures, particularly bridges [1, 2]. In contradistinction to conventional techniques, such as visual inspection, SHM enables continuous real-time monitoring of structural conditions. This capability facilitates the early detection of structural damage, allowing for timely implementation of remedial measures. SHM significantly enhances the information foundation necessary for the long-term and safe preservation of bridges, especially those exhibiting construction-era deficiencies (e.g., stress corrosion cracking). The Nibelungen Bridge in Worms (NBW) serves as a case study of this application.

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The NBW is a PC bridge that spans the river Rhine in southwestern Germany (see Figure 1). Completed in 1953, it was one of the first bridges to be erected using cantilever method. The structure has a length of 351 meters, with a span configuration of $23.2 + 101.6 + 114.2 + 104.3$ meters (see Figure 1). The cantilevered superstructures are coupled at the center of the main spans via vertically prestressed Gerber joints. The superstructure consists of two box girders connected by a deck slab and cross beams.

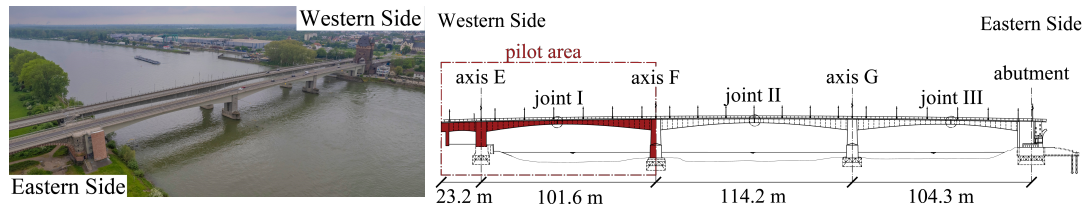


Figure 1. Aerial photograph (left) and side view (right) of the NBW.

At the time of its construction, in 1953, prestressed concrete technology was still in its infancy. As a result, the bridge exhibits damage mechanisms that are typical for structures from this period:

- 1) *Corrosion of internal tendons and reinforcements:* After its completion, NBW did not include a waterproofing system, and furthermore, cooling pipes damping the hydration heat were directly embedded in the webs and the bottom slab of the box girder. For many years, these structural weaknesses allowed de-icing salt to penetrate the interior of the structure.
- 2) *Insufficient shear load-bearing capacity:* At the time the bridge was built, the shear load-bearing capacity was validated using a main tensile stress criterion. Stirrups were not constructed in the cross-sections.

These deficiencies led to an assessment in the early 2020s, which determined that the remaining service life of the bridge would be limited to 15 to 20 years. Consequently, demolition was scheduled for 2025, with a replacement bridge planned for completion in 2028. However, in 2022, the preservation strategy was revised with the objective of extending the service life of the bridge beyond 2028. At present, the road authority Landesbetrieb Mobilität (LBM), the research project SPP 100+ and engineering firms are collaborating to develop suitable preservation concepts [3, 4]. A fundamental element of these endeavors is the initial monitoring system, which was installed and commissioned in May 2023 in the pilot area of the NBW (see Figure 1).

THE MONITORING SYSTEM OF THE NBW

The monitoring system includes the monitoring tasks of the central project of SPP 100+ at TU Dresden and of LBM. The challenge in designing an initial monitoring system for the SPP 100+ was to provide comprehensive data on environmental conditions and structural reactions that could answer a variety of different, yet undefined, questions. Based on engineering knowledge, monitoring measures were derived and concluded in a monitoring concept. The monitoring concept includes six monitoring tasks with a total of 20 measuring points (see TABLE I). These measures involve recording environmental conditions and the structural behavior of the bridge. All sensors are installed on the southern box girder of the pilot area (see Figure 2).

