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ADVANCED MODELLING OF CONCRETE STRUCTURES FOR IMPROVED SUSTAINABILITY

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Abstract. The safe and long-term serviceability of concrete structures is one of the methods how to improve the sustainability of the concrete industry. This study presents a pilot application of an integrated system for online monitoring and service life prediction of concrete bridges. The system consists of strain gauges measuring the structural response coupled with a laser rangefinder for detection of the bridge-crossing traffic. The measured data were used for the development of a computational model of the bridge. Next, the deterioration models were applied to the model to assess the long-term mechanical behaviour. In this study, we considered chloride-induced reinforcement corrosion. The numerical data are given for 100-years-long service life prediction.

Keywords: Ageing management, bridge monitoring, Finite Element Method (FEM), non-linear analysis, durability assessment.

1. Introduction

The concrete industry is responsible for approximately 5–7 % of the human-produced emissions of CO_2, mainly due to the manufacturing process of the cement clinker [1]. Among replacing the cement clinker with supplementary cementitious materials [2], carbon storage technologies [3], and structural design optimization [4], the long-term service life of concrete structures is one of the means how to reduce the ecological footprint of the concrete industry. On the other hand, the ageing infrastructure may represent a risk since degradation processes may compromise the structure's serviceability as in the case of the Libeň Bridge, Prague or, in the worst case, the structure may collapse as in the case of the Trója Bridge, Prague or the Morandi Bridge, Genoa. To prevent such scenarios, regular structural health inspections and repair works need to be conducted. Together with physical inspections, numerical tools may aid the ageing management of the structures.

The combination of non-linear finite element analysis with structural monitoring can considerably improve the prognosis of structural behaviour, deterioration, damage, and sustainability. Recently, a digital twin concept is often utilized: a digital replica of the real structure is developed, and simulation of the model behaviour under service conditions is performed. Based on the comparison with data from measurements on the real structure, the most significant model properties are identified using an advanced probabilistic approach. 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 conditions. Application of such a methodology allows reliable and accurate recognition of the structural damage and prediction of the remaining lifespan and structural sustainability, based on the deeply identified system, parameter sensitivity simulation, and advanced probabilistic methods.

In this study, a pilot application of an integrated system for bridge monitoring and life cycle prediction is presented using the results of the Wonka bridge, Czech Republic. First, the online monitoring system is briefly introduced and then details about the numerical model are given with a focus on the chloride ingress and reinforcement corrosion models. The numerical results are given for chloride attack assumed on the surfaces of the concrete box girder as well as the case when a sudden leak into the ducts of the unbonded pre-stressed cables occurs.

2. Wonka bridge description

For the pilot study, the Wonka bridge over the Elbe River located in Pardubice, Czech Republic was selected. It is a pre-stressed box-girder concrete bridge, which consists of three arches with spans of 50 + 70 + 50 m. The cross-section depth is up to 3.5 m. The mid-span cross-section and side views of the bridge are shown in Figure 1 and Figure 2, respectively.

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. Further details about the Wonka bridge and the safety format for evaluation of the structural resistance are given in reference [5].

3. Bridge monitoring system

3.1. Description of the system

In August 2018, a monitoring system was installed on the bridge to monitor the passing traffic and

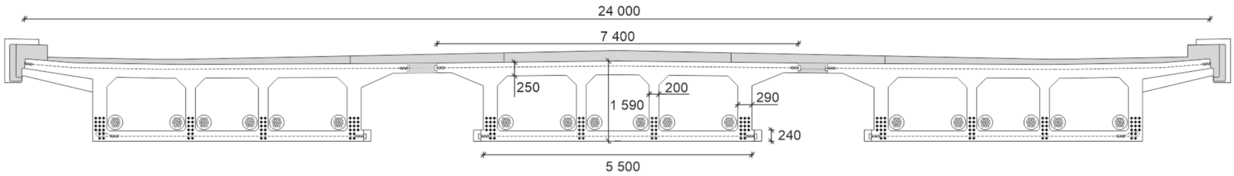

FIGURE 1. Cross-section view in the mid-span of the Wonka bridge.

