Digital Twins for Reinforced Concrete Structures

Jan Cervenka[0000-0003-4945-1163] , Jiri Rymes[0000-0003-3288-0826] , Libor Jendele, Radomir Pukl[0000-0003-4504-4405]

[1] Cervenka Consulting s.r.o., Prague, Czech Republic
jan.cervenka@cervenka.cz

Abstract. Digital twin is a new approach in structural life-cycle management, when a virtual replica of a real product or structure is developed. The virtual twin is used to test the product behavior under limit state conditions. The important feature of the digital twin is the connection of the virtual model with the real-life data obtained by its monitoring. The digital twin method can be used for the assessments of safety, durability and reliability of reinforced concrete structures. The presented digital twin model consists of a finite element mechanical model coupled with a chemo-mechanical model for the assessment of chloride ingress or carbonation and propagation of the subsequent reinforcement corrosion. The model is combined with the nonlinear modelling of cracking, bond failure and reinforcement yielding for static as well as dynamic analyses. The digital twin approach is demonstrated on pilot problems of bridge structures in the Czech Republic and Germany.

The latest development also extends the digital twin approach for the additive manufacturing of concrete structures, where the G-code generated by the robotic machine is directly used for the simulation of the construction process as well as for the assessment and verification of the final structural behavior under design loads as well as its long term behavior.

Keywords: Chloride Ingress, Corrosion, Digital Twin, Durability, Finite Element Analysis, Reinforced Concrete Structures, Additive Manufacturing.

1 Introduction

The functional infrastructure is one of the key aspects of an efficient modern economy both in developed and developing countries. In European Union, the majority of the critical infrastructure was built during the economic growth after World War II implying that the average age of the structures well-exceeds 50 years. Nowadays, the ageing infrastructure represents a significant financial burden for the public authorities. Based on the data from 22 selected OECD countries [1], the cost of infrastructure maintenance increased by 1.78 billion euros each year between 1997 and 2016.

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 [2] processes. One of the means how to reduce the negative environmental impact is to ensure the optimal structural design and lifespan.

The early diagnosis and prediction of the structural deterioration not only reduces the repair cost but may prevent limitation in serviceability of the structure and prevent the worst-case scenarios such as was the case of the collapse of a pedestrian Troja bridge in Prague or the Morandi Bridge in Genoa.

Digital twin refers to a virtual replica of a real structure, which is connected with online measurement data of the real structure. This enables the identification of the most significant model properties. The resulting calibrated models 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 assessment of their long-term 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.

Recently the digital twin approach and virtual prototyping was also applied to the modern construction methods such as the additive manufacturing of concrete structures. The G-code generated by the robotic machine is directly used to drive the simulation of the construction process as well as for the assessment and verification of the final structural behavior under design loads as well as its long-term behavior.

2 Pilot Applications

In this paper, two pilot applications of the proposed system are presented. The first one is the Wonka Bridge, Pardubice, the Czech Republic over the Elbe River, and the second is the Vogelsang Bridge, Esslinger, Germany over the Neckar River. The in-situ monitoring 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. The bridge is loaded mainly 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.

3 Monitoring System

The iBWIM (Bridge-Weigh-In-Motion) technology (PEC – Petschacher Consulting, ZT-GmbH) was used as the monitoring system.

The system consists of deflection measurement units coupled with a laser rangefinder, which is used for vehicle detection (see Fig. 2). The measurement units are mounted on the underside of the bridge; therefore, the traffic is not interrupted during the installation. Each unit consists of strain gauges and a data collector. The strain gauges are arranged booth in the transverse and longitudinal directions.

Fig. 1. Two bridge pilot applications, (top) Wonka bridge, Pardubice, Czechia, (bottom) Vogelsang bridge, Esslingen, Germany showing also the monitoring strain gauges.

The information from the coupled system of the strain gauges and the laser rangefinder can be used for rather unique analyses of the bridge traffic. It is possible to collect the data on the bridge response as well as about the vehicle speed, weight, and load distribution over the vehicle’s axles. The sensitivity of the measurement system is tuned to detect vehicles of a gross weight above 3.5 t. The monitoring system was calibrated by crossing the bridge with trucks of known weights.

Each passing vehicle is recorded by the monitoring system as an event and is given an event number. An example of the measured data during two single events are shown in Fig. 3. The data from the strain gauges are shown together with the information from the rangefinders, which detect the passing traffic. An example of the obtained data is given in Fig. 3.