In cooperation with the SPP 100+ central project, LBM has planned and installed a weather station and a thermal camera on the NBW to record outside air temperature, humidity, solar radiation intensity, and precipitation as well as traffic flow on the bridge. The monitoring tasks were planned with TU Dresden from the outset. They use the same technical infrastructure for data transmission, storage, processing and provision. Consequently, the measured data except for the thermal camera data (images and videos) is synchronized over time.

TABLE I. OVERVIEW OF SENSORS.

Label	Sensor type	Measurement variable	No. of sensors	Frequency	Monitoring task
Originally planned sensors from SPP 100+					
TI	combined temperature	air temperature (inside box girder)	2	10 Hz	IB - inside box girder condition
LI	and humidity sensor	humidity (inside box girder)	2	10 Hz	
TU	wired temperature sensors	component temperature	8	10 Hz	CT - concrete temperature
BU	IEPE accelerometers	acceleration	2	200 Hz	DB - dynamic behavior
DU	LVDT	concrete strain	2	10 Hz	SB - basic structural behavior
NU	tiltmeter	inclination	2	10 Hz	
LVU	LVDT	longitudinal displacement	2	10 Hz	
Additional sensors from LBM					
TA	combined temperature	air temperature (outside box girder)	1	10 Hz	EC - environmental condition
LA	and humidity sensor	humidity (outside box girder)	1	10 Hz	
N	precipitation sensor	precipitation intensity	1	10 Hz	
S	pyranometer	solar radiation intensity	1	10 Hz	
TC	thermal camera	traffic videos and pictures	1	event-driven	TF - traffic flow

Note: The labeling was defined following the monitoring task according to German language, they are not translated in this work.

In detail, environmental conditions, such as air temperature, humidity, and component temperature, are monitored at two positions along the bridge axis: one near axis E and the other close to the Gerber joint I of the first main span (see Figure 2). Wired temperature sensors measure the component temperature in the webs, bottom slab, and top slab of the southern box girder. Combined humidity-temperature sensors are used to monitor the air temperature and humidity inside the box girder.

The structural behavior of the bridge is monitored through static and dynamic measurements. Static measurements include sensors to monitor concrete strains, inclinations, and relative longitudinal deformations. To monitor the inclination of the cantilever ends at mid-spans, two uniaxial electrolytic tilt sensors labelled (NU) were installed to both sides of the Gerber joint in the longitudinal direction of the bridge. The monitoring task (DU) includes two inductive displacement transducers to monitor the strain state of the superstructure. The sensors were attached to the top and the bottom of the web, positioned 4 m and 0.3 m above the bottom slab, respectively. In addition, two potentiometric displacement transducers (LVDT) were installed on the bridge to measure the relative displacements between the cantilever ends. These transducers were

positioned at the Gerber joints in two different heights: near the top and the bottom slabs (see Figure 2). Two uniaxial Integrated Electronic Piezoelectric (IEPE) accelerometers (BU), positioned in the middle of the left cantilever beam and at the Gerber joint, with a measurement range of ± 5 g, are used to monitor the dynamic structural behavior. The measuring direction corresponds to the vector of gravity.