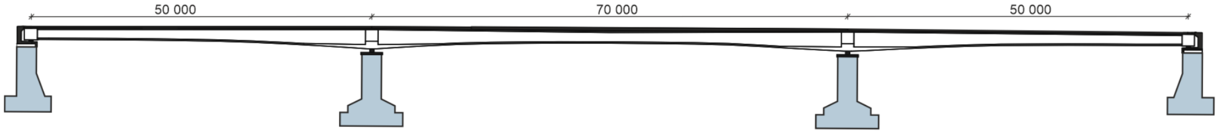

FIGURE 2. Longitudinal view of the Wonka bridge.

the load it induces. The iBWIM (Bridge-Weigh-In-Motion) technology (PEC – Petschacher Consulting, ZT-GmbH) was used. The system consists of strain gauges mounted on the underside deck of the bridge paired with a laser rangefinder, which detects the wheels of the traffic. The strain gauges were placed both in the longitudinal and transversal directions. The data from the monitoring system were collected for 60 days from August until October 2018 within the framework of the European cyberBridge project (`https://www.cyberbridge.eu/`). Except for the Wonka bridge, the monitoring data were acquired from another bridge with reinforced concrete girder bridge structural scheme, and the comparative study for both bridges was presented by the authors in [5].

The sensitivity of the system is suitable for vehicles of gross weight above 3.5 t. Based on the coupled information, the vehicle's speed, weight, and load distribution over the vehicle's axles can be obtained. Before the measurements, the system was calibrated by crossing the bridge with trucks of known weights.

4. Digital twin development

4.1. Model

Digital twin refers to a computational model, which is upon calibration used to replicate the structural behaviour. Using the measured data from the monitoring system, the simulation model can be calibrated and further used for the prediction of the structural performance during the service life of the structure.

In the presented study, the computational model was developed in the ATENA software [6]. ATENA is a tool for non-linear analysis of reinforced concrete structures using the finite element method. The mechanical behaviour of concrete is simulated using the elasto-fracture-plastic model of Červenka et al. [7], and Červenka and Papanikolaou [8]. In the material model, the plasticity approach is used to model the failure in the compression branch while smeared crack approach with a crack band is used to simulate the tensile softening.

The FE model of the bridge was created using layered shell elements with smeared reinforcement as shown in Figure 3. Two types of pre-stressing cables are in the model; unbonded cables inside of the girder box and the bonded cables in the webs of the box girder. To model the pre-stressing cables, one-dimensional compression/tension elements were used. The reinforcement geometry together with the deviators of the unbonded pre-tension cables is shown in Figure 3. The supports and pre-tension deviators were modelled using the solid wedge and hexahedral elements.

To estimate the design load-bearing capacity, the partial factor method according to fib Model Code 2010 [14] was used. According to this method, the structural resistance from a non-linear numerical model is obtained using the design material parameters. Applying the safety factors from Eurocode [15] and excluding the model uncertainty, the material partial safety factors give $\gamma_c = 1.46$ and $\gamma_s = 1.20$ for concrete and steel, respectively.

4.2. Chloride ingress and corrosion models

The durability assessment was conducted using the durability-related features of the ATENA software. It consists of a chloride ingress model and a model for the evaluation of reinforcement corrosion. Combining these two methods, the reduction of the reinforcement cross-section due to chloride attack can be evaluated. Previously, it has been shown that these features can be used to accurately predict the long-term deterioration of concrete bridges [16]. Before the results for the Wonka bridge are given, this model for durability assessment is briefly summarised.