4 Virtual Model Calibration

The virtual numerical models were developed in the FE simulation system ATENA [3]. The models were calibrated based on the results obtained from the bridge monitoring. The summary of the calibration results is shown in Table 1. After successful calibration, the numerical model are 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. The degradation model is described and validated in a previous publication [4] and briefly summarized in the Section 5.

Fig. 2. Typical arrangement of iBWIM monitoring system installed on an investigated bridge (left) a calibration truck crossing the bridge (top right), and a laser sensor for the detection of the passing vehicles and number of axles (bottom right).

The nonlinear behavior of the concrete material is modeled using a fracture-plastic material [5] that is implemented in ATENA software, and it enables the modelling of main aspects of reinforced concrete behavior such as concrete cracking, crushing, reinforcement rupture or yielding as well as possible bond failure mechanism.

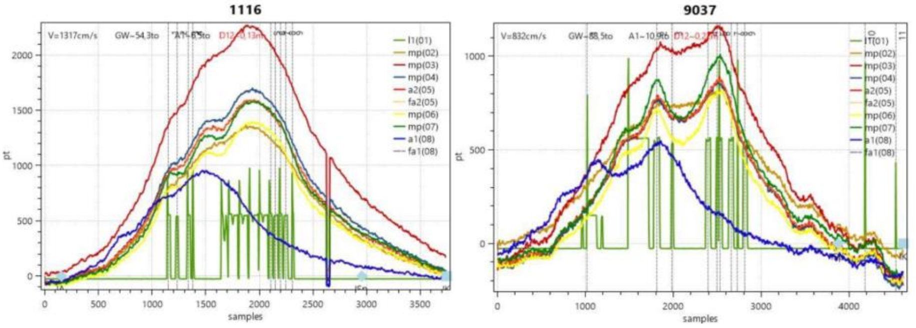

Fig. 3. Typical example of collected data at one of the most critical recorded events at Wonka bridge.

Table 1. Overview of the calibration data for the two pilot bridges

	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

5 Durability Modelling

One of the main degradation mechanism reducing the structural performance is the use of de-icing salts for road maintenance during the winter season. The chloride ions in the de-icing salts eventually penetrate the concrete microstructure towards the steel reinforcement, and this leads to a decrease in the pH level. Finally, 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 its 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 [6]. In engineering practice, this is commonly modelled using the diffusion equation with a time-dependent diffusion coefficient. When cracks occur in the concrete cover as a result of mechanical loads, chloride transport is accelerated. The chloride diffusion is simulated as a 1D diffusion process. Such an implementation can be very efficiently used also in large scale simulations.

The chloride concentration at the depth of the reinforcement is checked for each reinforcement bar that is modelled by discrete embedded reinforcement approach in

ATENA software considering also bond slip between concrete and reinforcement [7]. When the chloride concentration 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.

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 [8] and the recommendations published in the DuraCrete report [9]

The reinforcement corrosion process has an impact also on the reinforcement bond properties. The bond strength-slip material law used in this study was based on the fib MC 2010 [10] and for the corrosion effect on reinforcement bond, the formula proposed by Bhargava et al. [11] was used.

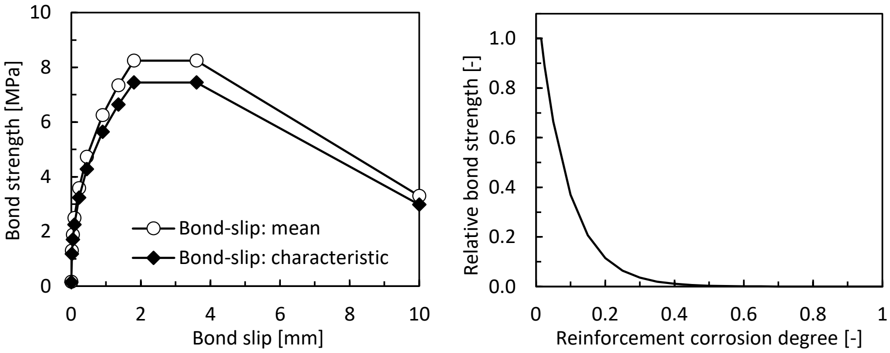

Fig. 4. (left) Reinforcement bond strength-slip function for the calculation with mean and characteristic material properties and (right) relative function for reducing the bond strength as a function of reinforcement corrosion [11].

