13th
Central
European
Congress on
Concrete
Engineering

Next Generation of Concrete Engineering
for Post-Pandemic Europe

13-14th September 2022

Jan ČERVENKA[1]
Jiří RYMEŠ[2]
Radomír PUKL[3]

Assessment of long-term reliability of reinforced concrete bridges using digital twins

Abstract: Chloride-induced reinforcement corrosion may compromise the serviceability and safety of the civil infrastructure. The early diagnosis together with advanced numerical tools of ageing management can contribute to the maintenance cost efficiency and long service life of reinforced concrete bridges. Such a role can be provided by real-time monitoring systems coupled with advanced numerical tools. The monitoring system is used to monitor the traffic passing the bridge as well as to deduce data for structural assessment. A digital twin refers to a computational model, which, upon calibration, is used to simulate the behaviour of the real structure as well as to predict its degradation rate in the future. In this study, a non-linear finite element model is calibrated based on the on-site measurements and advanced chemo-mechanical models are applied to estimate the chloride ingress, subsequent reinforcement corrosion rate, and its impact on the structural performance. Such an analysis is generally composed of multiple load intervals simulating the application of the typical load level, chloride attack modelling, and simulation of the structural overloading. It is assumed that the structure is subjected to the de-icing agents for up to 150 years since its construction. Finally, the structural resistivity is evaluated according to the methods given in the fib Model Code 2010.

1. Introduction

Ageing road infrastructure represents a severe burden for public expenses in many European countries while being essential for the economy. In this light, the role of civil engineers is to ensure serviceability and safety of civil structures. This role is even more emphasized by the recent collapses of several pre-stressed concrete bridges in the EU region.

One of the means how to improve structural safety is the application of monitoring systems. The products available on the market allow online access to the measured data and, besides structural-related outputs, can provide information about the daily traffic at the bridge that can be further used by the local municipalities.

Together with regular inspections and structural monitoring, numerical models can contribute to the improvement of the safety of civil structures. Similarly, as in other engineering fields, a digital twin concept has been utilized in structural engineering. This term refers to a computational model, which, upon calibration, is being able to replicate all important features of the real structure. For this purpose, finite element (FE) models are often developed. The calibration of the FE model can be done based on the data from the monitoring system. Furthermore, if the numerical model should allow for accessing the long-term structural performance, the degradation mechanisms need to be taken into account. For this purpose, the FE model can be coupled with a transport model simulating the penetration of the degradation agents into the structure.

In this study, two pilot applications are shown. The coupling of the monitoring system with a numerical model for a digital twin was used for the Vogelsang Bridge in Esslingen, Germany and for the Wonka Bridge in Pardubice, Czech Republic.

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[1] Ph.D., Červenka Consulting s.r.o., Czech Republic, jan.cervenka@cervenka.cz
[2] Dr.Eng., Červenka Consulting s.r.o., Czech Republic, jiri.rymes@cervenka.cz
[3] CSc., Červenka Consulting s.r.o., Czech Republic, radomir.pukl@cervenka.cz

2. Development of digital twin models

2.1. Description of structures

For the pilot study, the digital twin replica was developed for two concrete bridges: the Wonka Bridge, Pardubice, Czech Republic and the Vogelsang Bridge, Esslingen, Germany.

For the Vogelsang Bridge, which is overall composed of eight partial structures, two spans of 13.8 + 13.2 m were chosen for the assessment. From the structural point of view, the analyzed part is a non-prestressed RC beam with a height of 0.6 m.

The Wonka Bridge in the Czech Republic is a pre-stressed box-girder concrete bridge consisting of three arches, spanning 50 + 70 + 50 m. The bridge was built between 1956 and 1959. The cross-section depth is up to 3.5 m.

The bridges are loaded with the road traffic and subjected to the deterioration mechanisms originating from the external environment, such as penetration of the de-icing agents and carbonation of the concrete cover.

2.2. Bridge monitoring

For monitoring of the bridges, the iBWIM system provided by Petschacher, ZT-GmbH was used. The system consists of the strain gages installed on the underside of the bridge's deck as shown in Fig. 1. The advantage of this placement is that the installation process does not disturb the traffic. The gauges are coupled with a laser range finder for the detection of the vehicles. Thus, the measured strains can be assigned to a specific event when a truck passes the bridge.