After casting, the reinforcement bars are protected against corrosion by highly alkaline conditions in the concrete matrix [17]. However, during the structure's service life, the protective role of the concrete may be compromised mainly due to chloride-ingress or carbonation. In the case that a structure is subjected to the de-icing agents or salts from the seawater, the

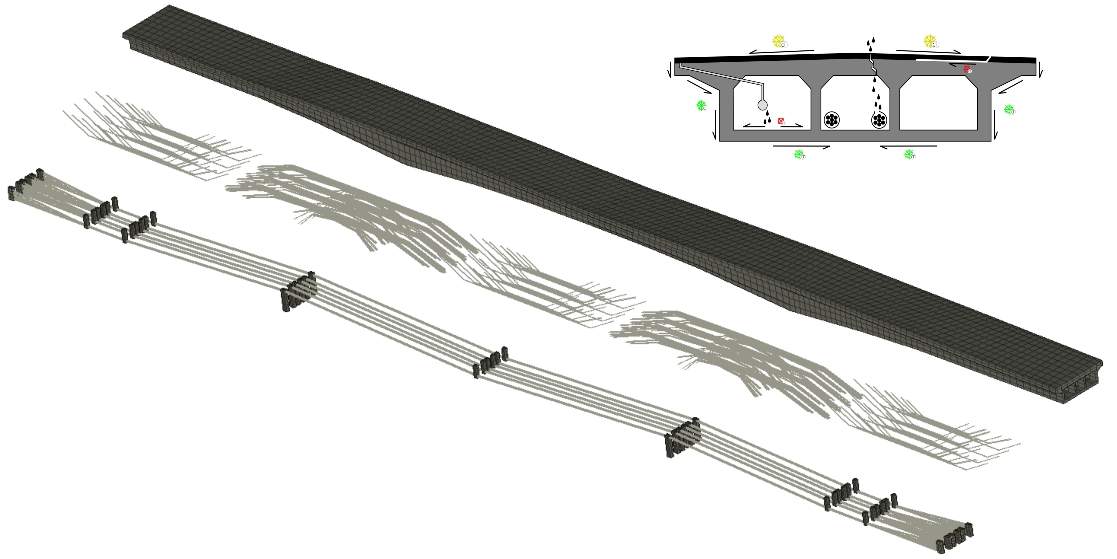

Figure 3. Model of the Wonka bridge during pre-processing showing the FEM mesh, pre-stressing cables in the webs of the girder, and the unbonded pre-stressing cables with the deviators. The cross-section view schematically shows the application of the chloride ingress boundary condition.

Parameter	Symbol	Value	Reference
Chloride diffusion coefficient	D_{ref}	$0.1005\,\mathrm{mm}^2/\mathrm{day}$	[9]
Decay rate factor	m	0.37	[10]
Surface chloride content	C_s	2.57 % *	[10]
Critical chloride content	$C_{s,crit}$	0.4 %	[9]
Pitting factor	R_{corr}	3.0	[11]
Corrosion rate after spalling	$\dot{x}_{corr,env}$	$37.5\,\mu\mathrm{m/y}$	[12]
Corrosion rate of unbonded cables due to leak in ducts	$\dot{x}_{corr,duct}$	$541.0\,\mu\mathrm{m/y}$	[13]

* Half and quarter values were used for outer and inner surfaces, respectively.

Table 1. Inputs for the chloride ingress and corrosion models.

chloride ions are transported through the porous system towards the reinforcement and once the critical chloride concentration ($C_{s,crit}$) is reached, the reinforcement corrosion is initiated [18]. This moment is referred to as depassivation of the reinforcement and the period from the beginning of the chloride attack to the moment of corrosion initiation is called the induction phase. Its duration generally depends on the structure's exposure conditions through the surface (boundary) chloride content (C_s) and the concrete mixture characteristics such as water-to-cement ratio or cement type, which affect the diffusion properties of the concrete matrix (D_{ref}) and the chloride binding ability of the material (m) [17]. Furthermore, the process is accelerated in the presence of microcracks [19]. The process of the chloride penetration and thus the duration of the induction phase is commonly estimated using a diffusion equation [10].

