Digital Twin for Modelling Structural Durability

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Abstract. The reinforcement corrosion due to chloride ingress is an important deterioration mechanism, which may compromise the service life of reinforced concrete structures. This study presents a bridge monitoring system coupled with an advanced chemo-mechanical computational method for an estimation of chloride ingress and reinforcement corrosion. Based on-site measurements, a digital replica of the bridge is calibrated and by applying the degradation models, the reduction of structural performance is simulated. Apart from the structural analysis, the data from the monitoring system can be used to deduce information about the daily traffic crossing the bridge. Pilot applications of the proposed coupled framework are shown for two concrete bridges, where a 150-years-long chloride attack was assumed for the assessment of the long-term structural performance. The structural resistance was evaluated by the methods based on fib MC 2010, namely the estimation of a coefficient of variation method (ECOV) and partial factor method (PFM).

Keywords: reinforcement corrosion, chloride ingress, fracture mechanics, non-linear simulation.

1 Introduction

The role of civil engineering for the 21st century is to ensure safe and reliable infrastructure while keeping both financial and ecological costs low. In the EU region, most of the infrastructure was built during the rapid economic growth after World War II implying that the age of many structures now well exceeds 50 years and the maintenance const now represents a severe burden for the public budgets. At the same moment, the concrete industry produced about 7 % of the man-made CO_2 mainly due to the production of the cement clinker, which is required for the construction processes [1]. One of the means how to reduce the negative environmental impact is to ensure the optimal structural lifespan. Apart from regular structural inspections, online monitoring systems can be installed on the structure to monitor structural performance characteristics in real-time. Such systems contribute to better structural safety and, through early diagnosis, help to reduce the cost of repair works.

Digital twin refers to a digital replica of a real structure. Based on the feedback from measurement data on the real structure, the most significant model properties are identified. These appropriate model properties are consequently used for assessments of safety, reliability, durability, and sustainability of the investigated structure under service as well as limit state conditions.

In this study, we show two examples of this methodology. The monitoring system was installed on the Wonka Bridge, Pardubice, Czech Republic and Vogelsang Bridge, Esslinger, Germany. Non-linear finite element (FE) models were subsequently developed for both structures. Upon calibration, the numerical models were used for accessing the long-term structural performance. By applying advanced chemo-mechanical models, namely for the chloride ingress and reinforcement corrosion, the degradation of the structure due to chloride attack was evaluated.

2 Bridge Monitoring System

Advanced measuring systems can be used to monitor structural behaviour in real-time. In this study, the iBWIM (Bridge-Weigh-In-Motion) technology (PEC – Petschacher Consulting, ZT-GmbH) was installed on the bridges. The system consists of strain gauges for deflection monitoring coupled with a laser rangefinder for detection of the vehicles crossing the bridge. The strain gauges are installed in both longitudinal and transversal directions on the underside of the bridge's deck, therefore, the installation can take place without any traffic disruption. The sensitivity of the used measuring system is suitable for the detection of vehicles with a gross weight exceeding 3.5 t. Before starting the measurements, the system is calibrated by crossing the bridge with trucks of known weights.

For instance, the coupled system of a laser rangefinder and strain gauges can be used to deduce data about the vehicle's speed, weight, or load distribution over the vehicle's axles. The data recorded during a single event are shown in **Fig. 1** (left) and the deduced information is summarised in Table 1. The relationship between the load and the structure's response is needed for structural evaluations, namely for calibration and validation of the numerical models. **Fig. 1** (right) shows the relationship be-