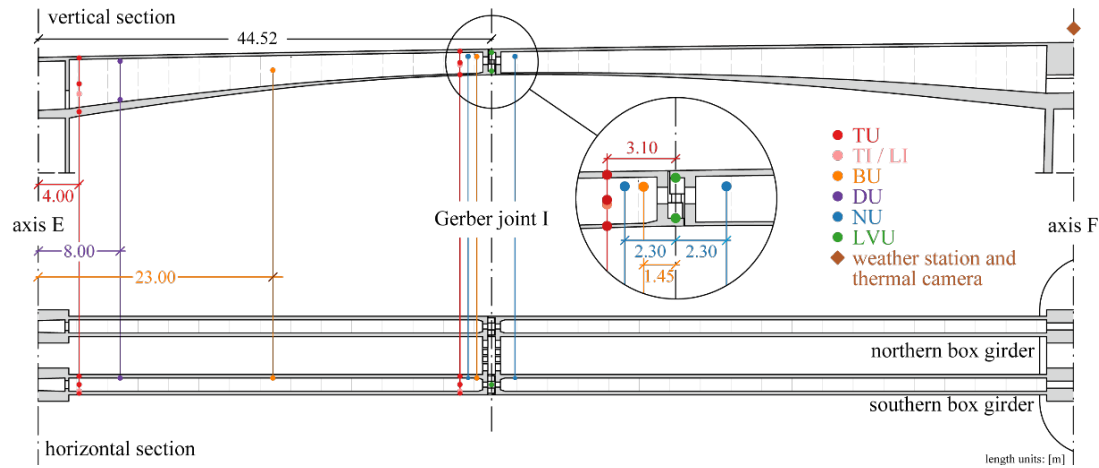


Figure 2. Position of sensors in the pilot area of the NBW.

Except for the accelerometers, which measure with 200 Hz frequency, all other sensors measure with a frequency of 10 Hz. For continuous long-term measurement, data storage is conducted at a reduced storage frequency. Each storage sample for each measurement point, except for accelerometers, should include the following values: the current measured value at the time of storage, as well as the average, maximum, and minimum values over a storage interval of 10 minutes. For accelerometers, short-term measurements are performed at a frequency of 200 Hz, with data storage occurring at a fixed interval of 60 minutes. A 120-second segment of data is stored at the beginning of each hour (e.g., from 09:59:55 to 10:01:55).

Further information regarding the planning, installation and implementation of the monitoring system, as well as its integration in the digital twin of the NBW, can be found in [5]. The referencing of the sensors on the structure is subsequently done by specifying the sensor label (see Figure 2) and the station of the sensor along the axis. For instance, TI E+41.3 m denotes the sensor measuring the air temperature inside the box girder, situated at 41.3 meters from the pier axis E.

DAMAGE IDENTIFICATION STRATEGIES

In SHM literature, two primary approaches for damage identification are discussed: a data-based approach and a model-based approach [6]. The data-based approach relies exclusively on the analysis of in situ data from the structure (e.g., acceleration data) and typically employs principles of statistical pattern recognition [7]. Conversely, damage identification within a model-based condition assessment is achieved by evaluating a physical model adapted to the real structure. The following sections present a model-based and a data-based approach currently being investigated at NBW.

Model-based Approach

The adaptation of a numerical model to real measurement data is a key step in the model-based approach. The parameters of a finite element (FE) model are iteratively adjusted until the model's responses closely match the measured quantities from the structure (e.g., accelerations). The complexity and high dimensionality of this adaptation process pose a significant optimization challenge [8]. After the adaptation process, damage detection is performed by comparing the identified system parameters of the adapted models at varying measurement times.

As part of SPP 100+, a concept for model-based SHM is being validated using numerical measurement results. The developed methods for damage detection include nonlinear FE-model-adaptation, genetic algorithms, and the implementation of artificial neural networks to enhance the reliability of the approach, as detailed in [9].

The complexity of the FE model is a pivotal element in the process of model adaptation. Simplified assumptions during the modeling process can result in erroneous outcomes and an inaccurate representation or incorrect adaptation of the system parameters. For a detailed representation of the NBW, a parameterized FE model was created in the FE software DIANA, consisting of 34,670 3D volume elements with 713,620 nodes, see Figure 3 (a). The FE model incorporates geometric nonlinearities as well as the non-linear material behavior of concrete. The geometry of the reinforcement and tendons was accurately modelled based on the available construction plans.

The system parameters were implemented into the FE model using surface functions [10]. To achieve a reliable approximation of the structural condition within a model-based condition assessment, it is necessary to implement additional sensors into the existing monitoring concept and to validate the initial model through load tests. Preliminary assessments of the model's initial plausibility entailed a comparison between the numerically derived temperature progression of the concrete at the pier clamp and the sensor data of the NBW. For this purpose, the air temperature data inside and outside of the box girder from sensors TA and TI E+4.0 m (see TABLE I) were applied to the FE model as a time-discrete variable temperature load. Then a heat flow analysis was performed to calculate the component temperature in the deck slab, webs, and bottom slab. Figure 3 (b) shows the temporal progression of the measured component temperatures (blue) and the simulated component temperatures (red) in the southern web of the box girder for June 2023.