Once the critical chloride concentration is reached at the depth of the reinforcement, the corrosion products start to reduce the cross-section area. From this moment, the propagation phase begins. The corrosion rate depends on the total chloride content, temperature conditions, and the duration of the corrosion process [20]. Since the corrosion products have a larger volume than steel, internal pressure builds up in the concrete cover. Once it exceeds the material strength, spalling of concrete cover occurs. After that, it can be assumed that the reinforcement corrosion continues and is driven by the conditions of the external environment ($\dot{x}_{corr,env}$). Further details about the models used for the evaluation of the chloride attack can be found for instance in reference [16].

The parameters of the chloride ingress and corrosion models are summarised in Table 1. The parameters of the durability model were estimated based on the available literature data, mainly the reports of the DuraCrete project [10] and long-term data collection by the RISE Research Institutes of Sweden [9].

Apart from the corrosion of the reinforcement placed inside the concrete elements, a case when a sudden leak occurs through the ducts of the unbonded cables was considered in this study. The rate of corrosion was estimated directly based on the available experimental data [13]. It was assumed that each wire corrodes separately and the combined uncorroded area

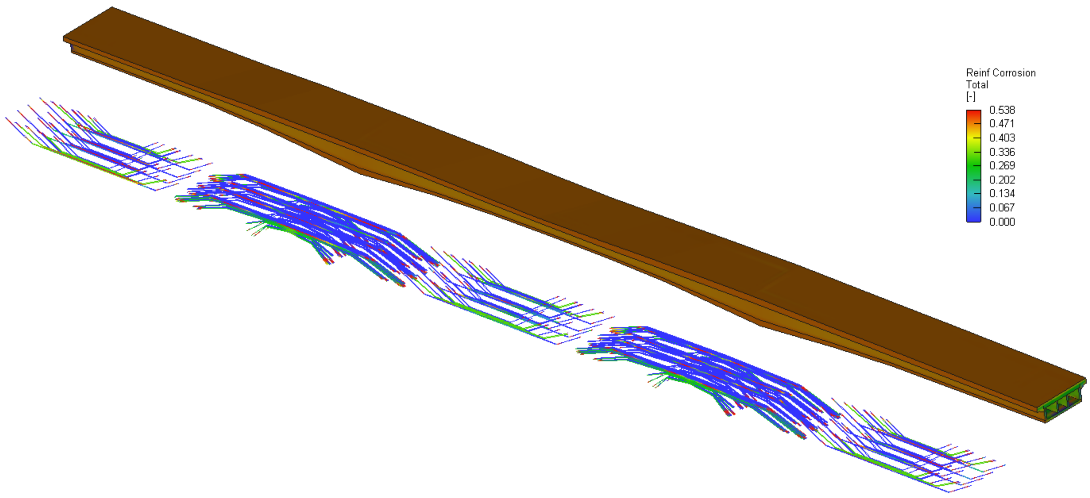

Figure 4. (top) Plot of the reinforcement corrosion of the smeared reinforcement in the shell elements and (bottom) corrosion of the pre-stressed cables in the webs of the girder box after 100 years of chloride ingress.

of all wires gives the cross-section of the pre-tensioned cable.

The deterioration of the structure due to chloride attack was considered under the loading by dead loads. Next, the design load combination according to Eurocode [21] was applied to the model and this state was taken as the reference unit load-bearing capacity of the structure. The loading by the design load combination was further gradually increased to determine the ultimate load-bearing capacity of the bridge. The duration of the deterioration process was varied to find the development of the load-bearing capacity in time. The durability analysis was conducted for 0, 30, 63, 100 years of the chloride ingress, which corresponds to the years 1959, 1989, 2022, and 2059, respectively. Furthermore, it was considered that a sudden leak into the protective duct of the cables of the unbonded pre-tension occurs in 2022 and the cables cross-section area corrodes for 5 and 8 years. This corresponds to the years 2027 and 2030.

4.3. Mechanical model calibration

For the initial calibration of the model, the deflection measured during a load test after the reconstruction works in 2006 was used. The mid-span deflection of 14.23 from the numerical model is in good agreement with the measured value of 14.36 mm. Next, the data from the monitoring system was used to compare the strain induced by the crossing vehicle of 28.46 t. This comparison gave strain values at the bottom deck of 8.88 μ and 8.35 μ for the numerical and measured data, respectively.

