13th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
DOI: 10.3217/978-3-99161-057-1-198

Digitalization of existing measurement equipment as a valid basis for monitoring and structural behavior

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ABSTRACT: To determine damage and its effects, dense time series data is required, along with information from other sources like temperature changes that influence the main damage parameter and the structure itself. This allows the assessment of structural behavior, separating periodic and temperature-related effects from damage and ageing-related changes in load-bearing capacity. However, existing monitoring systems often lack proper documentation on measured values and their limits. Analog systems, suitable for early service life monitoring, provide readings at long intervals (years). Poor accessibility to remote measuring points further limits comprehensive time series data, including temperature correlations and other environmental correlations.

This article presents an approach that can be used to digitize different types of sensors and measuring devices in order to enable the autonomous and continuous generation of measurement data. The examples range from displacement transducers to force measuring devices, which were already installed in analogue form on existing civil engineering structures. The aim is to use digitalization to demonstrate a simple and cost-effective approach on using existing measurement technology as an initial basis for giving a statement about the behavior of the structure, its state of preservation and thus, in addition to supplementing the inspection process, also serve as a starting point for further monitoring.

KEY WORDS: SHM, monitoring, retrofitting, structural behavior, autonomous sensors, digitalization.

1 MONITORING AND STRUCTURAL BEHAVIOUR

1.1 Introduction

Bridges, tunnels, retaining walls, and similar structures are critical components of road and rail infrastructure. Over time, these structures inevitably age and deteriorate, necessitating regular maintenance and thorough safety assessments in form of inspections. As traffic volumes and loads continue to rise, maintenance intervals are shortened, and budget is limited such evaluations become even more essential.

Given the high costs of maintenance and the even greater expense of premature renewals, accurate assessment and prediction models are crucial (predictive maintenance). These models must be based on precise, objective, and physically accurate data that can be derived from inspections, sample testing, and monitoring.

Most infrastructure operators have their assets already digitalized and manage those via databases and graphical interfaces. This already digitalized data contains master data, drawings, information from the newly built structure and sometimes 3D-presentations of the structure. Periodic data on the state of preservation, such as inspection reports and laboratory analyses, are crucial for assessment. However, they are often not yet digitalized, preventing automated processing.

As part of the research project Candice, which was done for the Austrian Motorway Operator (ASFiNAG), a database with a graphical web interface has already been established to address this issue [1]. Additionally, forecasts for maintenance measures and a condition index have been calculated [2, 3]. Monitoring data was also incorporated into these calculations.

While data fusion was still largely manual, the approach demonstrated the effectiveness of combining monitoring data with condition data from other investigations.

This paper focuses on the transfer from a mostly manual reading of analogue measurement devices to an automated data transfer from the object under consideration to a data-platform, where an automatic storage is done and an individual display of relevant data to the user is possible. The digitalization especially with IoT devices allows for a constant flow of data, that offers several advantages for the assessment of structures:

- Direct measurement of physical values, ensuring accuracy vs. no subjective/false readings;
- Long-term data collection, capturing variations due to time of day, seasonal changes, temperature, humidity vs. usually 1 value per year or less at different seasons and environmental conditions influencing the measurement;
- Capture of rare or extreme events and influences of effects due to extreme weather conditions, earthquakes, sudden load impacts, settlements;
- Quantitative data providing objective insights for decision making rather than subjective evaluations based on a visual inspection of the structure;
- Elimination of human bias, ensuring reliability in assessments;
- Basic data set for extrapolation purposes related to the future behaviour of the structure;
- Real time integration with simulation and prediction models, enhancing cost planning, maintenance planning and resource management.

