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11th INTERNATIONAL SYMPOSIUM FIELD MONITORING IN GEOMECHANICS

Cloud-based 3D digital twin and fiber optic instrumentation of a pre-stressed concrete bridge for the continuous evaluation and monitoring of its structural condition

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Abstract

All engineering structures must be regularly inspected, maintained, and adapted to changing needs, thus raising the question of their structural condition. Its evaluation often remains limited to external assessment and localized examinations. A new method based on the **digital twin** of a monitored structure is therefore proposed.

In Austria Tyrol, the A12 highway crosses the Inn valley via the 235m-long **Terfener Innbrücke**, which was constructed between 2018 and 2021 using the free cantilever method. The reconstruction of the bridge led to an **innovative monitoring project** based on the development of a 3D digital twin fed by fiber optic sensor data.

The goal of this pilot project is the continuous analysis of the aging process of the bridge through the long-term collection of measurements and their correlation to external influences such as traffic load and climate. The sensor data are **automatically integrated** into an advanced numerical model, allowing measurement/calculation comparisons, damage risk assessment, and maintenance optimization. A total of 60 fiber optic cables were installed to measure deformations and temperatures in a distributed manner: longitudinally via 4 linear lines of 235m length at the four corners of the box girder; transversally via 11x2 sections (box and deck) evenly distributed along the axis of the bridge; vertically in the two pillars of the bridge and pile foundations. A BOFDA Brillouin optical interrogator is permanently installed on-site and allows to query of the different fiber-optic cables, having a total length of nearly 7km, with a measurement point every 10cm. All data is made available via the WeStatiX SHM cloud-based platform, allowing for online virtual inspection of the physical structure, and visualization of the results of FEM structural analysis simulations performed daily. In addition, the platform enables continuous model calibration and predictive analysis via sophisticated artificial intelligence algorithms.

Keywords: Structural health monitoring, digital twins, predictive analysis, simulations

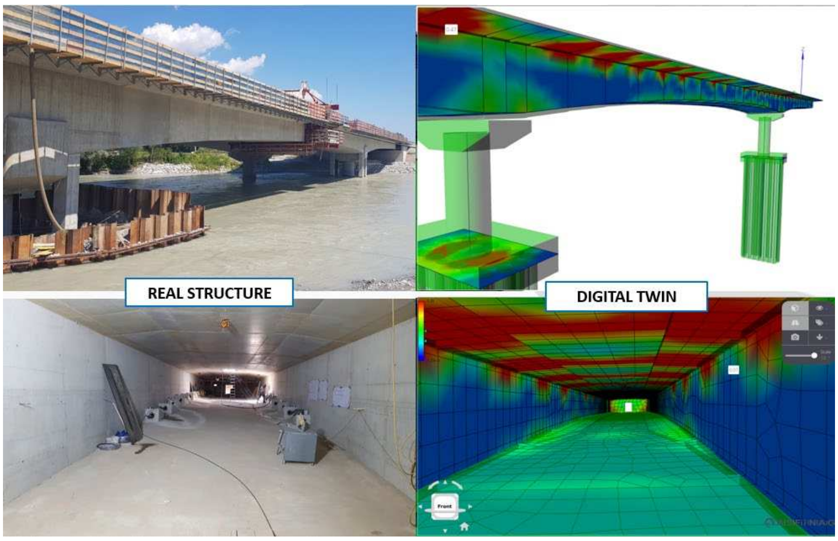

Figure 1: Comparison of real structure and digital twin of the highway pre-stressed concrete bridge Terfener Innbrücke.

1. Introduction

During its service life, every structure is subject to various types of actions. A bridge, for example, must be able to withstand the loads resulting from traffic, wind, snow, temperature variations, etc. These loads, especially in older structures, often exceed the actions assumed in the calculations. This may result in structural damage, which can limit the load-bearing capacity and serviceability. In contrast, novel calculation methods can be used to identify the load-bearing reserves and thus extend the service life of the structures.