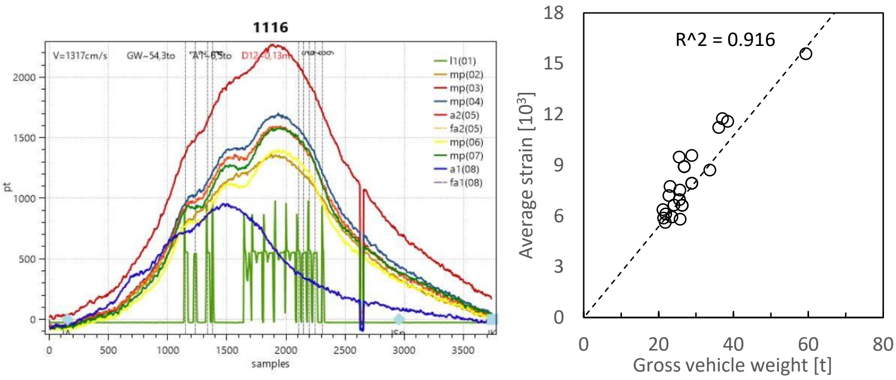

Fig. 1. (left) Example of the bridge monitoring data recorded during a single event on the Wonka Bridge and (right) the relationship between the vehicle's gross weight and the induced strain as recorded by the bridge monitoring system.

Table 1. Example of events and the measured values **Fig. 1** (left).

TST	*ID*	*V*	*AC*	*VC*	*GW*	*Axles*	*Length*	*A2A*	*Q*	*T*	*S*	*y*
20180825 07:00:50	1116	47.4	4	80	59.4	18.6 25.4 9.0 6.4	19.96	3.91 12.50 3.55	7	23.7	15.590	4.477

TST: time and date, *ID*: event number, *V*: velocity [km/h], *AC*: axle count, *VC*: vehicle class, *GW*: gross vehicle weight [t], *Axles*: axles weights [t], *Length*: first-to-last axle distance, *A2A*: axle-to-axle distance [m], *Q*: fit quality [%], *T*: temperature, *S*: average strain [10^{-3}], *y*: lateral distance [m].

tween the vehicle's gross weight and the strain they induced while crossing the bridge. The generally good correlation of this data confirms the reliability of the measurement.

Furthermore, the obtained data allows for analysing the traffic load distribution during a week or day thus the traffic temporal patterns can be deduced. **Fig. 2** (left) shows that approximately 250 vehicles above 3.5 t cross the bridge during weekdays while the traffic falls to approximately 100 vehicles during the weekdays. The results of the speed monitoring showed that the traffic crosses the bridge at approximately 90 km/m; however, mainly during peak hours, the speed decrease to approximately 65 km/h as documented in **Fig. 2** (right).

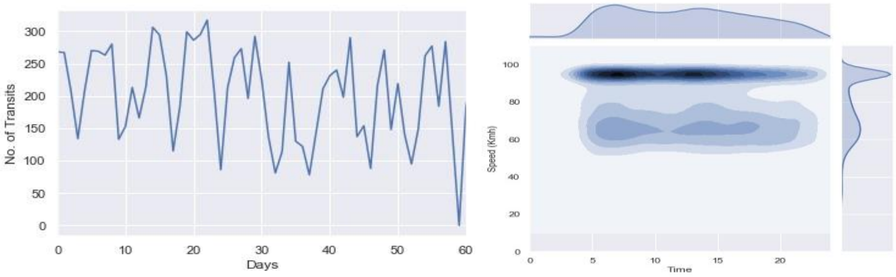

Fig. 2. Example of the daily traffic data crossing the Wonka Bridge showing the number of trucks above 3.5 t crossing the bridge (left) and how their speed varies during the day (right).

3 Numerical Simulation Methods

3.1 Non-linear Analysis

A digital twin refers to a computational model including its feedback with monitoring system, which is used to replicate the behaviour of the real process or object. In the structural engineering field, the digital twin often represents a structure or its section. Such a computational model should be capable of simulating all important aspects of the real structure. In the case of durability assessments, on top of the usual static analysis outcomes such as structural resistance, the model should predict the deterioration mechanisms and their impact on the structural performance.