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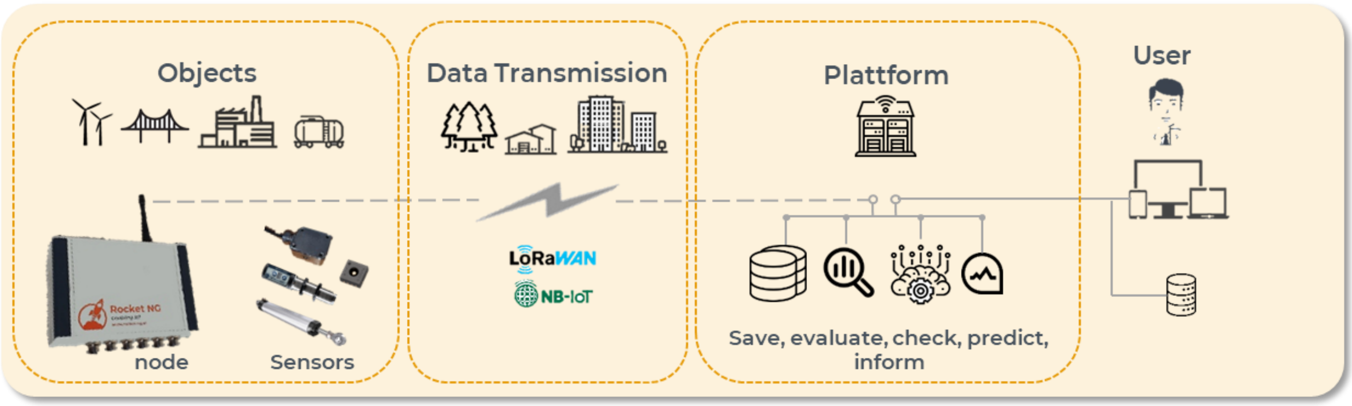

Figure 1: Interplay of the monitored assets (sensors and nodes), the data transmission, the platform, and the user.

In inspections the influence of temperature is frequently underestimated or too conservatively interpreted. In general, physical measures that are affected by environmental conditions are often difficult to assess, this holds for loads of pre-stressed anchors, inclinations, or displacements of components. As mentioned earlier accurate information is crucial to be used as a valid basis for decisions related to the maintenance, the safety assessment of the object and overall, the asset management combining both.

By leveraging monitoring, infrastructure managers can make informed decisions, optimize maintenance strategies, and extend their structures lifespan, making it a cost-effective solution. The description of the system used here clearly shows that digitalization and installing monitoring equipment are no longer hurdles.

1.2 IoT Type Monitoring

The IoT monitoring system presented and used in the following examples is an autonomous, innovative solution that enhances infrastructure monitoring for clients and contractors. It is in operation since many years across various applications and has already proven its reliability, robustness, and ease of use.

The system comprises of three main components as schematically shown in Figure 1:

1. On-site installation – sensors and IoT nodes placed on infrastructure assets are easily applicable even in areas without power access;
2. Data transmission network – nodes wirelessly transmit data to the platform for real-time assessment and can even be included into warning and alarm models;
3. Data platform – a secure database with evaluation models and web dashboards.

The design of the system for an autonomous operation, with battery-powered sensor nodes is capable of functioning for up to 15 years. Eliminating the need for fixed power sources significantly reduces installation complexity and associated disruptions, such as traffic closures. Data transmission is encrypted and automated, ensuring secure and reliable monitoring.

Key features and advantages of such an IoT system are:

- Plug & Forget: Fully automated system monitoring, with alerts for any issues;
- Edge Computing (AIoT): Onboard processing reduces data load and enables intelligent evaluation;
- Flexible Data Integration: External data sources can be fused for enhanced analysis;
- Instant Alerts: Critical conditions trigger automatic notifications via email, SMS, or warning and alarm systems;
- Real-Time Access: Mobile Apps and web-based dashboards provide instant insights - no additional software required;
- Data transmission is encrypted and automated, using the latest wireless technology.

The sensor node (16 × 11 × 7 cm) is designed for harsh environmental conditions and ensures robust performance. It provides power to sensors, controls measurement cycles, stores data, and transmits information via low power WAN (1.5 km range in urban areas, 20+ km in open environments). The node supports multiple sensor connections (1, 2, or 6 channels), enabling flexible deployment across different assets.