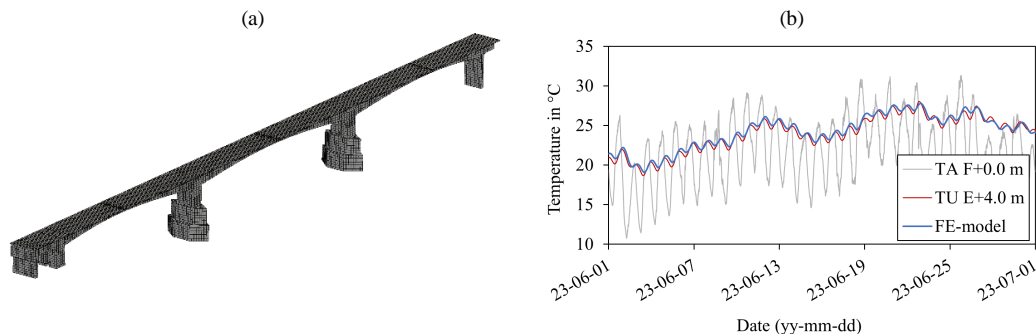


Figure 3. (a) FE-model of NBW and (b) comparison between measured and simulated component temperatures in the southern box girder at Station E+4.0 m

The results show good agreement between the model and the real measurement data with respect to the amplitude of temperature fluctuations and the temporal progression. The average deviation between the measurement data and the simulation results for June 2023 is 1.26%. Further investigations will include a comprehensive validation of the model through static load tests. In addition, the numerical reaction forces generated by the model can be verified not only in the pilot area but also along the entire length of the bridge using additional sensors (e.g., DFOS sensors [4]).

Data-based Approach

The corrosion of internal tendons and reinforcement represents a critical issue for the NBW, as outlined in the introduction. A structural investigation conducted in 2008 revealed elevated chloride concentrations in nearly all components of the box girder.

The process of corrosion is initiated when three fundamental conditions are met: the presence of electrolytes (moisture), oxygen, and the depassivation of steel. Depassivation can result from the carbonation of the concrete or chloride ingress near the tendons or reinforcements. Given the confirmed presence of chlorides and the presumption of ample oxygen available, it is imperative to monitor the influence of moisture for the purpose of assessing the corrosion risk of the superstructure.

Historically, defective drainage and waterproofing systems have been a contributing factor to substantial moisture and corrosion damage in the NBW, particularly affecting the deck slab. However, comprehensive rehabilitation works between 2010 and 2013, which included the installation of fully functional drainage, waterproofing systems and external surface protection systems, resolved the issue. As a result, the occurrence of moisture is predicted to be exclusive to the forms of humidity or condensation within the box girder. Consequently, the duration of condensation occurrence has been identified as a suitable indicator for corrosion.

Condensation cannot be directly measured with sensors; it can only be calculated by continuously measuring the relative humidity RH , ambient temperature T_a , and component temperature T_c . The calculation process for the duration of condensation occurrence is illustrated in Figure 4.

First, the dew point temperature T_D is calculated based on the relative humidity and ambient temperature inside the box girder. Subsequently, the temperature differential between the dew point temperature and the component temperature of the deck slab is determined. The deck slab has been identified as the most critical box girder component due to its high chloride contamination and exposure to traffic and environmental influences such as precipitation. Condensation occurs when the component temperature falls below the dew point temperature, fulfilling the condition $T_c - T_D(RH, T_a) < 0$. The measurement points used for this condition indicator are located inside the box girder near the Gerber joint (Station E+41.3 m, see Figure 2).