The calibration of the model was also used for the determination of the pre-stressing force in the cables since this value was not known in advance.

4.4. Results and discussion

Figure 4 shows the degree of reinforcement corrosion for the smeared reinforcement in the shell elements and the pre-stressed cables in the webs of the box girder after a 100-years-long chloride attack. At maximum, approximately 54 % of the cross-section area is lost due to corrosion in the most exposed sections of the pre-stressed cables. Apart from the pre-stressed cables, the maximum corrosion degree (i.e., the portion of corroded cross-section), reaches up to approximately 48 %.

Regardless of the duration of the chloride-induced reinforcement corrosion, the results showed a consistent failure mechanism suggesting concrete crushing near the bridge support due to the concentration of shear/compression stresses. The regions with compression strains exceeding -0.0035 are shown in Figure 5. The moment when the strain reaches this value was taken as the design load-bearing capacity of the structure for comparison of the results with different durations of the chloride attack.

Examples of load-deflection (L-D) diagrams for a structure intact by chlorides, for 63 and 100 years-long chloride attach are plotted in Figure 6 together with the case, where 8-years-long corrosion of the unbonded pre-stressing cables due to a leak into the cable ducts was considered. Furthermore, the load level, when the compressive strain of -0.0035 is reached in concrete, is indicated for the L-D diagrams. It can be observed that both the stiffness and the load-bearing capacity are reduced because of the chloride attack. On the other hand, the design load-bearing capacity exceeds the required design load level in all analysed cases. This is apparent from Figure 7, which plots the development of the design load-bearing capacity in time.

Furthermore, Figure 7 also shows how the load-

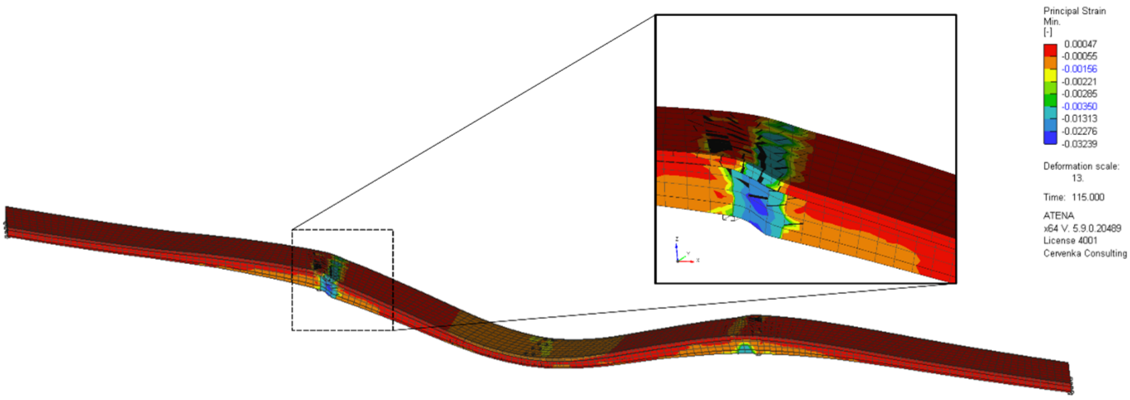

FIGURE 5. Deformed shape of the Wonka bridge after the peak load and the detail of the failure region near the left support.