After deconvolution of the raw data, information about vehicles speed, gross weight, number of axles, weights per axles, and vehicle's axle-to-axle and total lengths. Such data can be further used not only for structural monitoring but also by local municipalities for traffic monitoring. The system is calibrated before the measurements using a truck of known weight and it is generally suitable for trucks with a gross weight above 3 500 kg.

The monitoring was conducted as a part of the European cyberBridge project (www.cyberbridge.eu). The data from the monitoring system were collected for 60 days from August until October 2018 in the case of the Wonka Bridge. For the Vogelsang Bridge, the monitoring took 61 days from January until March 2019. The example of the measured data at the Vogelsang Bridge is shown in Fig. 2.

Fig. 1. Photo of the measuring sensors installed on the Vogelsang Bridge, Esslingen.

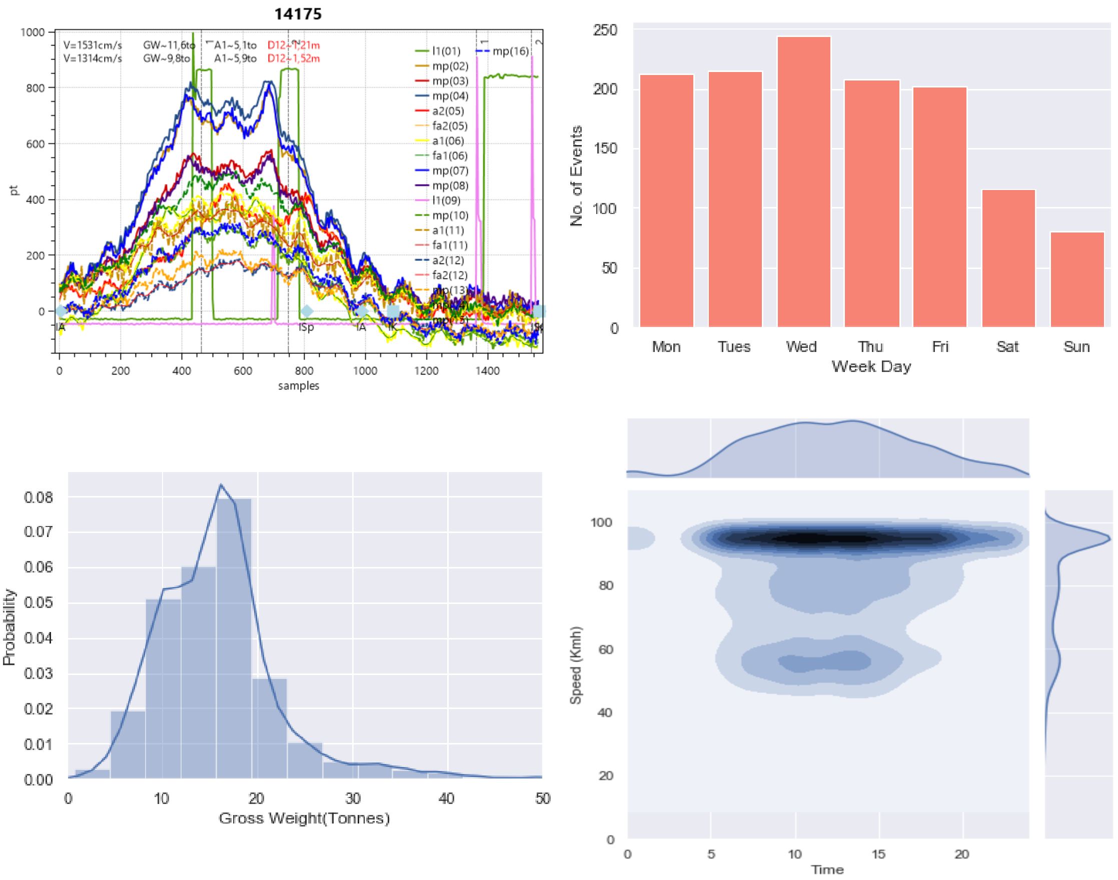

Fig. 2. Examples of the data obtained by the monitoring system on the Vogelsang Bridge: (top left) raw measured data, (top right) weekly distribution of heavy goods vehicles, (bottom left) distribution of vehicles' gross weight, and (bottom right) hourly distribution of vehicles' speed.

