Advanced life-cycle assessment of reinforced concrete bridges using digital twin concept

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ABSTRACT: This paper proposes a concept for enhancing the maintenance of aging reinforced concrete bridges using online bridge monitoring system coupled with advanced non-linear numerical modelling. Based on the on-site measurement data, a calibrated non-linear numerical model is developed and then further used for the simulation of the degradation mechanisms, such as chloride-induced reinforcement corrosion. This allows assessing the reduced structural load-bearing capacity and thus predict the rate of structural degradation. An example pilot study is presented showing the development and application of the digital twin for a two-span reinforced concrete bridge. The obtained numerical data are discussed and evaluated within the framework of the valid *fib* Model Code standard.

1 INTRODUCTION

In light of the ongoing climate change, the requirements for better environmental sustainability in the concrete industry becoming more and more urgent. It is estimated that the ecological footprint of the cement clinker production is up to 7 % of the total man-made CO_2 (Barcelo et al., 2014). Furthermore, as the World is still recovering from the COVID 19 pandemic, the global economy stagnates, and many contractors face a supply shortage of construction materials. Therefore, there is a demand for a long service life of the existing civil structures.

On the other hand, the long-term degradation acting on reinforced concrete bridges may compromise the serviceability and even safety of the civil infrastructure. One of the means how to face this issue is the development of computational models capable of estimating the impacts of long-term degradation on structural performance.

In this study, we present a pilot application example of a coupled system used for online bridge monitoring and subsequent advanced non-linear finite element (FE) simulation. Then, models for chloride ingress and reinforcement corrosion are incorporated into the FE static analysis, which allows for estimating the response of the structure affected by a chloride attack. By varying the duration of the degradation, the structural load-bearing capacity can be assessed at several stages of its service life. Finally, the reduction of the design structural resistance in time is evaluated based on the method implemented in the fib 2010 model code for the safety assessment by non-linear analysis.

This paper extended the previous study (Červenka and Rymeš, 2023) by implementing the reinforcement bond properties into the model and modifying the loading protocol used for the numerical simulation.

2 ON-SITE DATA ACQUISITION

2.1 *Vogelsang bridge*

The on-site data were measured on a two-span section of the Vogelsang Bridge located in Esslingen am Neckar, Germany. The monitored part represents a reinforced concrete bridge with spans of 13.8 m and 13.2 m. The girder has a constant height of 0.6 m.

The bridge is loaded by the traffic loads and subjected to deterioration mechanisms from the external environment, mainly carbonation of the concrete cover and the chloride attack due to the use of the de-icing salts used for road maintenance in the winter period. Both these mechanisms gradually reduce the pH concentration in the concrete and may eventually lead to reinforcement corrosion and thus reduce the mechanical performance of the structure.

2.2 *Bridge monitoring*

The bridge monitoring was conducted within the framework of the European cyberBridge research project (www.cyberbridge.eu). The data acquisition took 61 days from January until March 2019. The iBWIM (Bridge-Weigh-In-Motion) system was provided by Petschacher, ZT-GmbH, and consists of strain gauges installed on the underside of the bridge deck coupled with a laser rangefinder for detecting the passing traffic. Coupling the structural monitoring sensors with traffic detection allows for obtaining the data needed for structural assessment as well as daily traffic data.

The sensitivity of the system is suitable for monitoring traffic with a gross weight above 3.5 t. Before the data acquisition, the monitoring system was calibrated by the trucks of known weight. Further information about the bridge monitoring can be found for instance in reference (Červenka and Rymeš, 2023), including examples of the obtained data.

3 NUMERICAL SIMULATION

3.1 *Non-linear numerical modelling*

A non-linear FE model for structural analysis of the bridge was developed using the ATENA software (Červenka, Jendele and Červenka, 2022). The software allows realistic simulation of the material behaviour, including concrete cracking in tension or crushing in compression according to the material model developed by Červenka et al. (Červenka, Červenka and Eligehausen, 1998) and Červenka and Papanikolaou (Červenka and Papanikolaou, 2008). In this model, the softening after tensile cracking is evaluated based on the amount of dissipated fracture energy using the smeared crack approach with a crack band while the plasticity approach is used for the simulation of concrete crushing in compression. Reinforcement can be implemented either as smeared or discrete while its material response follows a multilinear stress-strain diagram and thus the reinforcement yielding or even rupture can be simulated.