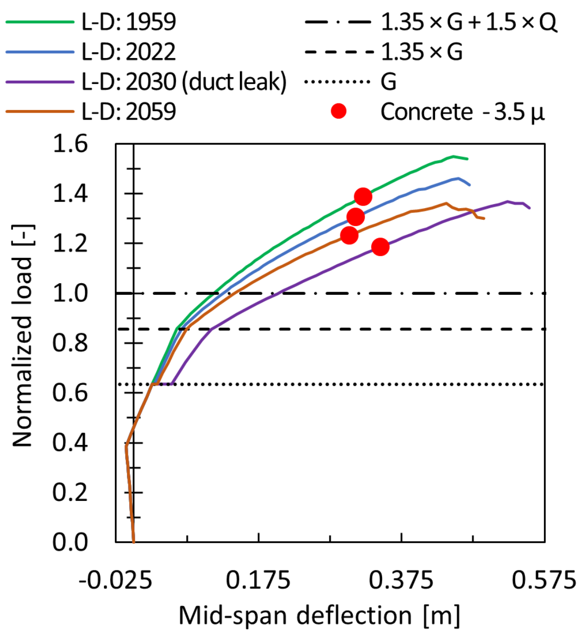

FIGURE 6. Typical load-deflection (L-D) diagrams for the Wonka bridge with the indication of the load level when the minimum principal strain in concrete exceeds the value of -0.0035.

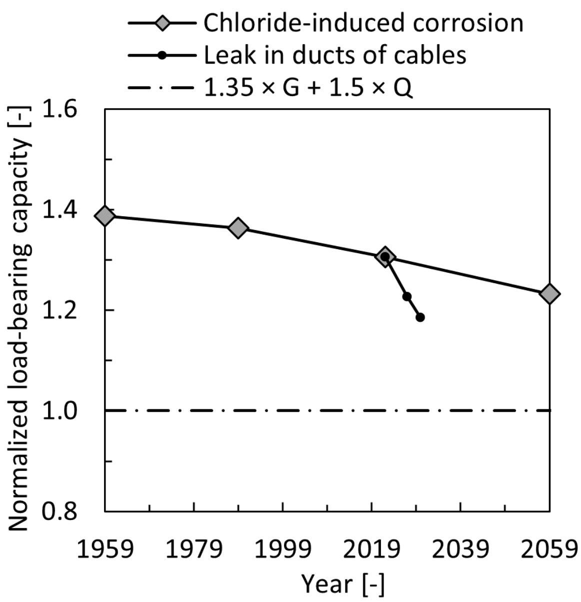

FIGURE 7. Prediction of the development of the design long-bearing capacity of the bridge affected by chloride-induced reinforcement corrosion and potential leak in the cable ducts of the unbonded pre-tension.

bearing capacity of the bridge is reduced if the chlorides from the de-icing salts leak through the protecting ducts to the cables placed in the box girder. In such a case, the bridge structural performance is reduced at a much higher rate. However, as the cables are pre-stressed only to 64 % of the material's yield strength, the cables still have sufficient capacity for potential stress increase. Therefore, the numerical model predicts that the bridge can still transfer the design loads even after 8 years of corrosion of the cables of the unbonded pre-stressing.

The numerical results suggest a failure due to the crushing of concrete, which is brittle by nature. On the other hand, the L-D diagrams show that the failure is preceded by the mid-span deflection of the bridge of approximately 0.4 m. Generally, the long-term deterioration study showed a good resistance of the structure towards chloride attack. This resistance is mainly provided by a robust structural design, which provides sufficient capacity for the redistribution of the tensile stresses even if the cross-section area of the steel reinforcement is reduced due to corrosion.

5. SUMMARY

This study presents a durability analysis of the Wonka Bridge located in Pardubice, Czech Republic. The long-term assessment is based on the integrated system, which is composed of an online system for bridge monitoring and a numerical model. Using the measured data, the numerical model is calibrated and then used for evaluation of the structural deterioration due to de-icing agents. The effect of the chloride attack was evaluated using the chloride transport and reinforcement corrosion models implemented in the framework of non-linear FE analysis. This allowed for the prediction of the time development of the design load-bearing capacity of the bridge.

The results revealed that although the mechanical performance characteristics are continuously reduced due to the chloride-induced corrosion, the bridge shows sufficient load-bearing capacity within the examined service period. This is mainly due to the robustness of the initial structural design. On the other hand, the results showed that in the case of a potential leak into the ducts of the unbonded pre-stressed cables, the structural performance is rapidly compromised. Therefore, it is suggested to regularly inspect the state of the cable ducts in the box girder.

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