The system requires no on-site configuration or specialized technical knowledge, significantly simplifying installation. Proper sensor mounting remains critical for ensuring measurement accuracy, though once installed, the network configuration and data transfer are entirely automated and need no interaction by the installation team. Furthermore, the system supports a wide range of sensor types, including:

- Displacement, strain, and force gauges;
- Pressure and temperature sensors (for air, solids, and liquids);
- Humidity sensors (ambient and material-based, including dew point calculations);
- Pluviometers and acoustic sensors for environmental monitoring;
- Corrosion monitoring and cathodic protection assessment;
- Water level measurement
- Water content and pore pressure determination in soils;
- Inclinations (for piers, retaining walls, mast, settlement of buildings and excavations …).

Energy efficiency is a key design consideration, with preference given to low-power sensor alternatives to maximize battery life.

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2 SELECTED APPLICATIONS

2.1 Reasons and benefits

As structures age, the parameters used to assess structural safety and durability worsen. This is particularly crucial for structures that approach their planned service life or which are in environments where environmental or load parameters change significantly over time. Examples here are the ground water conditions in geotechnical engineering or the impact due to winter maintenance such as de-icing agents. Due to the ageing infrastructure in Europe and most parts of the world digitalization of existing structures can be one tool to help address these issues with respect to longer lasting and safe infrastructure especially along road and railway networks.

By implementing dense monitoring systems, structures can be evaluated based on real-time, precise measurements rather than relying on conservative estimates dictated by standards. This approach can offer the possibility to extend the service life of structures by accurately measuring loads and issuing alerts before critical situations arise. The importance of such measurements increases as structures age, making digitalization even more crucial for older structures compared to newer ones.

However, most of the already installed measurement equipment is still analogue, nevertheless a wide range of these can be digitalized. In geotechnical engineering structures are often equipped with extensometers and inclinations for the determination of movements, load cells for the measurement of the currently applied anchor force and additionally, temperature and humidity measurements are available.

In the following some applications will be presented showing the potential of digitizing already existing measurement equipment and therefore offering an easy and cost-effective first insight into the behavior of a structure.

2.2 Digitalization of anchor load measurements

The retaining wall discussed here is shown in Figure 2 and is in service since the mid-1990s and some anchors are equipped with analog load measurement systems often applied in Austria.

Figure 2: View of the anchor wall.

In the course of an inspection, no serious defects or damages were found on the wall and the adjacent areas and a generally good state of preservation was attested. However, it was recognised that some of the anchor load measuring devices were only partially functional. Furthermore, a comprehensive time series regarding the anchor loads was not given.

For this reason, it was investigated how the existing hydraulic load cells could be reprocessed for analogue readings and how digitalisation would be possible. The digitalization solely required an additional hydraulic connection and a smart node, which could easily be installed within one hour at the site.

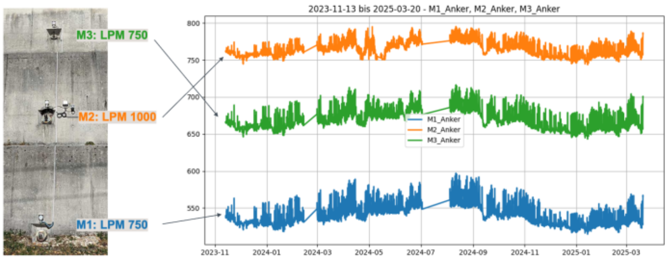

Figure 3: Time-series of anchor load measurements on three anchors along a cross-section.

Measurements show that the anchor loads are temperature-dependent, with significant variations throughout the year as shown in Figure 3. The observations further show that the higher capacity hydraulic load cell (indicated as LPM 1000) exhibits smaller force variations, than the two smaller (LPM 750) ones.