2.3. Numerical modelling

A digital twin is an engineering concept for reproducing the behaviour of a real physical object. For the structural assessment, a digital twin can be developed by the means of numerical modelling, most commonly by the finite element method. To predict the real structural behaviour, the non-linear modelling in the ATENA software was adopted. The non-linear models are capable of simulation concrete crushing in compression, cracking in tension or yielding and rupture of steel reinforcement and pre-stressing cables. For concrete, the model of Červenka et al. [1], and Červenka and Papanikolaou [2] was used.

Tab. 1. Summary of the calibration results of the FE models

	Measured	Model
Wonka Bridge, Czech Republic		
strain [μ]	8.35	8.88
Load test mid-span deflection [mm]	14.36	14.23
Vogelsang Bridge, Germany		
strain (group 203) [μ]	77	74
strain (group 204) [μ]	30	43

The FE models were calibrated based on the results obtained from the bridge monitoring. The summary of the calibration results is shown in Tab. 1. Upon calibration, the numerical model should be able to reproduce all important aspects of the real structure, including the long-term performance affected by the ageing mechanism. These mechanisms were implemented into the FEM model through the mechano-chemical model, which considers the acceleration of the deterioration due to the presence of mechanical cracks. Further details about the degradation modelling are given later.

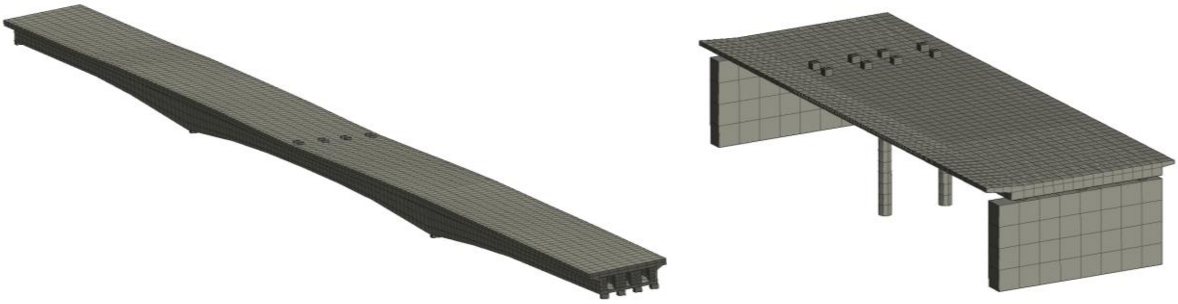

Fig. 3. FEM models: (left) Wonka Bridge, and (right) Vogelsang Bridge, Esslingen.

2.4. Structural degradation

For both structures, the main ageing mechanism is related to de-icing salts used to maintain the roads during the winter season. The chlorides contained in the de-icing salts penetrate the concrete microstructure and are transported towards the steel reinforcement. As the chloride concentration increases, the pH of the porous system decreases, and the concrete can no longer protect the reinforcement against corrosion. Furthermore, the chloride ingress is accelerated in a presence of mechanical cracks. In our modelling, the moment when the corrosion of the reinforcement starts is assumed as the end of the induction phase.

During the propagation phase, the corrosion rate is assumed to be dependent on the chloride content, exposure temperature, and corrosion duration. Since the corrosion products are larger in volumes than the initial steel, the stress builds up in the concrete cover. Assuming the tensile strength of the concrete and the corrosion depth, the moment of spalling of the concrete cover is calculated. After that, it is assumed that the corrosion continues at the rate controlled by the external environment. The different stages in the degradation process are schematically shown in Fig. 3. The models applied in the degradation modelling are based mainly on the DuraCrete recommendations [4], published experimental data [5], and models available in the literature [6].

As the rate of chloride penetration depends on the width of mechanical cracks present in the structure, the load level during the simulation of the degradation process affects the rate of the decrease of the structural performance. Therefore, a representative load level needs to be chosen. In this study, we compared two approaches; for the Wonka Bridge, the chloride attack was assumed under characteristic dead loads while the ultimate design load level was used for the Vogelsang Bridge.

