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. Therefore, the structures must be monitored to assess their structural condition. Normally, the assessment is rather limited as it is based on external and local surveys and monitoring. A new advanced 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 was accompanied by 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 providing the possibility to compare measurement/calculations, to assess the damage risk and to optimize maintenance activities. 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 to regularly interrogate the different fiber-optic cables of 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, which are performed daily. In addition, continuous model calibration and predictive analysis via sophisticated artificial intelligence algorithms can be performed on the platform.

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

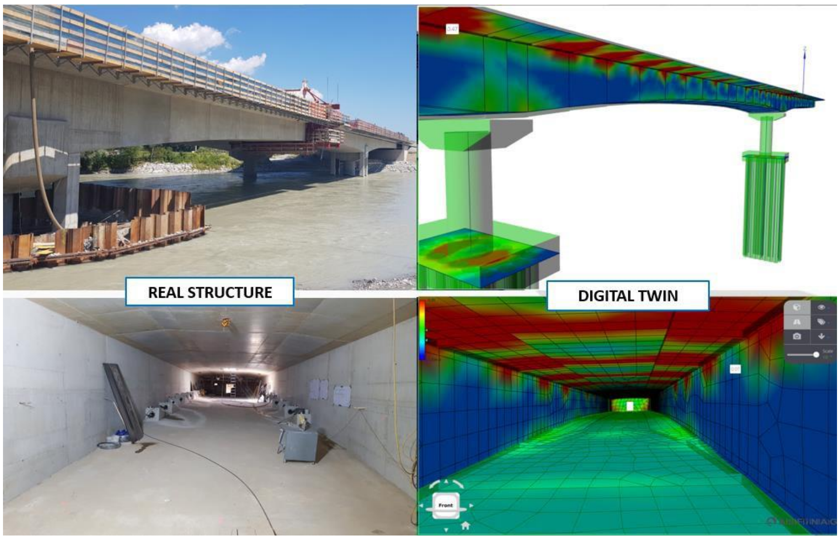

***Figure 1**: Comparison of real structure and digital twin of a highway prestressed concrete bridge.*

1. Introduction

During its service life, every structure is subject to various types of influences. A bridge, for example, must be able to withstand the loads from the traffic, wind, snow, temperature variations, etc. These loads, especially for older structures, often exceed the assumptions made in the calculations. This may result in structural damage, which can limit the load-bearing capacity and serviceability. Novel calculation methods can be used to better 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 high-resolution data for crucial parameters on the structure and their visualization by a **digital twin**, specifically developed to predict the behavior of the observed object. By the use of **artificial intelligence** technologies, predictive analysis can be performed to more accurately assess the evolution of the measured data and thus to improve the planning of inspections and maintenance interventions. The digital twin can also be used to simulate in real-time the global behavior of the object at each point, through the automatic execution of nonlinear **finite element analysis**. Based on the measurements, the digital twin can be constantly calibrated through advanced inverse analysis procedures, aimed at minimizing the discrepancy between the measurements and the results of numerical simulations. On the monitoring platform, the digital twin can be visualized in three dimensions and, therefore, the monitored structure can be virtually inspected by online navigation through the digital twin.