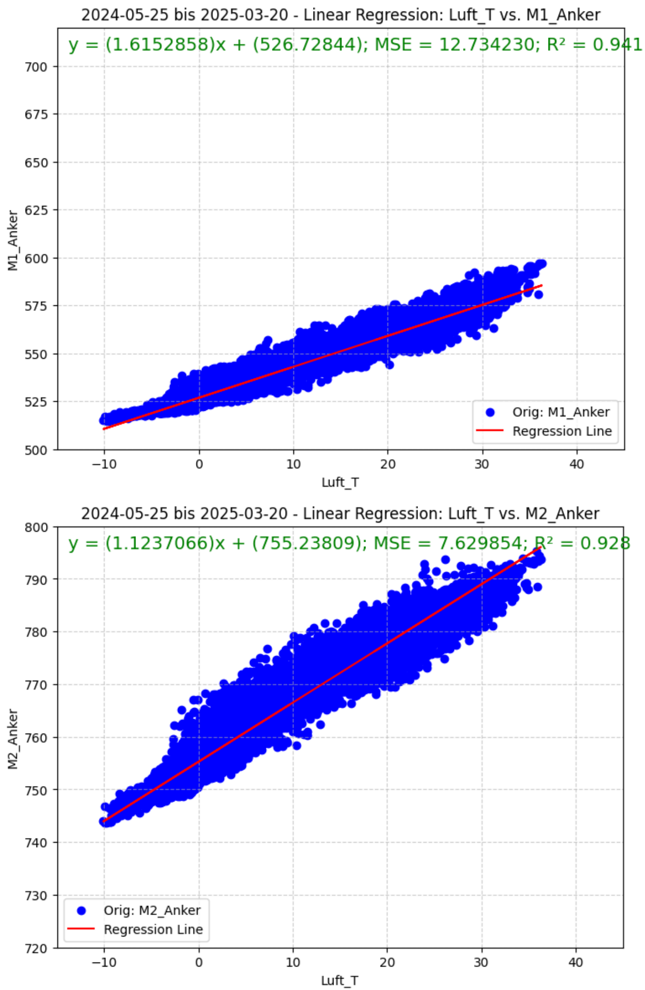

Figure 4: Correlation between anchor load (ordinate) and air-Temperature (abscissa) over a periode of 1.5 years; top: M1 (LPM 750); bottom: M2 (LPM 1000).

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Figure 4 illustrates the correlation between currently applied anchor load and air temperature for the two different LPM sizes, which were 750kN and 1000kN as given in the designation. It can be easily observed that there is an almost linear correlation between the anchor load measured and the air temperature. Thus, the change of the anchor load versus the air temperature can be calculated for:

1.55 kN/°C LPM 750

1.10 kN/°C LPM 1000

These values may be unique for the configuration found at this site and may not be applicable to other sites or structures. Nevertheless, those ranges of temperature related measurement results for anchor load plates are in alignment with the experience from anchor wall inspections as well as analogue readings of such measurement equipment.

2.3 Digitalization of extensometers

Figure 5 shows a detail of a extensometer of a retaining wall that is in service since decades. Based on observations during an inspection, it was recommended to shorten the measurement intervals, as the prevailing boundary conditions were now assessed to be more critical. In order to bridge the period until the structural reinforcement could be carried out, a suitable permanent monitoring system was implemented.

The extensometers were upgraded with nodes and sensors so that data was immediately available online and limits could be monitored 24/7. During the dense monitoring phase, a torrential rain event changed the environmental conditions even more. The new system was able to detect this immediately and action could be taken if necessary. Later, during the construction phase for the installation of new prestressed grouted anchors, valuable insights were also gained regarding the impact of anchor drilling on the system behavior of the structure.

Other applications include anchor force monitoring, bridge joints, pier tilting and deflection. Autonomy in the field is a must for economical implementation or upgrade of such monitoring.

Figure 5: Upgrade of existing extensometer for 24/7 and online measurement.

2.4 Static and dynamic crack width measurements

Crack monitoring was conducted on the center span of a three-span (45/70/45 m) cantilever bridge [4], where cracks were observed in the bottom plate and the webs of the hollow box. These cracks occured in the transition zone, where the floor slab shifts from prestressed to non-prestressed, near the anchorages. Cracks in the floor slab are located within the prestressed zone, inclined at approximately 45° to the bridge axis, while those in the web follow a similar angle with continuous prestressing in this area.