For a **clear** and **reliable** assessment of the state of any structure and the facilitation of decision-making processes related to inspection and maintenance, a **novel system for monitoring and predictive analysis** has been recently introduced. This system involves the continuous acquisition of measured data on the structure by a **digital twin**, specifically developed to predict the behaviour of the observed object. The use of **artificial intelligence** technologies allows for performing predictive analysis, for a more accurate assessment of the evolution of the measured data, improving the planning of inspections and maintenance interventions. The digital twin can also allow simulating in real-time the global behaviour of the object at each point, through the automatic execution of nonlinear **finite element analysis**. Based on the measurements, the digital twin is constantly calibrated through advanced inverse analysis procedures, aimed at minimizing the discrepancy between the measurements and the results of numerical simulations. The monitoring platform allows for the online three-dimensional visualization and navigation of the digital twin, and therefore perform a virtual inspection of the monitored structure.

2. Definition of simulation-based digital twin

Based on the documentation made available for the generic structure, an advanced three-dimensional digital twin of the object can be developed. The digital twin can also be used to automatically perform multi-physics finite element simulations.

Several application cases are possible:

- **Slope stability monitoring**: inverse analysis calibration and back analysis techniques find great application in geotechnics, especially for the monitoring of slope stability. The geomechanical digital twins gets iteratively optimized to identify the unknown geotechnical parameters, ensuring a good match with the measurements. By using advanced constitutive models for soil mechanics, the stress and deformation fields are computed precisely and used to continuously evaluate and predict the stability of the monitored slope.
- **Tunnel monitoring**: reliable tunnel digital twins can be built and synchronized with measurement data during and after the construction. By employing simulation and AI it is possible to minimize the risk of collapse during the excavation phases, maximize safety, optimize the safety measures, and the management of inspections.
- **Bridge monitoring**: bridges can be continuously monitored via different sensors applied to the carriageway and foundation systems. An application case is presented in the following paragraph.

With the proposed system, a computational model is constantly updated and calibrated based on the data provided by the sensors installed on the real asset. These data allow to identify the state of deterioration of the object and to plan in time possible inspection and rehabilitation interventions, minimizing the risks of collapse.

2.1 Calibration by inverse analysis

The finite element model undergoes continuous calibration through inverse analysis, using advanced optimization and artificial intelligence algorithms.

Potential unknowns of the problem that cannot be measured directly will be identified indirectly, minimizing the discrepancy between measured data and the results of the computational model.

Through iterative calibration, the system progressively increase the reliability and accuracy of the digital twin over time.

2.2 Cloud-based 3D visualization

In the case study described in this article, the visualization of a 3D digital twin and measured data is possible directly online from any type of internet-connected device, through the cloud-based platform *WeStatiX SHM*.

The graphical interface allows the virtual inspection of the model, the analysis of the measured data, the evaluation of the occurrence of any problems, and the results of the finite element calculation.

The system also allows to analyse the evolution of the state of the object over time, comparing the expected and actual trends of the available data.

2.3 Data processing and predictive analysis

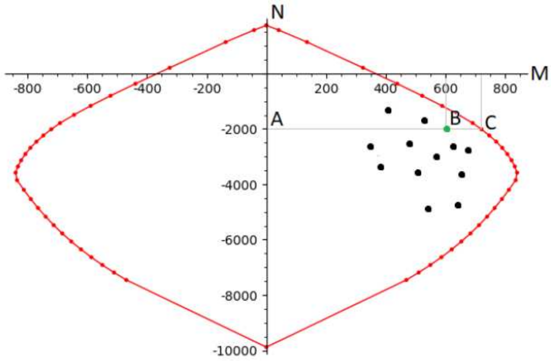

Figure 2: Example of calculation of utilization factor UF by using a M-N interaction diagram: UF = AB / AC

The system carries out the automatic processing and graphic visualization in the web browser of the calculated and measured data. These are presented to the end-user in a clear and understandable manner, so as to adequately summarize the relevant information and avoid confusion in the reader.

In the picture below, for example, it is possible to see a utilization ratio of 0.52: as this is calculated as the ratio between the acting forces and the resisting ones in all mesh nodes of the finite element model (please see the picture on the side), a value lower than 1 states the good state of health of the structure.