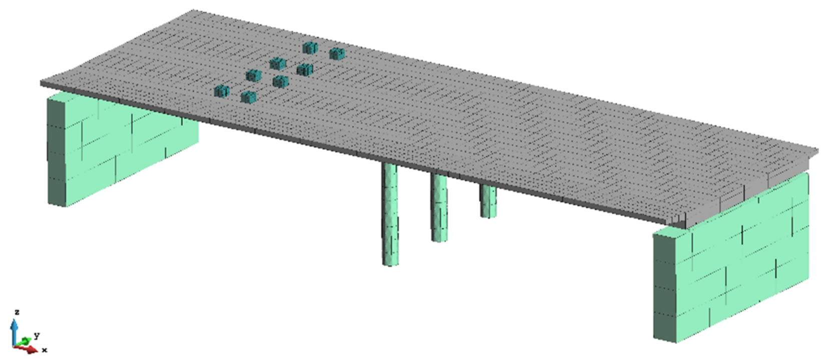

Figure 1. Digital twin of the Vogelsang Bridge.

Utilizing these advanced numerical techniques, a digital twin of the real stricture can be developed. This concept is used any many engineering fields to simulate the behaviour of a real product. In the case of structural engineering, the digital twin is often a computational model, which gives the response of the structure or its section. To assess the durability of a structure, additional degradation models can be implemented in the FE model to simulate various mechanisms affecting the structural performance in time. The FE model of the Vogelsang Bridge is shown in Figure 1.

3.2 *Chloride ingress and reinforcement corrosion*

In the case of reinforced concrete bridges, one of the main degradation mechanism reducing the structural performance is the use of de-icing salts for route maintenance during the winter season. The chloride ions presented in the salts gradually penetrate the concrete microstructure towards the steel reinforcement, which leads to a decrease in the pH level. Eventually, as the alkalinity of the concrete decreases, the corrosion protective function of the concrete cover is lost, and the reinforcement corrosion is initiated leading to the reduction of the cross-section. In the ATENA software, this mechanism is simulated with a chloride ingress model coupled with a reinforcement corrosion model.

The chloride transport through the concrete porous system is a combined diffusion/binding process as the transported ions are absorbed into the C-S-H gel or precipitate as new compounds within the concrete microstructure (Taylor, 1997). In engineering practice, this is commonly modelled using the diffusion equation with a time-dependent diffusion coefficient. Additionally, when cracks occur in the concrete cover as a result of mechanical loads, chloride transport is accelerated. In the case of the structural calculations, as the chloride transport is limited to the regions below the surfaces subjected to the chloride attack, thus the chloride penetration can be simulated as a 1D diffusion process. Such an implementation reduces the time needed for the solution of the diffusion problem, which reduces the overall computational time.

During the calculation, chloride concentration at the depth of the reinforcement is checked and once it exceeds a critical level, the reinforcement corrosion is initiated. Its rate depends on the chloride concentration, temperature conditions, and the duration of the corrosion process. Since the corrosion products are larger in volume than the uncorroded steel, the pressure builds up in the concrete cover, and eventually spalling of the cover occurs. In the corrosion model, this is considered by evaluating the corrosion depth against the tensile strength of the concrete and once the spalling occurs, it is assumed that the corrosion process continues at the rate controlled by conditions of the external environment.

The long-term chloride attack is simulated in multiple steps during this calculation. At each step, the degree of corrosion is calculated and then used to reduce the cross-section area of the reinforcement elements in the model. Based on this, a new static equilibrium is found and the crack width is updated. In the next solution step, the updated crack width is used to accelerate the chloride diffusion process.

The implemented models are mainly based on the research of Liu and Weyers (Liu and Weyers, 1998) and the recommendations published in the DuraCrete report (The European Union–Brite EuRam III, 2000). Further details about the simulation of the chloride penetration and the reinforcement corrosion and how it is implemented into the static FE calculation can be found in the reference (Hájková *et al.*, 2016), including validation of the approach.