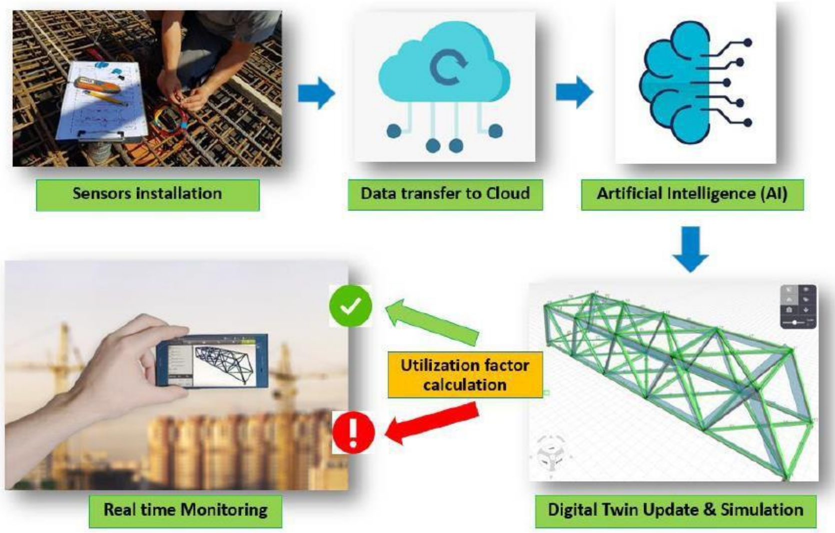

Figure 2: *Operation of the monitoring and predictive analysis system based on digital twin development and calibration, automatic simulation and 3D visualization in the cloud.*

2. Definition of a 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 multiphysics finite element simulations.

Several application cases are possible:

- **Slope stability monitoring**: inverse analysis calibration finds great application in geotechnics, especially for the monitoring of slope stability. The geomechanical digital twins get iteratively calibrated by inverse analysis 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 applying 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**: the whole bridge can be continuously monitored via sensors installed in the carriageway and foundation systems. An application example is presented in the following paragraph.

The computational model is constantly updated and calibrated based on the data recorded by the sensors installed on the site. Thus, the state of deterioration of the object can be identified and possible inspection and rehabilitation interventions can be planned in time, 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, it is planned to progressively increase the reliability and accuracy of the digital twin over time.

2.2 Cloud-based 3D visualization

The visualization of the 3D digital twin and measured data is possible directly online from any type of internet-connected device, thanks to the cloud-based platform *WeStatiX* with a graphical interface.

On the platform, the measured data can be analyzed, the results of the finite element calculation can be evaluated and, therefore, the virtual model can be check and examined for any problems in the structure.

It is also possible to analyze 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

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, which is calculated as the ratio between the acting forces and the resisting ones on several points of the structure. A value lower than 1 indicates a good state of health of the structure.

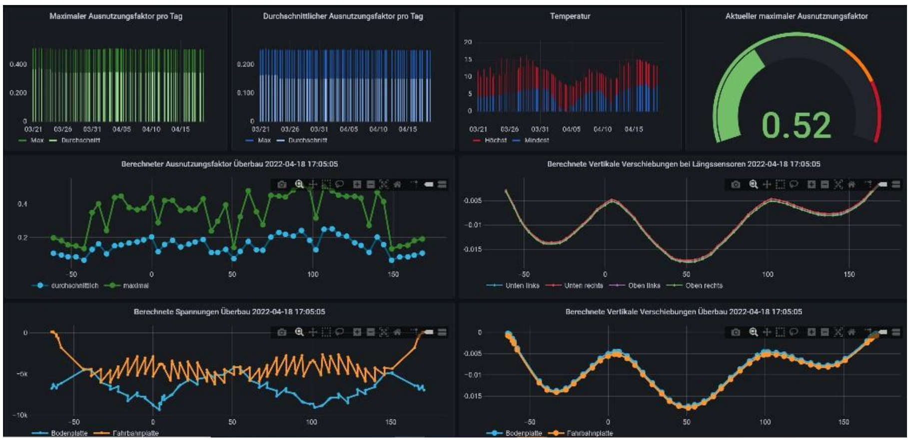

***Figure 3**: An example of the visualization of the monitoring data in the dashboard.*

For each measurement, it is also possible to export a detailed technical report containing the measured 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 with predefined thresholds, in agreement with the customer. The acquired data are processed by artificial intelligence algorithms to determine the behavior and future deterioration of the object, provide indications about the areas susceptible to displacements or damage and to plan any interventions in time.

On the basis of the results of the predictive analysis, it is possible to intensify or reduce the onsite maintenance and to adjust management costs to the requirements.

3. An application example: the Terfener Innbrücke

The described method was successfully applied to the **Terfener Innbrücke**, a bridge located at km 54.3 of the A12 Inntal motorway over the Inn, with a separate supporting structure for each directional carriageway. The new construction of the Terfener Innbrücke is a three 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 parameters such as deformation and temperature. The measurements are analyzed and the model is automatically updated. Finally, good quality predictions are made helping to detect problems at an early stage and to efficiently **plan and perform inspections** and the required maintenance work.