Crack width monitoring, represented in green in Figure 6, covers five to six equally spaced cracks (~20 cm apart). The cracks run perpendicular to the measurement indications, with individual widths reaching up to 0.3 mm and a total width (sum of individual cracks) of up to 1.2 mm. Each group of cracks is monitored collectively, with the total crack width recorded.Warning thresholds were set for immediate detection of critical crack widths. Figure 7 illustrates crack width variations over a year. While significant, these variations remain within acceptable limits. Temperature measurements were incorporated to account for thermal deformations, as shown in Figure 7. The right-side diagram reveals that lower temperatures generally correlate with greater total crack widths, though the temperature effect is minimal.Detailed investigations revealed sudden spikes in crack width readings, suggesting abrupt crack openings. These spikes were detected in measurements taken at 15-minute intervals, indicating that dynamic loads were not fully captured by these static readings. To assess dynamic loads, the system was switched remotely to dynamic measurement mode, eliminating the need for on-site visits. In this mode, 10 measurements per second were taken and processed in the node (edge computing), evaluating maximum, minimum, and mean values over 5-minute intervals.On the platform, the dynamic range of crack width was calculated as the "Total Crack Width Range @ 5-minutes" (TCWR), representing the difference between maximum and minimum values within a 5-minute slot. Figure 8 shows the TCWR over a week, highlighting significant variations. During weekends, the TCWR remains low due to Austria's truck driving ban, with a notable increase at 22:00 on Sundays when the ban is lifted, peaking at 0.4 mm. Similar peaks occasionally occurred at 19:00 on weekdays.The highest TCWR (0.4 mm) was used to calculate the stress range in the reinforcement. Since mean stress is less influential for such steels, stress range remains the dominant fatigue parameter. The stress range calculation followed Eurocode 2 but incorporated refined parameters from literature [5]. Results indicated a dynamic stress range of ~90 N/mm², well below critical limits. Combined with static calculations of mean stress, the findings confirm that reinforcement stresses are not critical.

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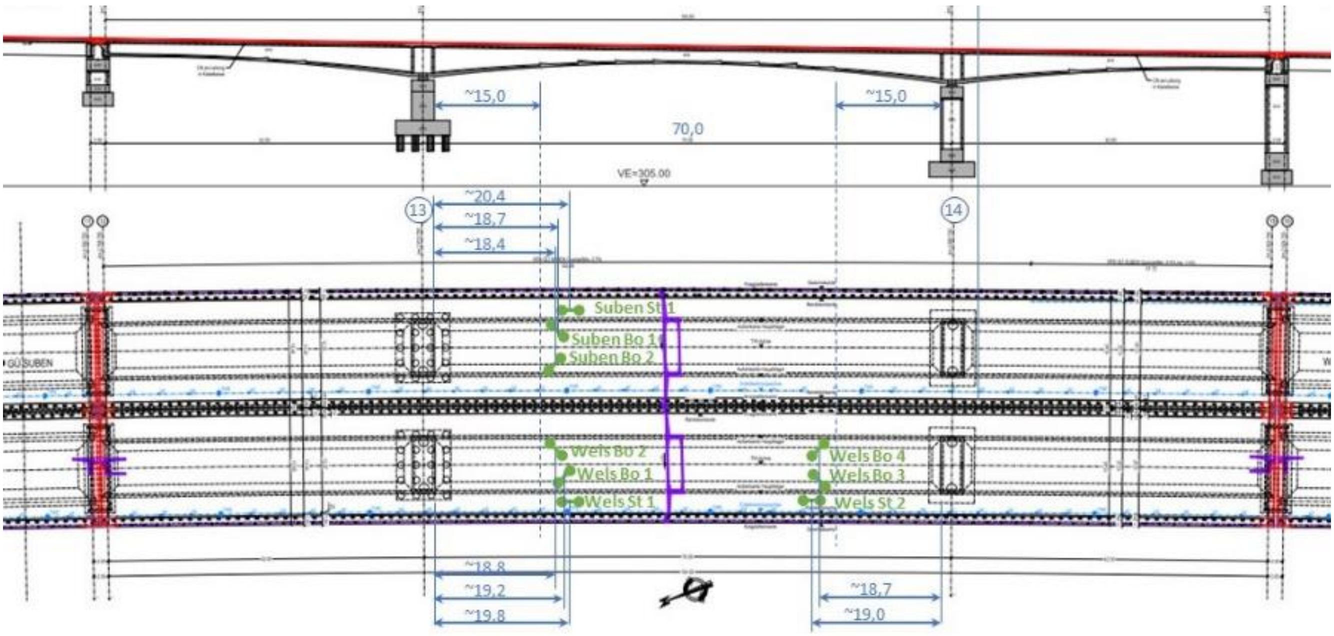