3.3 *Reinforcement bond*

In the case of FE simulations of the reinforced concrete structures, either smeared or discrete reinforcement modelling is generally used. In the case of the smeared reinforcement, the cross-section area of the reinforcement is assumed to be smeared over the entire thickness of the concrete solid element thus effectively increasing the element's tangent modulus. Compared to the smeared modelling, discrete reinforcement modelling introduces additional one-dimensional finite elements in the model, which correspond to the actual reinforcement placement in the structure. During the analysis run, the strain continuity between the solid concrete elements and the 1D reinforcement links is assumed during the assembling of the stiffness matrix; however, in a real concrete sample, a slip between the concrete and reinforcement may occur.

For sufficiently fine meshes, the strain discontinuity between the concrete and reinforcement can be simulated as cracking of the elements surrounding the discrete reinforcement elements. It has been shown that this approach can reproduce the crack patterns and the crack width obtained in laboratory experiments if fine elements of the size of several centimeters are used (Cervenka *et al.*, 2022). However, in the case of typical engineering applications, the mesh size is often one or two orders higher. Such course meshes cannot adequately capture the localization process of the fine microcracking around the steel reinforcement bars. Therefore, to capture the bond-slip in engineering simulation, an additional degree of freedom is added to represent the slip between the steel. The bond strength-slip law then enters the simulation as a non-linear material constitutive law, which needs to be met during the iterative solution.

The bond strength-slip material law used in this study was based on the fib MC 2010 standard (International Federation for Structural Concrete, 2013). Furthermore, as the goal of the numerical simulation is to assess structural degradation due to reinforcement corrosion, the relationship between the reinforcement corrosion and relative bond strength by Bhargava et al. (Bhargava *et al.*, 2007) was used.

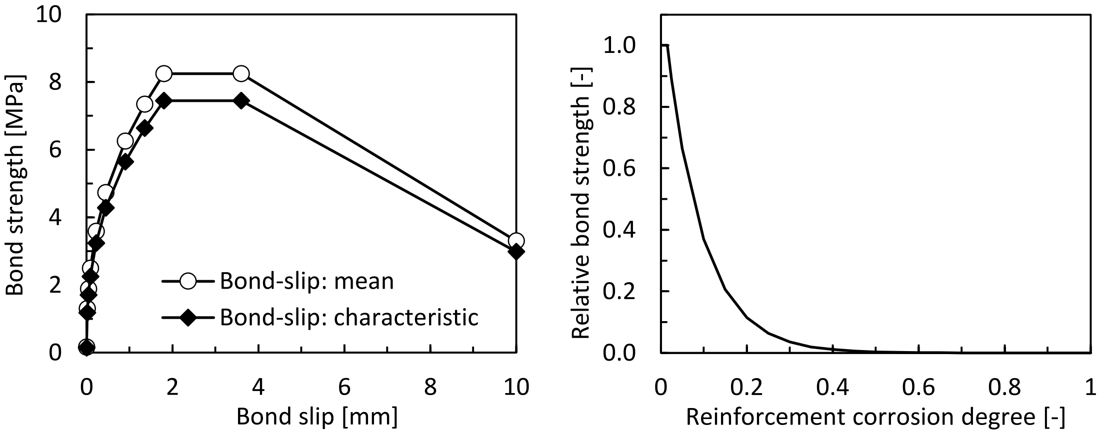

Figure 1. (left) Reinforcement bond strength-slip function for the calculation with mean and characteristic material properties and (right) relative function for reducing the bond strength as a function of reinforcement corrosion (Bhargava *et al.*, 2007).

3.4 *Analysis workflow*

In the case of non-linear analyses, the structural response under a given load combination cannot be assessed as a simple superposition of the given load action as in the case of linear calculation. As the load induces irreversible material response mainly in a form of tensile concrete cracking, each sequence of load applications induces a unique structural response. Therefore, the application of load in a non-linear numerical model should respect the load sequence of the real structure. Furthermore, as the mechanical crack width influences the rate of chloride ingress, the load level also affects the rate of degradation, when exposed to the chloride attack.

In this study, the investigated load combination at the ultimate limit state (ULS) includes the permanent load actions (i.e., the dead loads) and the variable load actions (i.e., the distributed and concentrated traffic loads). For the durability study, the following sequence of load intervals was used to simulate the service life structural history:

1) Design dead loads: self-weight and other dead loads,
2) Design live loads: concentrated and distributed traffic loads,
3) Unloading design live loads from 2),
4) Simulation of the chloride degradation,
5) Overloading with design live loads.