For the presented study, the numerical part of the digital twin was developed by the means of FE method within the framework of the ATENA software. The mechanical behaviour of concrete is simulated using the elasto-fracture-plastic model of Červenka et al. [2], and Červenka and Papanikolaou [3]. The applied material model can simulate the real concrete behaviour, including the compressive crushing described by the plasticity approach and the tensile cracking described by the smeared crack approach with a crack band.

3.2 Ageing Modelling

Ageing management is a term, which comprises various tools for ensuring the long-term, safe, and reliable service life of civil structures. In this sense, an online monitoring system coupled with a non-linear numerical model can be used together with the regular structures inspections to monitor the structure’s health. Furthermore, the numerical model can be used to evaluate various scenarios, that might occur during the service life, and their impact on the structure’s performance. In this study, we focused on the reinforcement corrosion induced by the chloride ingress as concrete transport infrastructure is vastly subjected to de-icing agents during winter.

The chloride ingress and reinforcement corrosion models applied in the analysis assume two phases of the process. First, during the induction phase, the chlorides penetrate the concrete microstructure. This process is often described by the diffusion equation [4]. The rate of chloride ingress depends both on the material behaviour through the chloride diffusion coefficient and the chloride-binding ability, and the structure’s exposure conditions determined by suitable boundary conditions. Furthermore, in the presence of mechanical cracks, the chloride ingress is accelerated. Once the chloride concentration around the reinforcement reaches the critical level, the corrosion is initiated, and the propagation phase begins.

At first, the rate of the corrosion process is driven by the chloride concentration, temperature, corrosion time, and, through the pitting factor, how well the corrosion is localized. As the corrosion proceeds, it is assumed that only the uncorroded portion of the reinforcement cross-section transfers the mechanical stresses. Since the corrosion products have a larger volume than the steel, internal pressure builds up in the concrete cover. The implemented model assumes that once the critical corrosion depth is reached, spalling of the concrete cover occurs. This critical corrosion depth depends on the concrete strength, the initial reinforcement diameter and the concrete cover. After the spalling of the concrete cover, it is assumed that the corrosion continues with the rate given by the structure's exposure conditions.

Furthermore, in this study, we show an example of an analysis, where a sudden leak into the protective duct of the pre-stressed tendon was considered for the Wonka Bridge. This was done explicitly by reducing the tendons' cross-sectional area based on the prescribed corrosion rate.

Further details about the model can be found for example in reference [5]. For the study presented here, the input data were based mainly on the DuraCrete project report [4], long-term measurements of chloride ingress in concrete by the RISE Research Institutes of Sweden [6], and the corrosion rates of tendons published by the US Federal Highway Administration [7]. Further details can be found in reference [8] for the Wonka Bridge and reference [9] for the Vogelsang Bridge.

By varying the duration of the chloride attack, the different extent of the reinforcement corrosion is obtained in the numerical model. Since the chloride diffusion model takes into account the impact of mechanical cracks, the analysis results depend on the chosen load level for the application of the chloride ingress. In this study, two methods were used. 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. The duration of the chloride attack was assumed up to 150 years. For the Wonka Bridge, which was constructed in 1959, it was assumed that a sudden leak occurs to the protective ducts of the unbonded cables after 63 years of its service (i.e., in 2022). The corrosion of the unbonded pre-stressed cables was assumed for 5 and 8 years. Finally, for both structures, the overloading was simulated to obtain the design structural resistance at different moments of their service life.

3.3 Structure Resistance Assessment

General structural design requirements specify that the design structural resistance (R_d) should be greater than the effects of the design loads (E_d):

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

According to fib Model Code 2010 [10], three kinds of methods are admissible for non-linear analyses, i.e., the full probabilistic method, global resistance methods, and the partial factor method (PFM).