6 Long Term Structural Assessment

For structural assessment by non-linear numerical model, a suitable loading sequence should be defined that respects the load sequence of the real structure as well as the investigated load combination required by the codes. In addition to standard loads, the analysis history should take into account the effect of chloride in-gress and resulting degradation due to reinforcement corrosion.

The following sequence of load intervals represents a typical approach that was for instance used in the case of the second pilot structure (i.e. Vogelsang bridge):
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 chloride attack with a duration of 25, 50, 75, 100, 125, and 150 years was applied in the interval 4 after partial reloading of the applied live and dead loads to simulate a more realistic scenario, when the chloride propagation and corrosion can be expected to occur at characteristic load levels without the partial factors. After that the live loads were again gradually applied until reaching the peak load. The main result is a set of load-displacement curves as shown in Fig. 6 for overloading at different ages. The applied global resistance approach ECoV was originally proposed in [12], and it requires always two analyses using mean material and characteristic parameters. The resulting evolution of design resistance in time is shown in Fig. 7. The graphs show that in case of Wonka bridge sufficient reliability can be assured for additional 87 years. In the worst case when leakage into the tendon area is considered, the bridge life prediction is drastically reduced, and the bridge state will be critical around year 2028.

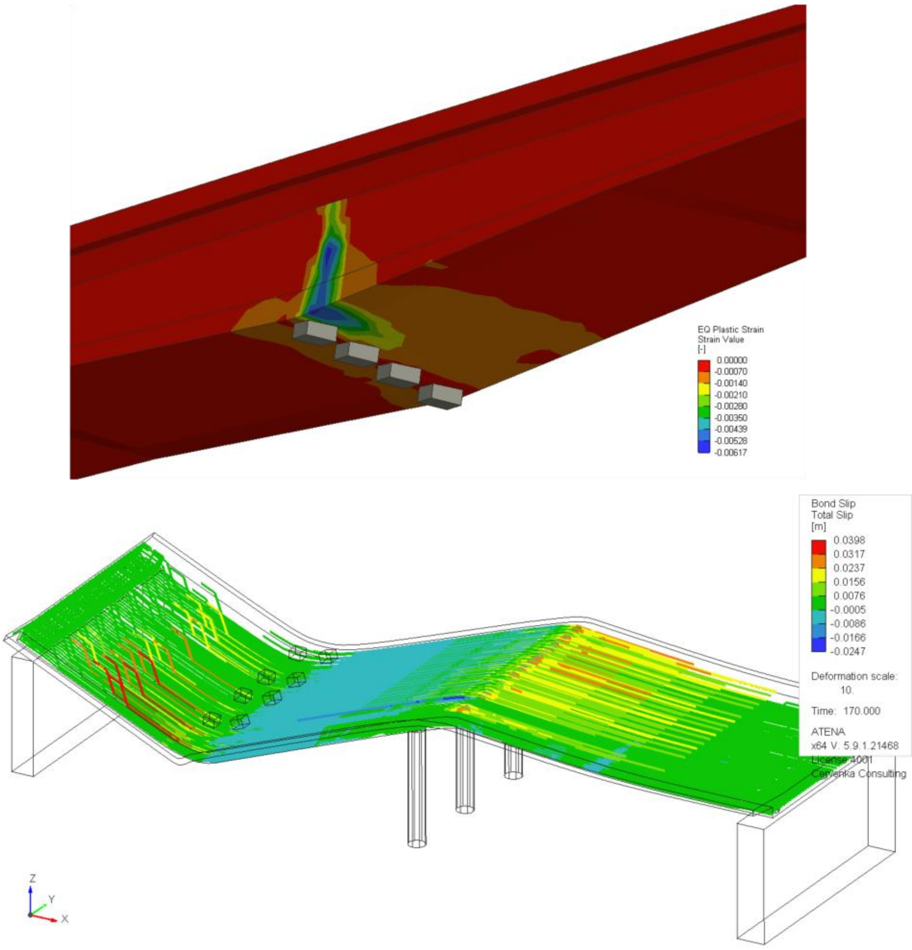

Fig. 5. Typical failure modes in the simulation, (top) shear failure with concrete crushing for Wonka bridge, (bottom) bending failure with reinforcement yielding for Vogelsang bridge. The bottom figure shows the bond slips between reinforcement and concrete for each bar taking into account the effect of corrosion at failure for the analysis with 150 years of corrosion.