The application of the ULS design loads in intervals 1) and 2) should simulate a critical overloading situation, which may occur during the structure's service life. In the non-linear model, such an event results in crack development. On the other hand, the long-term degradation mechanism act on the structure at lower loads than the USL design load level thus the application of the chloride attack at ULS load level may overestimate the real situation. Therefore, the model was unloaded to the design dead load level, which resulted in a partial reduction of the previously localized cracks. Subsequently, the chloride attack with a duration of 25, 50, 75, 100, 125, and 150 years was simulated. Finally, the live loads were again gradually applied until reaching the peak load.

3.5 *Safety framework*

The results from the non-linear calculations were evaluated based on the *fib* MC 2010 standard (International Federation for Structural Concrete, 2013), which permits the application of non-linear simulations for structural assessment. It is worth mentioning that a similar approach is about to be introduced into the new generation of Eurocodes.

Generally, the safety method can be divided into three categories: full probabilistic, global resistance, and partial factor methods. In this study, the ECoV method, which belongs to the global resistance category, is applied. The general design requirement specifies that the design structural resistance (R_d) should be greater than the effects of the design loads (E_d). Therefore:

$$E_d < R_d \quad . \tag{1}$$

The underlying assumption of the ECoV method is that the structural resistance follows the log-normal distribution, which can be described by the mean (R_m) and characteristic (R_k) structural resistances. These values can be obtained by two analysis runs: one using the mean and one using the characteristic parameters in the applied material models. Then, the coefficient of variation (V_R) of the structural resistance can be calculated as:

$$V_R = \frac{1}{1.65} \ln\left(\frac{R_m}{R_k}\right) \quad . \tag{2}$$

Then, the global resistance factor (γ_R) is calculated as:

$$\gamma_R = \exp(\alpha_R \, \beta \, V_R) \quad , \tag{3}$$

where $\alpha_R = 0.8$ and $\beta = 3.8$ are the sensitivity factor and reliability index, respectively.

Finally, the design structural resistance according to the ECoV method gives:

$$R_{d,ECoV} = \frac{R_m}{\gamma_R \, \gamma_{Rd}} \quad , \tag{4}$$

where γ_{Rd} is the uncertainty of the numerical model. In the case of the ATENA software, γ_{Rd} = 1.16 for all failure modes (Červenka, Červenka and Kadlec, 2018).

4 RESULTS

A typical outcome of the durability analysis is shown in Figure 3 using the model with mean material characteristics and a 150-year-long chloride attack. The crack patterns in concrete are shown for several stages of the calculation. First, when the ULS design load is applied, maximum cracks of approximately 0.3 mm develop in the mid-span and above the center piers of the bridge. Upon unloading to the design dead load level, these cracks partly close and their with is mostly below 0.1 mm. At this stage, the chloride penetration and subsequent reinforcement corrosion are simulated on the top and bottom surfaces of the bridge deck. As a result, the reinforcement cross-section area reduces, the mid-span deflection increases, and the cracks grow. Finally, after 150 years of chloride-induced degradation, cracks of approximately 0.3 mm are predicted in the mid-spans of the decks as well as above the center piers. As the load level is increased, the reinforcement yielding soon occurs, which results in rapid crack growth. At the peak load, cracks exceeding 3.5 mm are predicted by the model.

Similarly, in Figure 4, the development of the stresses in the discrete reinforcement elements is plotted during the calculation. It can be observed how the reinforcement stress increases as a result of the reinforcement corrosion.