For each measurement made, the system makes available a detailed technical report containing the measurements data, the results of the structural calculation, and an assessment of the current state of the structure.

An automatic alarm system can be set up in case of exceeding predefined thresholds, which are to be agreed upon with the customer. The acquired data are processed by artificial intelligence algorithms with the goal of determining the behaviour and future deterioration of the object, providing indications about the areas susceptible to displacements or damage, and allowing to plan any interventions in time.

On the basis of the results of the predictive analysis, it is possible to intensify or reduce the maintenance on the site, consequently reducing management costs.

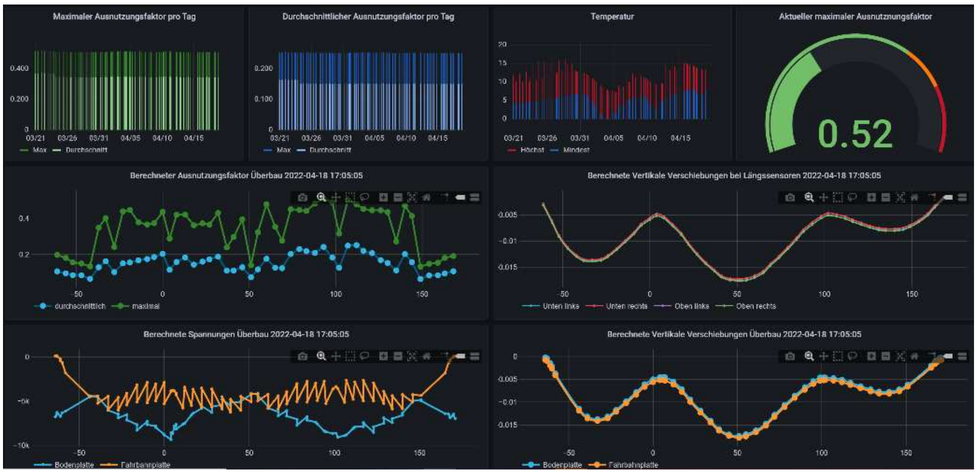

Figure 3: An example of the visualization of the monitoring data in the cloud-based dashboard.

3. An application case: the Terfener Innbrücke

The described method has been successfully applied to the **Terfener Innbrücke**, a bridge located at km 54.3 of the A12 Inntal motorway which serves to overpass the motorway over the Inn, with a separate supporting structure for each directional carriageway. The new construction of the Terfener Innbrücke is a 3 spans prestressed concrete structure with a box girder cross-section and it has one bridge support structure per directional carriageway. The supporting structures are erected in free cantilever from the bridge piers, without any downward support.

Figure 4: The Terfener Innbrücke

The physical bridge is linked to the digital twin through the sensors installed in different locations, which measure the values of variables such as deformations and temperatures. After the analysis of those variables, the model gets automatically updated, improving the quality of the predictions. Finally, good quality predictions allow to plan and execute inspections and the required maintenance efficiently, detecting problems early.

The measured values of the installed sensors, as well as those calculated with the digital twin, can be visualized in an intuitive dashboard, which is explained in detail in the subparagraph *Monitoring Data and Analysis*.

3.1 The digital twin

The 3D finite element model was developed according to the design dimensions based on the provided documentation (as-built and reinforcement drawings, structural calculations, etc.).

In order to achieve sufficient accuracy of the results in terms of local deformations, the individual cables were modelled independently and the three-dimensional model was developed with shell elements. The nonlinear calculation includes more than 40 sequential steps and sub-models to model each construction phase and takes into account inelastic time-dependent deformations due to creep, shrinkage and temperature. The model allows for the calculation of the deformation of the optical fiber cables (sensors) from the time of the first measurement, taking into account the loading history of the structure.

The numerical analysis allows to take into account the stress losses caused by friction and curvature of the cables, as well as the anchor slip during slackening. The stressing forces calculated by FEM were compared with those calculated by the designer using an analytical calculation method.

In order to validate the results of the calculation model, a comparison was made between the concrete stresses calculated by the designer and those calculated by this FEM model.