Figure 6: Overview of the three-span cantilever bridge. The monitoring of the total crack width is shown in green and the cracks run perpendicular to the measurements.

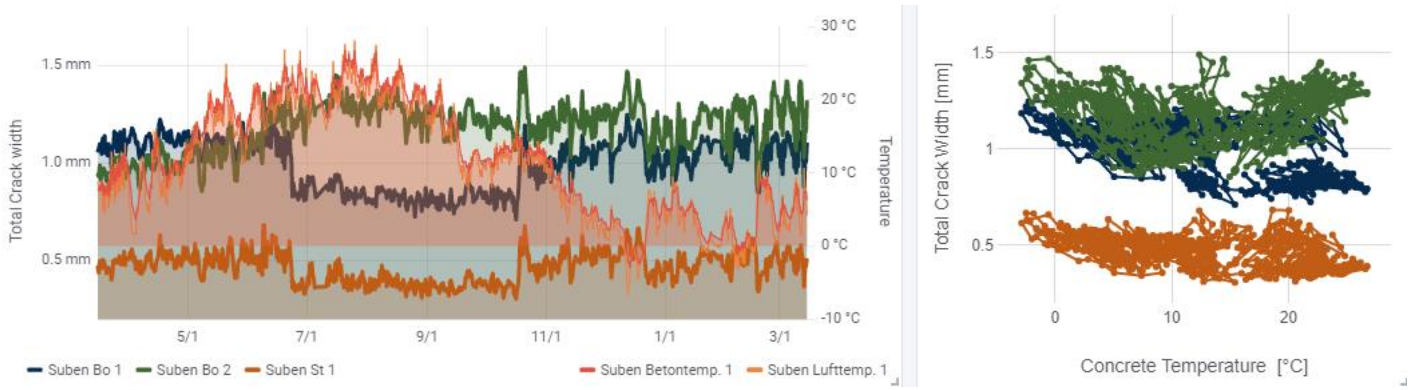

Figure 7: Variation of crack width for one year. Left diagram shows the values vs. time and the right diagram shows the values vs. concrete temperature.

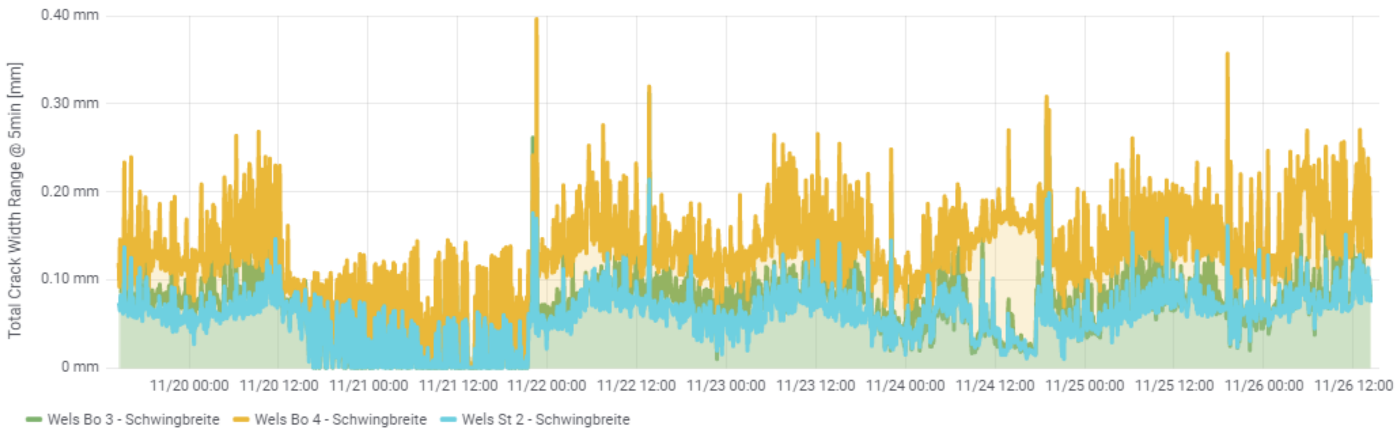

Figure 8: Max-Min-range of crack with for one week.