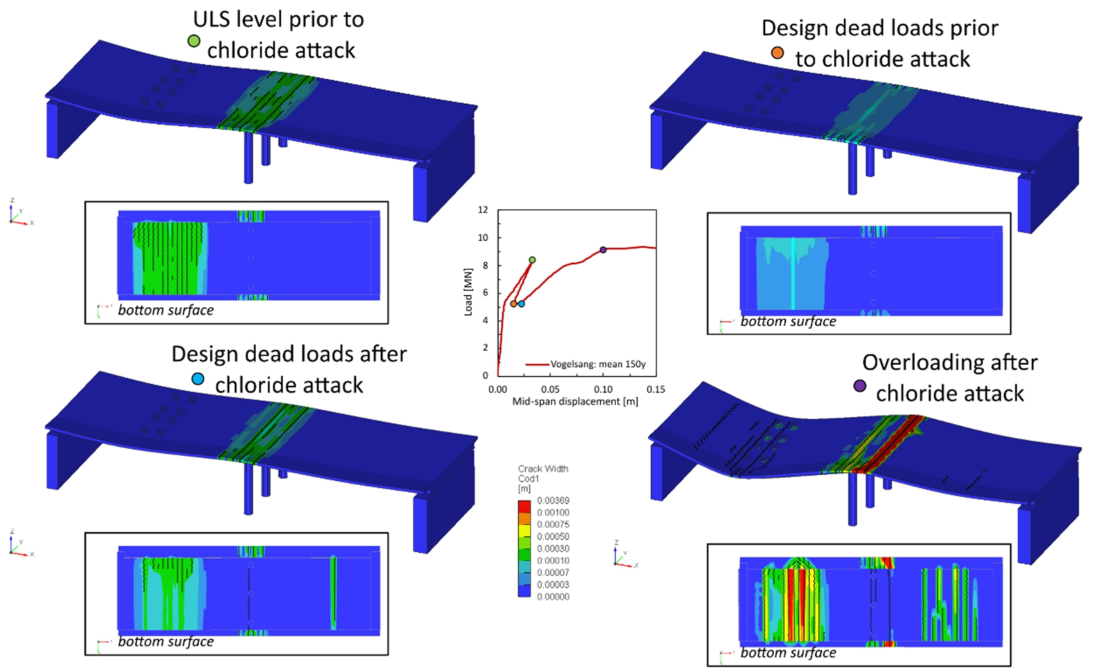

Figure 3. Distribution of the crack width in the concrete at various stages of the calculation for the model with mean material properties and 150-year-long chloride attack (deformation magnified 15x, only cracks larger than 0.1 mm are emphasized).

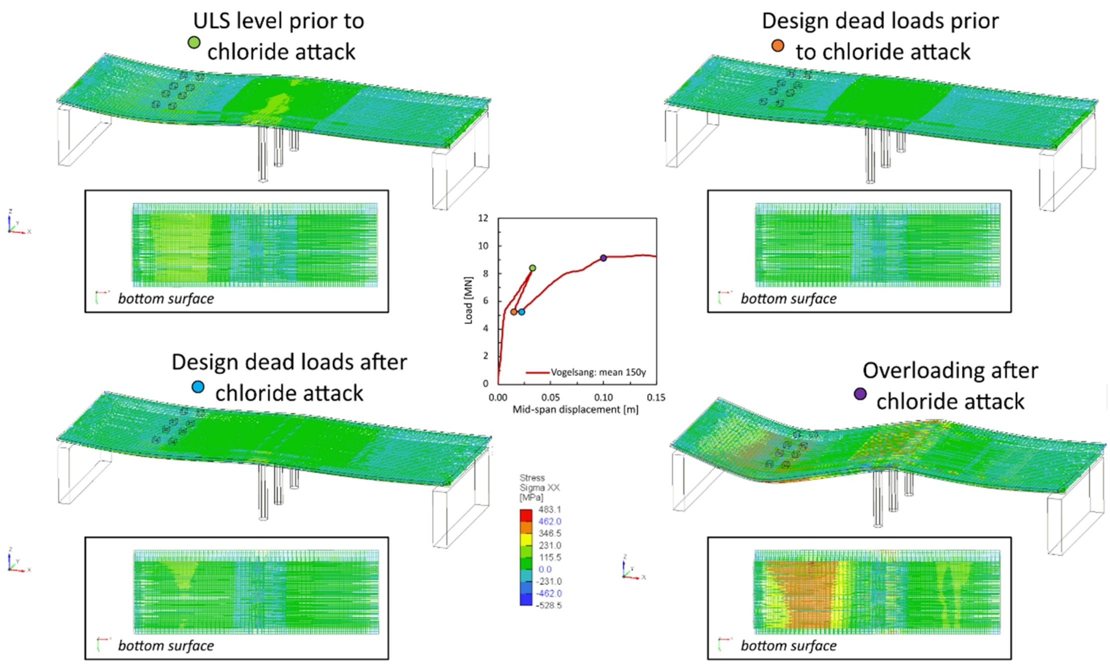

Figure 4. Stresses in the reinforcement at various stages of the calculation for the model with mean material properties and 150-year-long chloride attack (deformation magnified 15x).