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*. Additionally, the structure can be fully visualized by using WeStatiX.

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.).

To increase the accuracy of the local deformation calculations, the individual cables were independently modeled 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 considers inelastic time-dependent deformations due to creep and shrinkage and temperature. The model calculates the deformation of the fiber-optic cables (sensors) from the time of the first measurement, taking into account the loading history of the structure.

The numerical analysis can include 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 with an analytical calculation method.

To validate the results of the calculation model, a comparison was made between the boundary stresses calculated by the designer and those calculated by this FEM model.

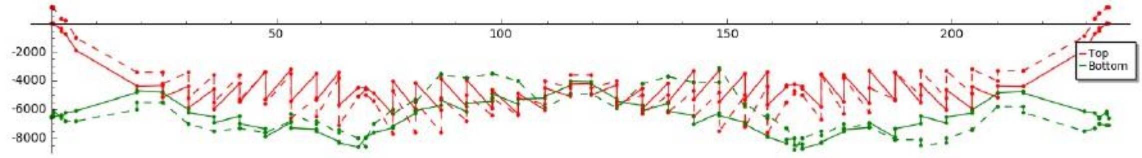

Figure 5*: Comparison of the longitudinal stresses obtained with different calculation models over the length of the bridge.*

In the FE calculation performed by the designer, the bridge is modeled with bar elements, considering the leveling of the bar-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. For comparison, it was necessary to average the stresses in the deck slab and the floor slab. A good agreement of the results can be observed between the different calculation models.

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

3.2 The sensors

The structure is monitored for deformations and the temperatures with distributed fiber optic sensing. A total of 60 fiber optic cables were installed to measure deformations and temperatures: **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 to interrogate the different fiber-optic cables of a total length of nearly 7km, with a resolution of 10cm. The measurements can be easily visualized within the analysis interface.