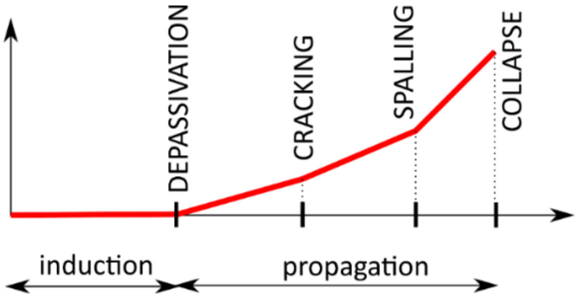

Fig. 3. Schematic representation of the stages in the degradation process.

2.5. Validation of the modelling framework

The corrosion model has been previously tested against experimental data obtained on the Nougawa Bridge, Japan. More details can be found in reference [7] and a brief summary is given here. The Nougawa Bridge was built in 1930 in a coastal area with a severe risk of reinforcement corrosion. At the end of structure's service life, the bridge was removed and subjected to experimental investigation. Among other parameters, the concrete mechanical properties and reinforcement corrosion level were measured. Furthermore, one load-bearing beam was subjected to a bending test. The obtained data represent a suitable test for validation of the numerical framework for digital twin simulations.

In the numerical model, the resulting reinforcement corrosion after 79 years yielded 63.6 %, which agrees well with the measured value of 62.5 %. Similarly, for the bending test data, the numerical load-displacement diagram showed a good match with the results measured during the experiment, including the post-peak response. These data are reproduced from [7] in Fig. 4.

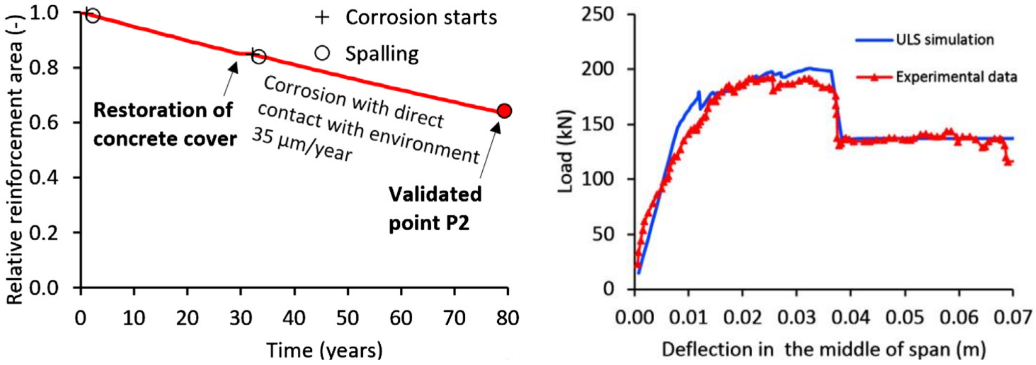

Fig. 4. Summary of the validation of the corrosion model using experimental data from the Nougawa Bridge, Japan. Reproduced from reference [7].

2.6. Safety format for structural check

The structural design check aided by non-linear numerical analysis is already established in the fib Model Code 2010 [8]. The guidelines are given for the full probabilistic method, global resistance methods, and the partial factor method. In this study, the ECOV method, which belongs to the global resistance method category, was used. It relies on the assumption that the structural resistance follows the lognormal distribution, which can be characterized by the mean and characteristic structural resistances. Then, the coefficient of variation can be calculated as:

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

where:
V_r – coefficient of variation, R_m – mean structural resistance, R_k – characteristic structural resistance.

The global resistance factor then gives:

$$\gamma_R = \exp(\alpha_R\, \beta\, V_R) \quad , \tag{2}$$

where:
γ_R – global resistance factor, $\alpha_R = 0.8$ - sensitivity factor for the reliability of resistance, $\beta = 3.8$ - reliability index.

The design structural resistance according to the ECOV method finally yields:

$$R_{d,ECOV} = \frac{R_m}{\gamma_R\, \gamma_{Rd}} \quad , \tag{3}$$

where:
$R_{d,ECOV}$ – ECOV structural resistance, γ_{Rd} – model uncertainty.