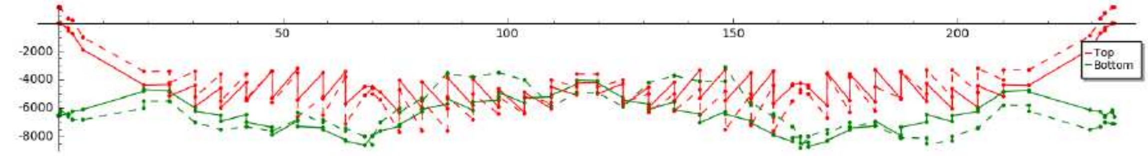

Figure 5: Comparison of the averaged concrete longitudinal stresses (kPa) in the bridge deck slab (red) and floor slab (green), obtained with different calculation models (shell model - solid lines, beam model - dashed lines)

In the FE calculation performed by the designer, the bridge is modelled with beam elements, taking into account the levelling of the beam-web cross-section according to Euler's theory. Using a model with shell elements, it can be seen that the stresses generated by the tendons are concentrated near the anchorage and then propagate throughout the structure. Therefore, in order to make a comparison, it was necessary to average the stresses in the deck slab and the floor slab. Although the calculation was performed with different calculation models, a good agreement of the results can be observed.

Every day, several finite element analyses of the bridge is performed on the basis of the monitoring data obtained from the installed sensors: the congruence of the results shows the good reliability of the calculation method used.

3.2 The sensors

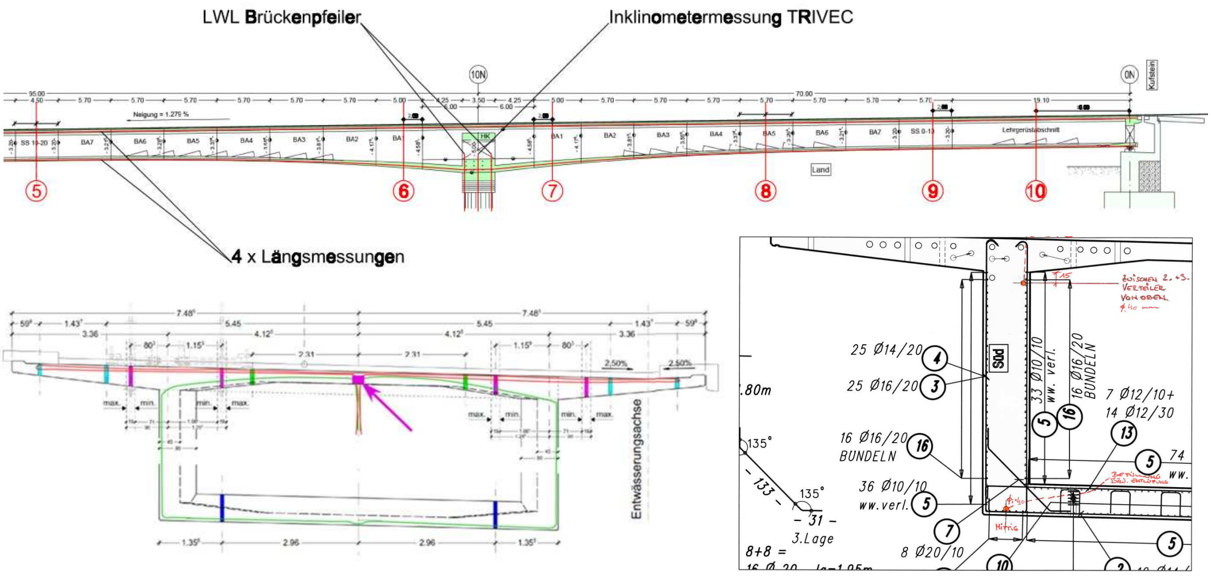

Figure 6: Fiber-optic sensors installation scheme showing the location of longitudinal cables (top and bottom-right pictures) and transversal cables (bottom-left picture)

The bridge is monitored with fibrisTerre's distributed fibre-optic sensors (Brillouin BOFDA technology), which are placed inside the structure (see picture above), measuring its deformation and temperature. A total of 60 fiber optic cables were installed to measure deformations and temperatures in a distributed manner: **longitudinally** via 4 linear lines of 235m length at the four corners of the box girder; **transversally** via 11x2 sections (box and deck) evenly distributed along the axis of the bridge; **vertically** in the two pillars of the bridge and pile foundations. Longitudinal and vertical cables were inserted into special pipes which were then injected with cement mortar, while transversal cables were loosely inserted into the structure prior to concrete casting.