In case of the Vogelsang bridge, the life expectancy of about 132 years is predicted. The graphs also show that once the corrosion starts the Vogelsang bridge degrades slightly faster than the Wonka bridge. This is due to the fact that if the leakage into the tendon area is prevented, the diffusion of chlorides into the prestressing cables in general takes much longer compared to the normal reinforcement in the Vogelsang bridge.

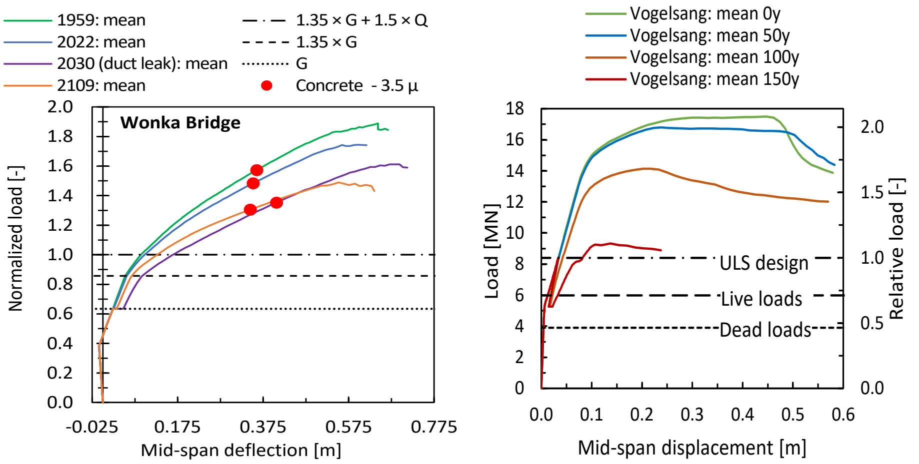

Fig. 6. Resistance curves for the Wonka Bridge (left) and Vogelsang Bridge (right) with mean parameters. The red points indicate when crushing strain -3.5 µ is reached in concrete.

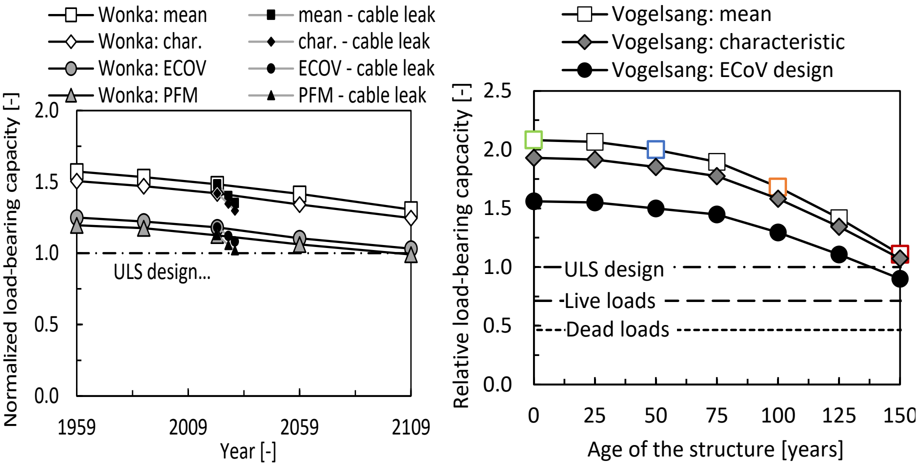

Fig. 7. The resistance evolution due to reinforcement corrosion for the Wonka Bridge (left) and Vogelsang Bridge (right). For the Wonka Bridge, the black triangle points show a scenario, where a leak into the protective ducts of the unbonded pre-stressing cables occurs.

7 Application to Virtual Prototyping in Concrete Additive Manufacturing

The last application example shows, the latest development of applying the virtual prototyping to the new construction technology of additive manufacturing of concrete structures. Additive manufacturing is an emerging technology that has been already widely adopted in many technological fields, including concrete engineering. This new construction technology can greatly benefit from the application of the digital twin approach, where a numerical simulation is run either before or even concurrently with the actual printing. It can reproduce the lab experiments and further predict new printing scenarios saving time and costs or preventing potential construction issues or even total or partial collapses at the sire. Furthermore, it allows for optimizing the process by predicting necessary interruptions or adjustments of the printing speed during the construction process. Fig. 9 shows a real example of a small 3D printed house in Czech Republic [13]. The printed structure was also tested in laboratory and simulated in order to simulate its construction process and evaluate the effect of the printing speed on the structural stability. The simulation showed that the printing speed needs to be decreased to about 50 mm/s to prevent structural collapse during uninterrupted printing (Fig. 9).