The structural response for each analysis run can be represented in a form of a load-displacement (L-D) diagram as shown in Figure 5 (left), where examples of curves for models with mean material properties are plotted. As described previously, the load is first increased to the ULS design load level to simulate an overloading scenario; however, the chloride-induced reinforcement corrosion is simulated at a lower load level. This is exhibited by the increase of the deformation at constant load on the L-D diagram. While for the model of a 50-years-long chloride attack, the degradation is rarely visible, for longer degradation periods, it can be seen how the mid-span deflection increases because of reinforcement corrosion, and subsequently, both stiffness and maximum load-bearing capacity are reduced during overloading simulation.

To deduce the design structural resistance, the analysis is conducted with mean and characteristic material properties for each duration of the chloride attack. Then, based on the maximum load from both analysis runs, the design load-bearing capacity is calculated using the ECoV method (see section 3.5) at the given age of the structure. From the plot in Figure 5 (right), it can be observed that the design load-bearing capacity exceeds the ULS design load level until the age of the structure of 125 years.

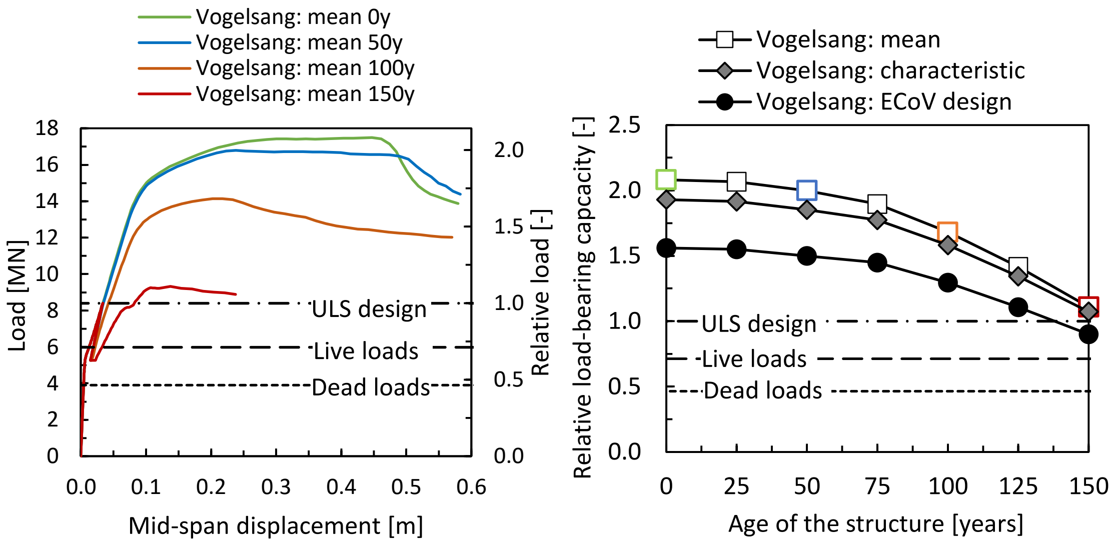

Figure 5. (left) Typical load-displacement diagrams for the calculation with mean material parameters for bridge unaffected by the chloride attack and for chloride attack of 50, 100, and 150 years and (right) reduction of the structural load-bearing capacity in time.

5 SUMMARY

This study presents a comprehensive approach for the assessment of the long-term structural performance of reinforced concrete bridges. In the first step, a bridge monitoring system is used for the data acquisition from the existing reinforced concrete bridge. Subsequently, this data is then used to develop a digital twin of the structure, which can be used for structural assessment. Furthermore, advanced chloride diffusion and corrosion models were used to simulate the structure degradation due to the use of de-icing agents. This model takes into account degradation of reinforcement cross-sectional area and also its bond parameters due to corrosion. The presented approach can predict the reduction of the structural performance in time. The obtained results are evaluated according to the *fib* MC 2010 standard to obtain the design load-bearing capacity of the bridge.

ACKWNOLEDGEMENTS

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