A BOFDA Brillouin optical interrogator is permanently installed on-site and allows a query of the different fiber-optic cables, having a total length of nearly 7km, with a measurement point every 10cm. The sensor data can be visualized easily within the system interface.

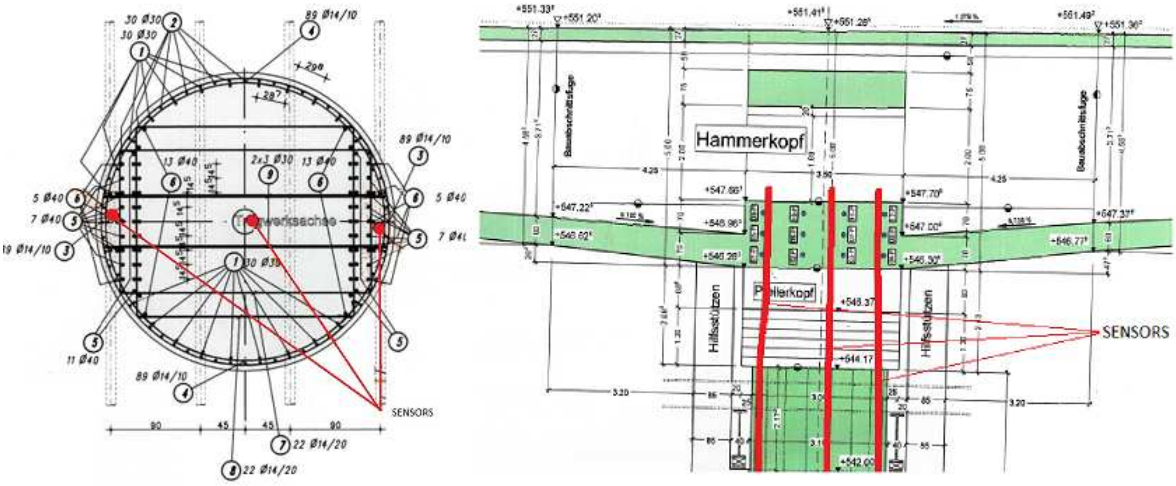

Figure 7: Detail about the sensors installed on the pillars and piles.

In particular, in each pillar are located three sensors (see picture above): the two on the sides are fiber-optic sensors while the central one is a tri-axial inclinometer.

These are applied from the pillar to the bottom tip of the piles, allowing the calculation of the soil deformation and soil subsidence and evaluating the soil-structure interaction.