Fig. 8. Final view of the 3D printed building and its laboratory load testing.

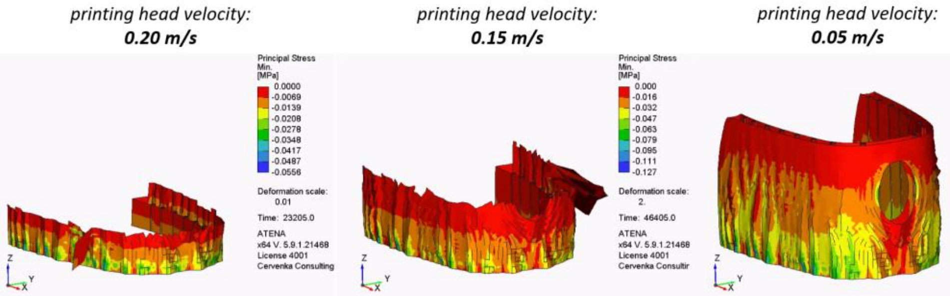

Fig. 9. Virtual prototyping of the 3D printed structure simulating the occurrence of failure for various printing speeds.

8 Summary

Paper presents three case studies of the application of the digital twin approach to the assessment of existing structures as well as to the design and construction of new structures using the new technology of additive manufacturing in construction industry.

The digital twin approach combines the monitoring data with the numerical simulation. This enables to provide more in-depth information for structural maintenance in case of existing structures. In case of construction of concrete structures by additive manufacturing this approach can be used to optimize the construction process to ensure the structural stability or to evaluate the effects of the construction process on the reliability and safety of the final product.

The paper was prepared with financial support of the Czech Technological Agency under the project CK03000023 "Digital twin for increased reliability and sustainability of concrete bridges". The 3D printing methods are developed under the project CK FW06010422 "Simulation and design of structures from digital concrete". The financial support is greatly acknowledged.

References

1. OECD. Infrastructure maintenance (indicator). 2021.
2. Barcelo L, Kline J, Walenta G, Gartner E (2014) Cement and carbon emissions. Mater Struct Constr 47:1055–1065
3. Cervenka V, Jendele L, Cervenka J.: ATENA Program Documentation: Part 1 Theory. Prague, 2023, www.cervenka.cz/products/atena.
4. Hajkova K., Smilauer V., Jendele L., Cervenka J.: Prediction of reinforcement corrosion due to chloride ingress and its effects on serviceability. Engineering Structures, 2018, Vol. 174: 768-777.
5. Cervenka J, Papanikolaou V.K.: Three dimensional combined fracture–plastic material model for concrete. International journal of plasticity, 2008, Vol. 24, 2192–2220
6. Taylor, H. F. W., 'Cement chemistry', Cement chemistry. doi: 10.1680/cc.25929
7. Jendele, L., Cervenka, J., Modelling Bar Reinforcement with Finite Bond, Computers and Structures, 84, 1780-1791, 2006.
8. Liu Y, Weyers E. Modeling the time-to-corrosion cracking in chloride contaminated reinforced concrete structures. Mater J 1998;95(6):675–80.
9. The European Union–Brite EuRam III (2000) Probabilistic performance based durability design of con-crete structures: Final technical report of Duracrete project.
10. International Federation for Structural Concrete (2013) fib Model Code for Concrete Structures 2010.
11. Bhargava, K. et al. (2007) 'Corrosion-induced bond strength degradation in reinforced concrete-Analytical and empirical models', Nuclear Engineering and Design, 237(11), pp. 1140–1157. doi: 10.1016/j.nucengdes.2007.01.010.
12. Červenka, V., 2008, Global Safety Format for Nonlinear Calcu-lation of Reinforced Concrete. Beton- und Stahlbetonbau 103, Special Edition, Ernst&Sohn. pp. 37-42.
13. https://www.scoolpt.com/prvok/, Scoolpt – design studio specializing in 3D printing, "It is not a house it is also a sculpture!"