The global resistance method is represented by the ECOV method, which is based on the assumption that the structural resistance follows the log-normal distribution. The parameters of the distribution can be estimated by two analysis runs; one with characteristic (R_k) and one with mean (R_m) material properties. From this viewpoint, the ECOV method can be categorized as a semi-probabilistic method, whose coefficient of variation V_R is calculated as:

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

and the global resistance factor γ_R:

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

where α_R is the sensitivity factor for the reliability of resistance and β is the reliability index. For general design practice, $\alpha_R = 0.8$ and $\beta = 3.8$ can be assumed.

Finally, the design resistance according to the ECOV method is expressed as:

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

where γ_{Rd} is the uncertainty of the numerical model, which was for this study γ_{Rd} = 1.16 according to the previous research [11].

Furthermore, for the Wonka Bridge, the structural resistance obtained by the ECOV method was compared with the results of the partial factor method ($R_{d,PFM}$), which relies on design material characteristics. For their estimation, partial safety factors were based on Eurocode [12]. Excluding the model uncertainty from the material parameters, the partial safety factors give γ_c = 1.46 and γ_s = 1.20 for concrete and steel reinforcement, respectively.

4 Examples of Application

4.1 Pilot Applications

Two pilot applications of the proposed system are presented in this section for the Wonka Bridge, Pardubice, the Czech Republic over the Elbe River and the Vogelsang Bridge, Esslinger, Germany over the Neckar River. The in-situ data were previously collected within the framework of the European cyberBridge project (www.cyberbridge.eu).

The Wonka Bridge in the Czech Republic is a pre-stressed box-girder concrete bridge consisting of three arches with spans of 50 + 70 + 50 m. The cross-section depth is up to 3.5 m. The bridge was constructed between 1956 and 1959. During the service life, the bridge is loaded by road transport and pedestrians. Furthermore, the bridge is subjected to the deterioration mechanisms originating from the external environment, such as penetration of the de-icing agents and carbonation of the concrete cover. The data from the monitoring system were collected for 60 days from August until October 2018.

The Vogelsang Bridge in Germany consists of eight partial structures built in three different construction types. The bridge was built between the years of 1971 and 1973. The total length is approximately 595 m and it has a total area of 9 744 m² including ramps. For the monitoring, two spans of 13.8 + 13.2 m were chosen. From the structural point of view, this section is a continuous non-prestressed beam with a height of 0.6 m. The bridge monitoring ran for 61 days from Jan. until Mar. 2019.

4.2 Calibration of Digital Twins

Upon development of the model for FEM analysis, its ability to capture the behaviour of the real structure needs to be checked and, eventually, the unknown parameters in the model are calibrated using the feedback from the bridge monitoring data. This calibration is conducted by comparison of the measured and computed strains. For the Wonka Bridge, single strain measurements together with mid-span deflection data from a static load test were used while, in the case of the Vogelsang Bridge, data from two groups of strain gauges were used for the calibration. The results of the calibration are summarized in **Table 2** for both bridges.

Table 2. Summary of calibration results for two digital twin models.

	Measured data	Numerical results
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

4.3 Results of Durability Assessment

As shown in **Fig. 3**, in the case of the Wonka Bridge, the predicted failure mode is compression/shear crushing above the support of the bridge (see Discussion section). Accounting for the brittle nature of this failure mechanism, the ultimate load-bearing capacity was assumed as the moment when compressive strains in concrete reach the value -0.0035. In the case of the Wonka Bridge, owing to the robustness of the structural design, the corrosion of the unbonded pre-stressed cables does not result in a significant reduction of the resistance, although the structural performance is compromised due to an apparent increase of the mid-span deflection.

The Vogelsang Bridge collapsed due to bending. First, reinforcement yielding occurred followed by expansion of the region with concrete crushing as shown in **Fig. 4**.

Fig. 3. Longitudinal view of the Wonka Bridge shows the stress in the bonded cables and cracks in the box girder at the peak load. The detail shows the development of the crushing zone above the support of the bridge.