3.4 Monitoring Data and Analysis

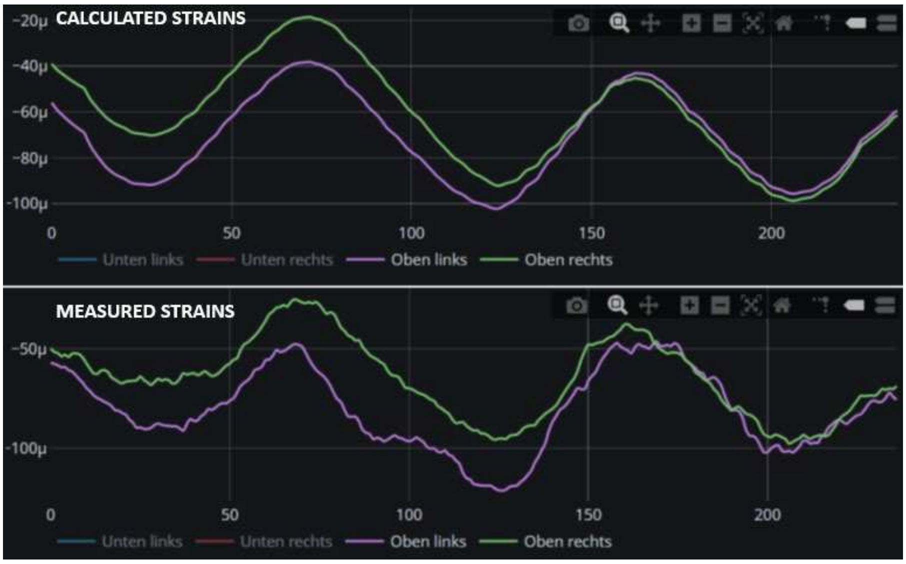

Figure 8: Comparison of calculated and measured strains: the difference is less than 5%.

As previously mentioned, after collecting the data and performing the analysis, it is necessary to present the outcome in a clear and understandable way, in order to avoid any confusion among the persons in charge. Therefore, the interface with the user is an important component of the process because it guarantees a correct interpretation of the monitored data and of the results of the post-processing.

The digital twin of the Terfener Innbrücke was developed for being visualized in *WeStatiX SHM*. Every day the measured data are used to calibrate the model and run a finite element simulation of the entire structure: the results obtained from that simulation are directly visible on the digital model and can be further analysed through the properly developed graphs.

Through the graphical user interface, it is possible to visualize different results, like: internal forces, displacements, utilization factor, deformations, stresses. Therefore, it is possible to check the calculated status of the structure.

The digital system allows continuous updating, storage and evaluation of the results of the structural analysis, as well as automatic evaluation in case certain limits of the static calculation are exceeded. The user interface provides access to an interface through which the monitoring data can be evaluated and compared with the finite element simulation results.

The interface allows the user to evaluate the time variation of the results and monitoring data to make correlations or evaluate the effects of certain conditions.

Since the digital twin is continuously operating, it is possible to observe the results of the analyses carried out until any moment. In particular, the deformations in the structure are largely dependent on the applied temperature and the thermal expansion coefficient of the structure. As expected, the bridge exhibits shortening/elongation due to temperature changes in winter and summer.

The evolution of the permanent deformations of the structure from the time of the first zero measurement to the present time is compatible with the results of the numerical simulations. The system presents an asymmetry of deformations due to creep and shrinkage of the concrete, which is partly due to the different construction and tensioning times of the structure.

The evolution of the coefficient of utilization is currently stable, without major daily variations, with values around 54-55%.

4. Conclusions

The proposed monitoring and predictive analysis system is based on the combination of the latest digital technologies for web-based 3D visualization, multi-physics numerical simulation, iterative calibration and AI-based data processing. The targets and advantages of the system are:

- **Digitalization of information**: Creation of a web platform on which the responsible persons can access the digital twin and gain information about the current status in real time – the focus is on a simple, clearly understandable visualization of relevant information.
- **Aggregation of data**: The data aggregation of individual monitoring systems into a global self-learning system.
- **Real-time adaptation**: The creation and continuous calibration of a numerical model (digital twin) based on the measurement data, which adapts to changes in real time.
- **Prediction, not reaction**: Use of artificial intelligence algorithms, which enable the predictive analysis to provide information in advance about the expected behaviour of the object, to analyse possible risks and thus to optimize safety measures.
- **Objective evaluation**: Develop a reliable and objective method that maximizes the level of knowledge of the asset, and that does not rely on subjective evaluations of single individuals.

These are accomplished by using a cloud-based platform, which provides the client with a user-friendly, accurate, and reliable method to continuously assess the state of the structure, allowing for 3D virtual inspection, indicating whether maintenance work has to be undertaken, as well as the degree of exploitation of the structure and its temporal evolution.

On the basis of the data acquired by the set of sensors, we expect to reach high reliability of the digital twin and of the predictive analysis procedures in a relatively short time. This system will increase the knowledge about the state of the object, minimizing the risk of unexpected damages and optimizing maintenance interventions. The proposed technology has its strength in the possibility of improving progressively, by "learning" from the data made available.

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