3. Results

The overloading simulation showed bending failure mode for the Vogelsang Bridge due to the yielding of the reinforcement in the midspan as shown in Fig. 5. Upon the reinforcement yielding, a concrete crushing region develops. Different failure mode was observed for the Wonka Bridge. Close to the support, the shear forces together with the deviators of the pre-stressing cables subject concrete to significant compression stress, which result in the development of a splitting crack above the support as shown in Fig. 6. Although this failure mode is more brittle than the bending failure predicted for the Vogelsang Bridge, the concrete crushing failure is preceded by significant mid-span deflection. For the compression failure mechanism, the load, at which concrete compressive stains exceed a value of -3.5 ‰, was taken as the maximum load.

For both structures, the failure mode remained unchanged regardless of the duration of the degradation mechanism.

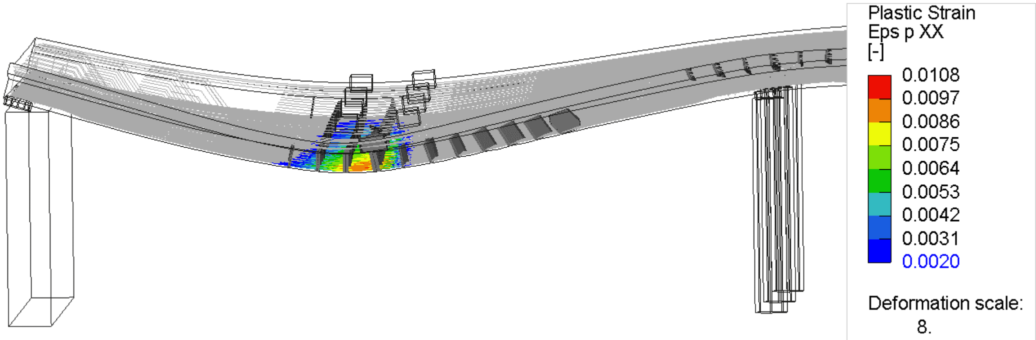

Fig. 5. Plastic strains in the bending reinforcement in the model of the Vogelsang Bridge. The cracks wider than 0.8 mm above the support and in the midspan are shown.

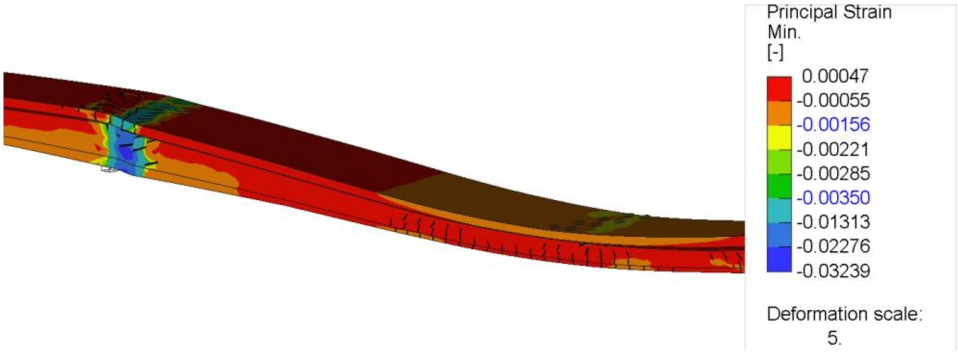

Fig. 6. Formation of the concrete crushing region above the support in the model of the Wonka Bridge.

Typical load-displacement curves are shown for both bridges in Fig 7. For both structures, the reduction of the load-bearing capacity due to chloride-induced reinforcement corrosion is evident. The design load-bearing capacity at different ages was obtained by varying the duration of the simulated chloride attack.