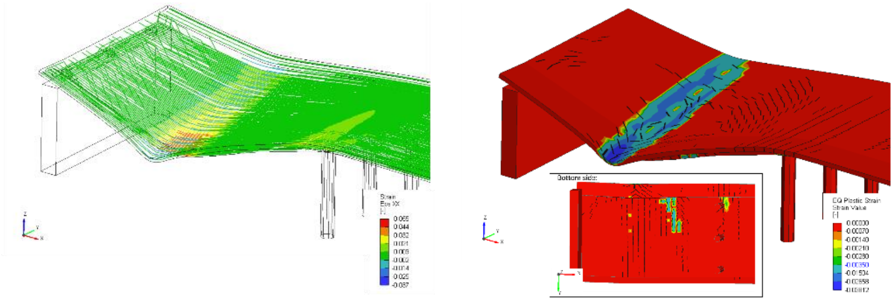

Fig. 4. (left) Deformed shame and plastic strains in the main reinforcement and (right) zone of concrete crushing at the peak load for the Vogelsang Bridge.

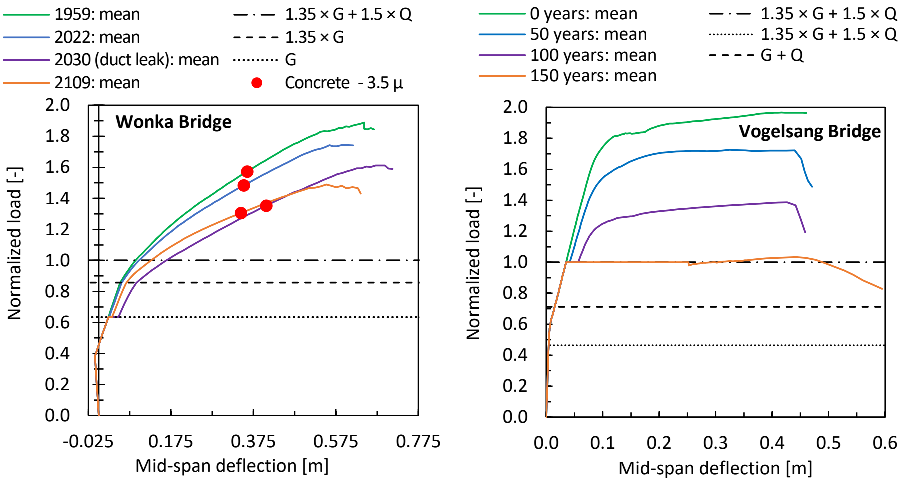

Fig. 5. Typical load-displacement curves for the Wonka Bridge (left) and Vogelsang Bridge (right) for the analyses with mean material properties. For the Wonka Bridge, the load when the compression strain of -3.5 µ is reached in concrete is indicated.

Typical load-deflection curves are shown in **Fig. 5**. The data are given for the analyses with mean material parameters giving the mean structural resistance (R_m).

Fig. 6 shows the reduction of the load-bearing capacity in time due to chloride ingress and subsequent reinforcement corrosion. The curves are given for the mean (R_m) and characteristic (R_k) structural resistance, which were used to calculate the design structural resistance according to the ECOV method ($R_{m,ECOV}$). For comparison, the development of the design structural resistance according to the PFM ($R_{m,PFM}$) is plotted for the Wonka Bridge.Both structures show good resistance against the deterioration up to 100 years of service life.