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Energy consumption in dynamic measurement mode is higher due to continuous recording, processing, and data transmission at higher intervals. Battery life in this mode is estimated at ~1 months. However, after one week in dynamic mode, the system was switched back to 15-minute intervals for routine crack monitoring. The system has been operational for 4.5 years, with battery replacement expected in over six years.

The digitalization of the crack measurement was here an absolute game change because with manual readings it would have been enormously costly, the readings would not have been so dense, the temperature dependence would have been difficult to determine and dynamic measurements would not have been possible. through the digitalization of crack measurement, not only were costs saved by reducing on-site visits (and costs for lifting platforms), but the measurements also provided significantly more assessment options. This reduced the number of unknown effects and enabled a more detailed analysis, leading to a focused, durable, and cost-efficient rehabilitation.

3 DESIGN OF EXISTING STRUCTURES WITH AN INCREASED KNOWLEDGE LEVEL

There are currently only limited technical and legal guidelines on how to deal with existing infrastructure - especially with regard to existing damage or defects. Although there are already corresponding principles and concepts for this in maintenance and asset management, there is still a lack of corresponding guidelines and regulations, particularly in terms of recalculation and assessment.

Although the application of numerical models and the use of high-quality material laws can be used to define the bandwidths here, realistic modelling - especially of damage - is only possible to a limited extent. An example of this can be found in bridge construction. ÖNORM B 4008-2 [6] has laid the foundation for the recalculation of existing structures. Here, for example, the load models can be adjusted based on monitoring the traffic loads. This thus corresponds to a real load, which in turn can enable a more truthful design of the component loads and, above all, the deformations.

Furthermore, the integration of monitoring systems into this process could make a significant contribution. With regard to the difficulties of verifying the serviceability limits, the models can be adapted to a digital twin by comparing them with monitoring results. Based on such processes, damage patterns and their effects on the load-bearing behavior can also be taken into account more accurately.

4 CONCLUSIONS & SUMMARY

Using an IoT-based monitoring system provides a scalable, autonomous, and cost-effective approach to long-term infrastructure assessment. Its combination of wireless communication, edge computing, and real-time data processing enhances decision-making for maintenance and safety assessments. By eliminating complex on-site configurations and reducing energy consumption, such systems offer a robust and sustainable solution for modern infrastructure monitoring that does not require extensive training of workers on site.

The digitalization of existing structures is essential for extending the service life and ensuring safety, especially as ageing and deteriorate prolong. Many structures, particularly in geotechnical and structural engineering, already have measurement systems in place, such as extensometers, inclinometers, and load cells. By upgrading these systems with modern sensors and online monitoring, real-time data can replace conservative assumptions, enabling more precise assessments. This helps detect critical changes early, preventing failures and reducing maintenance costs.

As infrastructure worldwide continues to age, digitalization becomes increasingly important to maintain structural integrity efficiently. Furthermore, with the progression of climate change-related effects such as the rise in mean temperature or the more frequent occurrence of torrential rainfall events, a more rapid increase in possible damage is to be expected, especially for civil infrastructure. Autonomous, cost-effective monitoring solutions can therefore offer a new possibility for monitoring, health inspection and structural assessment and can be seen as a valid basis for the asset management and the decision making related to it.

The presented applications demonstrate how existing measurement devices can be seamlessly integrated into digital systems, providing valuable insights for long-term structural health management.

ACKNOWLEDGMENTS

We like to thank the Austrian Railways (ÖBB) and Austrian Motorways (ASFINAG) for their support in research projects that supported these results.

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