The results for January 2024 are shown in Figure 4. This month represents the only instance since the monitoring system's commissioning in which condensation water was calculated. The corresponding area is marked in red. The results demonstrate that condensation events are rare. However, extended observation periods are required to provide a reliable assessment of the damage potential caused by the formation of condensation. Additionally, the presented method enables only a qualitative evaluation of corrosion by identifying critical periods with augmented damage potential. In future studies, condensation formation must be quantified and linked to the corrosion process.

This will enable the definition of threshold values to support infrastructure operators in decision-making for maintenance management.

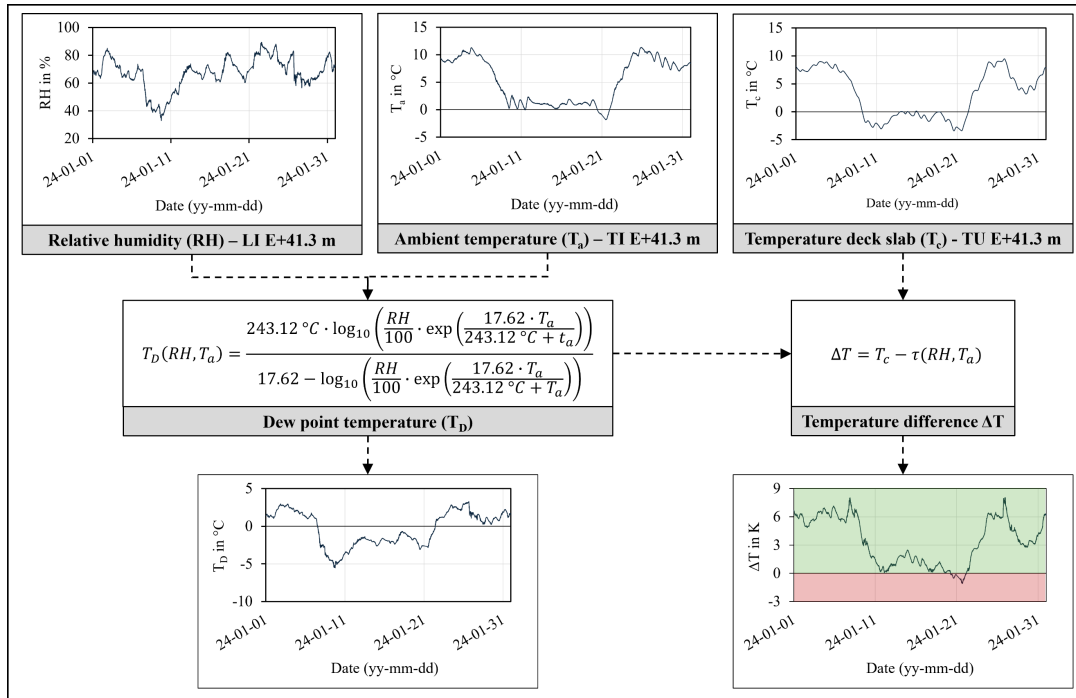


Figure 4. Schematic representation of the calculation process of dew point temperature and the duration of condensation occurrence for January 2024.

CONCLUSION AND OUTLOOK

The investigations demonstrated the feasibility of using both model-based and data-based approaches to support the preservation of the NBW. The model-based approach yielded promising results in accurately simulating the heat flow in the superstructure. In contrast, the data-based approach provided valuable insights into corrosion risks, particularly through the monitoring of condensation formation. The findings emphasize the importance of integrating SHM data into decision-making processes for bridge maintenance. However, the paper also identified areas for future research. To enhance the reliability of the FE-model, further validation through load tests, along with the integration of additional sensors across the entire bridge (not just in the pilot area) is essential. Furthermore, it is imperative to extract features for damage identification for the model-based approach (e.g., to monitor shear cracks). Conversely, in the data-driven approach, the effects of condensation on the corrosion process must be quantified, and threshold values that correlate with corrosion risk must be determined.

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