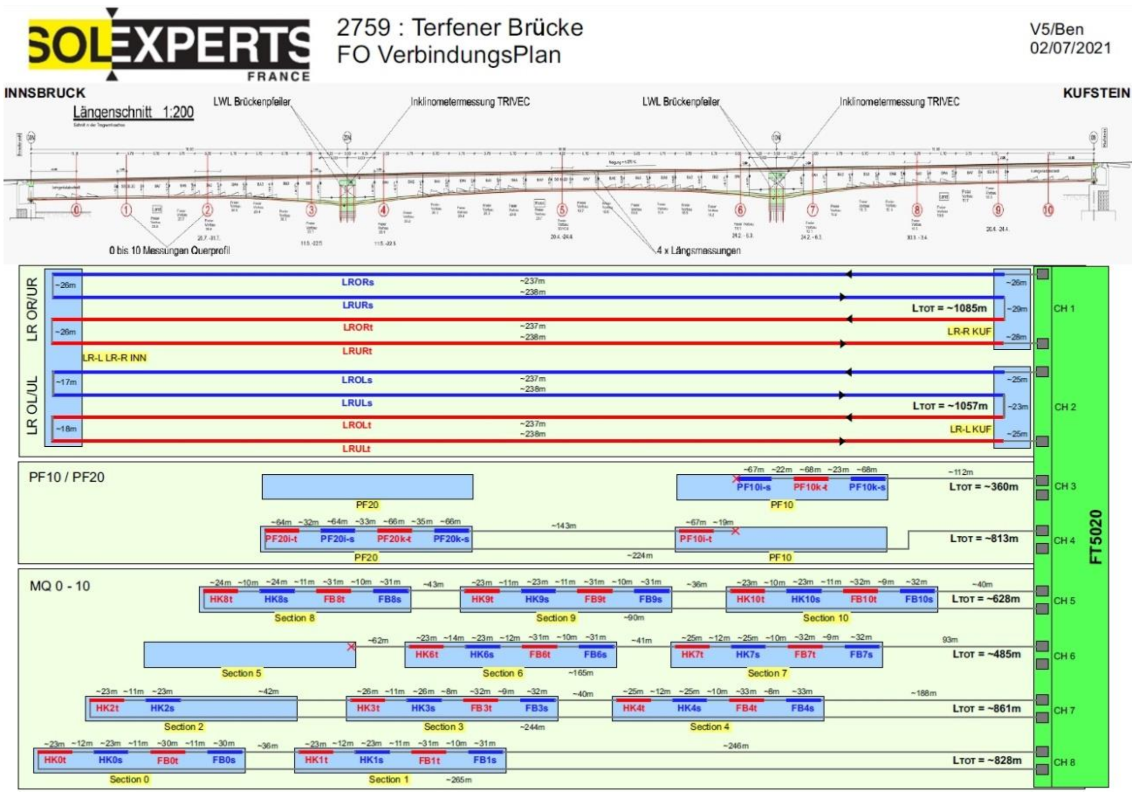

Figure 6*: Installation plan of the fiber optic sensors*

Figure 6*: Installation of the fiber optic cables in the structure (left)*
and splicing of the cables (right)

In addition, each pillar is equipped, besides two fiber-optic sensor cables on the sides, with a TRIVEC in the center for axial and radial displacement measurements along the borehole. With the instrumentation from the top to the bottom of the pillars, the soil deformation and soil subsidence can be calculated and the soil-structure interaction evaluated.

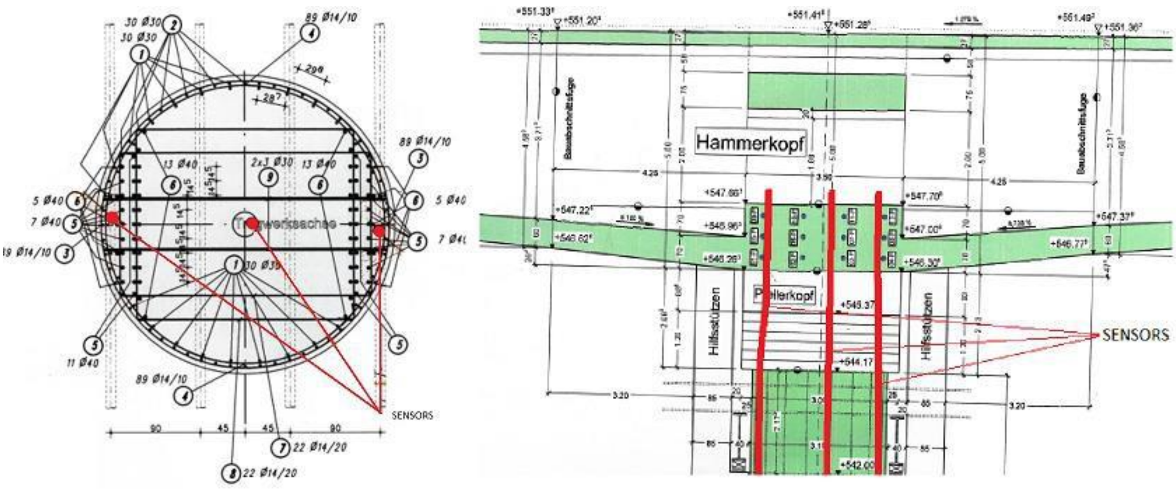

Figure 6*: Detail about the sensors installed on the pillars and piles.*

3.4 Visualization and Analysis

The proper presentation and visualization of the measured data and the analysis results in a clear and understandable way is crucial. Therefore, the interface to the user is an important component of the system because it ensures a correct interpretation of the monitored data and of the results of the post-processing by the responsible persons.

The digital twin of the Terfener Innbrücke was developed for being visualized in *WeStatiX*. 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 structure 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.

In addition, 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, is integrated. The measurement can be evaluated and compared with the finite element simulation results.

Furthermore, the time variation of the results and measured data can be evaluated to make correlations or evaluate the effects of certain conditions.

The digital twin is already operating. Therefore, the results of the analyses carried out until this moment can be compared. The bridge currently shows shortening due to low winter temperatures because the deformations in the structure are largely dependent on the ambient temperature and the thermal expansion coefficient of the structure. .