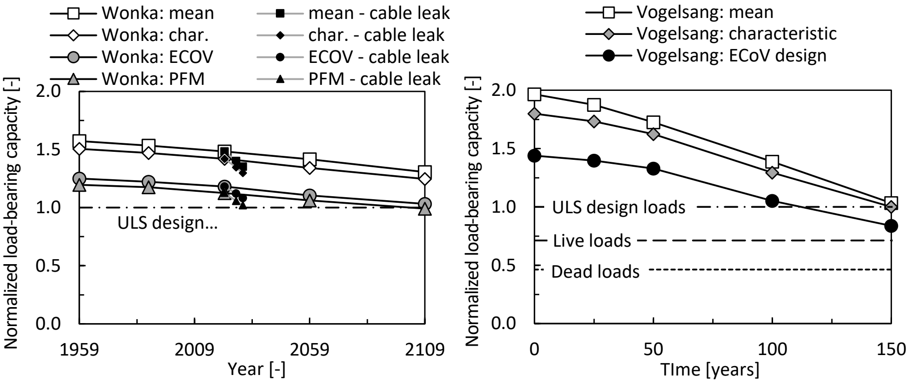

Fig. 6. Reduction of the load-bearing capacity in time due to chloride-induced reinforcement corrosion for the Wonka Bridge (left) and Vogelsang Bridge (right). For the Wonka Bridge, the black data points between the years 2022 and 2030 show a scenario, where a leak into the protective ducts of the unbonded pre-stressing cables occurs.

4.4 Discussion on the Application Results

At the peak load, the Wonka Bridge collapses due to a combination of shear/compression stresses in the concrete of the box girder above the support. The bonded pre-stressing cables efficiently transfer the shear load in the box girder due to their optimal inclination with respect to the direction of the shear stress while the unboned cables mainly contribute to the transfer of the bending moment. Both types of pre-stressing cables are bonded at the upper section of the box girder. Due to this mechanism, the concrete above the support is compressed in the vertical direction. At the maximum load, a longitudinal crack forms in the web of the box girder, which leads to the splitting of the concrete above the support. Although this failure mechanism is brittle by nature, the collapse of the bridge is preceded by a significant increase of the mid-span deflection exceeding 0.4 m due to the strain accumulation in the long external cables.

In the case of the Vogelsang Bridge, the bending failure mode develops in the mid-span at the peak load. Before the peak load is reached, reinforcement yielding occurs, which increases the deflection of the bridge. If the load is further increased, ultimate compression strain is reached in the compression zone and a region with concrete crushing forms.

Based on **Fig. 6**, the chloride-ingress reduces the structural performance at a faster rate for the Vogelsang Bridge than for the Wonka Bridge. This is mainly due to two factors: different load levels at the application of chloride attack and different failure mechanisms. For the Vogelsang Bridge, the chloride attack was simulated when the structure was subjected to the ULS design load level. Therefore, the rate of the corrosion process might be faster than in reality since the computed crack width, which accelerates the chloride diffusion process, maybe overestimated at this load level. This can be seen as a conservative approach. On the other hand, in the case of the Wonka Bridge, the chloride attack was assumed at the characteristic dead load level, which might be more realistic. Under lower load levels, the computed width of mechanical cracks is smaller thus the rate of chloride diffusion is lower. In addition, the main pre-stressing reinforcement is located in the middle of the walls further from the concrete surfaces thus more protected from chloride ingress.

The second reason behind the difference in the degradation rate in **Fig. 6** originates from the different failure modes for the two bridges. In the case of the Vogelsang Bridge, at the peak load, a concrete crushing zone develops after reinforcement yielding in the mid-span due to the bending moment. In this case, the reduced reinforcement area directly impacts the ability to transfer the stresses in the tensile zone. On the other hand, the failure mechanism of the Wonka Bridge originates from the compression/shear stresses above the support. Although the failure mechanism is facilitated by the corrosion of the stirrups in the web of the box girder, the ability of concrete to transfer compression loads plays a key role.

For the Wonka bridge case, two safety formats are compared in **Fig. 6.** It shows that PFM method provides slightly more conservative results than ECOV. This can be expected as the semi-probabilistic ECOV method can be considered more advanced and with higher accuracy

5 Summary

The paper presents a digital twin approach combining advanced monitoring system with non-linear numerical model to predict the time development of the reliability of two reinforced concrete bridges. It demonstrates the importance of the monitoring system feedback for the calibration of the model. The numerical simulation was used to predict the reinforcement corrosion and its impact on the structural resistance using the new safety formats for non-linear analysis introduced by fib model code 2010.

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