In Fig. 8, the development of the design load-bearing capacity according to the ECOV method is plotted. It can be observed that in the case of the Vogelsang Bridge, the decrease in the design load-bearing capacity is faster than for the Wonka Bridge. This is explained by the different failure mechanisms at the peak load. For the Vogelsang Bridge, a bending failure due to reinforcement yielding is predicted, which is more sensitive to the reinforcement corrosion. On the other hand, the collapse of the Wonka Bridge is due to the concrete crushing above the support, which, although facilitated by the decreasing confinement provided by the reinforcement, is less sensitive to corrosion. Also, for the Vogelsang bridge, the chloride attack was simulated at the ULS load level, which lead to the formation of larger mechanical cracks, thus accelerating the chloride ingress to the concrete. Based on the results summarized in Fig. 8, a service life longer than 100 years can be expected for both bridges.

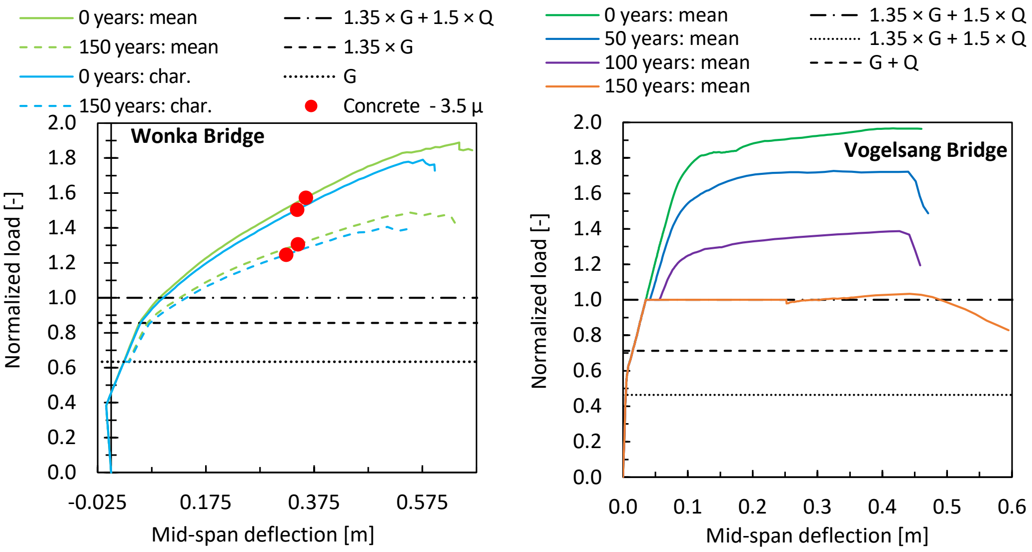

Fig. 7. Typical load-displacement curves: (left) comparison of the analyses with mean and characteristic material properties for different ages of the Wonka Bridge, and (right) analyses with mean material properties showing a gradual decrease in structural performance for the Vogelsang Bridge.

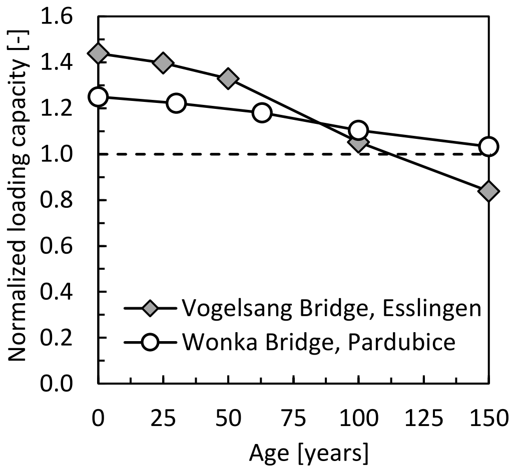

Fig. 8. Development of the load-bearing capacity in time due to reinforcement corrosion for the Wonka and Vogelsang Bridges.

4. Summary

This paper presents a framework for the development of a digital twin that can be used for a long-term evaluation of pre-stressed reinforced concrete bridges. The non-linear numerical models were calibrated based on the data obtained from the on-site monitoring system. Applying the advanced mechano-chemical degradation models allowed for estimation of the chloride ingress and subsequent reinforcement corrosion, which was considered for the structural evaluation. The results from the numerical model were interpreted using the guidelines given in fib model code 2010.

Acknowledgement

The financial support of the Czech Technological Agency, project CK03000023 “Digital twin for increased reliability and sustainability of concrete bridges” is greatly acknowledged.

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