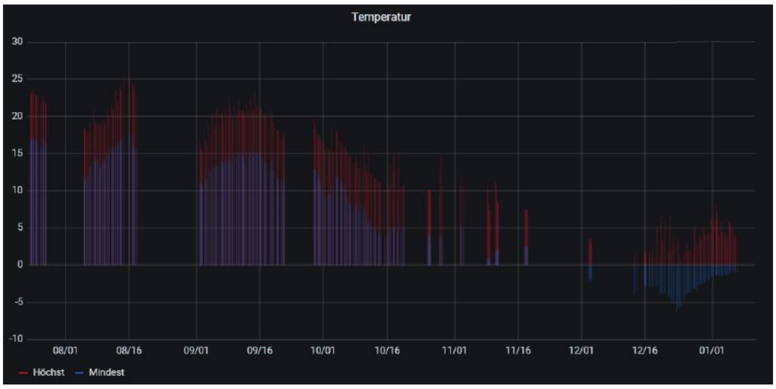

Figure 7: *Temperature development over time*

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 almost stable around 54-55%, without major daily variations.

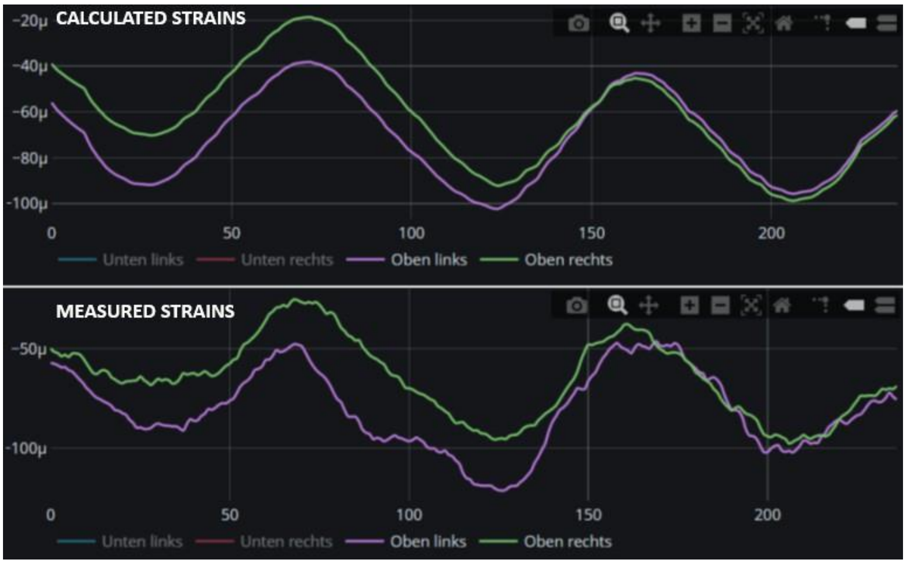

Figure 8: *Comparison of calculated and measured strains: the difference is less than 5%.*

4. Conclusions

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

- **Distributed fiber optic sensing:** A cost-effective method for the long-term monitoring of deformations and temperatures with a high resolution in small to large structures
- **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.
- **Merging of data**: The data merging of individual monitoring systems into a global self-learning system.
- **Real-time visualization**: The creation and continuous calibration of a numerical model (digital twin) based on the measurements to visualize 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 behavior of the object, to analyze possible risks and thus to optimize safety measures.
- **Objective evaluation**: Develop a reliable and objective method that maximizes the level of knowledge of the object, and that does not rely on the evaluation of single individuals.

The system uses a cloud-based platform, which provides the client with a user-friendly, accurate, and reliable access the state of the structure with the possibility for 3D virtual inspection. Thus, maintenance work can be properly planned and the degree of exploitation of the structure and its temporal evolution can be assessed.

Because of the high-resolution distributed strain and temperature measurements by the fiber-optic sensors and by additional measurements, we expect to reach a high reliability of the digital twin and of the predictive analysis procedures in a relatively short time. The entire 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 recorded data.

References

ASFINAG, 2022, Österreichweit einzigartiges Pilotprojekt für modernstes Monitoring geht auf Terfener Innbrücke (A 12 Inntalautobahn) in Betrieb', https://www.asfinag.at/ueber-uns/presse/pressemeldungen/belastungsversuche-terfener-innbrucke/

WeStatiX SHM 2021, accessed 10 April 2022, https://shm.westatix.com/