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Monitoring of civil engineering structures – current and future use cases

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ABSTRACT: Monitoring represents an effective approach for addressing the diverse challenges associated with the maintenance of civil engineering structures. It contributes to improving both the availability and safety of these structures. By increasing the amount of information available about the structure, monitoring supports better-informed decisions regarding its preservation. Due to the complexity of monitoring applications, specific use cases are outlined. A key advantage of these use cases is that new technologies can be tested within well-defined and limited scopes. The use cases "monitoring of known, localized damage," "monitoring of known deficits identified through reassessment or resulting from outdated design procedures" and "monitoring aimed at assessing traffic loads and their effects" currently account for the majority of implemented monitoring measures. Their practical implementation is demonstrated through case studies from the Brandenburg State Road Authority. Additional use cases, such as "monitoring to support structural inspections" - for example through the use of imaging techniques - and "monitoring of major structures," such as large viaducts, are gaining importance, with initial practical examples already present in Europe. Future applications reveal potential for expanded use, particularly in the context of "monitoring to support predictive lifecycle management." This will become increasingly important in the implementation of digital twins, as announced in the national BIM master plan. Furthermore the concept of a "Birth Certificate" is intended to establish a reference state of the structure prior to commissioning, which can then be used for comparison with future measurements over time. The integration and interaction of these individual use cases pave the way for the implementation of digital twins.

KEY WORDS: STRUCTURAL HEALTH MONITORING, USE CASES, BRIDGES, DIGITAL TWIN

1 INTRODUCTION

Currently, the maintenance management of civil engineering structures is characterized by a reactive approach, where interventions are only initiated once visible damage has occurred. The introduction of a predictive lifecycle management strategy offers considerable potential to fundamentally improve the reliability, resilience and long-term availability of infrastructure systems.

Today's civil engineering structures are confronted with a growing set of challenges — including aging infrastructure, significant maintenance backlogs, rising traffic loads, and a shortage of qualified personnel to plan and carry out necessary maintenance activities.

These challenges are contrasted by advancements in the field of digitalization. Examples include planning with Building Information Modeling (BIM), data analysis using artificial intelligence (AI) methods, the implementation of digital twins, and the use of augmented or virtual reality (AR/VR) for periodic condition assessment as part of structural inspections. These technologies -including the use of monitoring systems as highlighted in this article - can contribute significantly to supporting the objectives of structural maintenance. By combining these various methods, a holistic evaluation of digitally available information becomes possible, paving the way for more efficient, proactive, and integrated infrastructure management.

2 CURRENT USE OF MONITORING ON FEDERAL HIGHWAYS

This article follows the definition of monitoring provided in the DBV (German Concrete and Construction Technology Association) guideline. According to this definition, monitoring describes the overall process of recording, analyzing, and evaluating structural responses and/or loads using a measurement system over a representative period of time (i.e., temporal development of the measured variable; continuous, periodic, or event-based measurements, either global or local) [1].

Monitoring is currently limited to addressing existing damages and deficits, as shown by a survey conducted by the German Federal Ministry for Digital and Transport (BMDV) among state road authorities and the Federal Highway Company. The survey, conducted in 2020, identified approximately 100 monitoring applications, which primarily involved bridges built between 1960 and 1980. The main reason for implementing monitoring was to capture structural responses, typically using deformation and temperature sensors [2].

There are several reasons why the use of monitoring on bridges along federal highways remains relatively limited. One major factor is the lack of specialized knowledge regarding the implementation of monitoring. This gap can be addressed through the development and application of standardized guidelines such as the DBV leaflet "Monitoring: Planning,

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Contracting, and Operation," the DGZfP (German Society for Non-Destructive Testing) leaflet B 09 "Continuous Monitoring of Structures," and the pre-published report "Guidelines for Strategic Monitoring of Structures" [1; 3; 4].

Professional training, along with the involvement of engineering firms and specialist consultants for the various aspects of monitoring, can also provide valuable support. Another key barrier is the difficulty in demonstrating the economic benefit of monitoring. The methodology presented in the research project "Economic Analysis of Monitoring Measures" for evaluating the cost-effectiveness and added value of monitoring can help encourage broader adoption [5]. The high complexity of the topic - particularly regarding the planning, implementation, and evaluation of monitoring measures - is another limiting factor. In this regard, the use of defined application cases and the step-by-step introduction of new technologies within clearly defined and manageable scopes can provide effective support.

3 USE CASES MONITORING

The implementation of use cases is a strategy to increase the use of monitoring. Use cases can be derived from project objectives and represent processes for achieving those objectives [6]. The advantage of use cases is that the use of new technologies can be tested in defined and limited areas, allowing obstacles to be overcome. The monitoring use cases existing in the federal highway sector are shown in Figure 1.

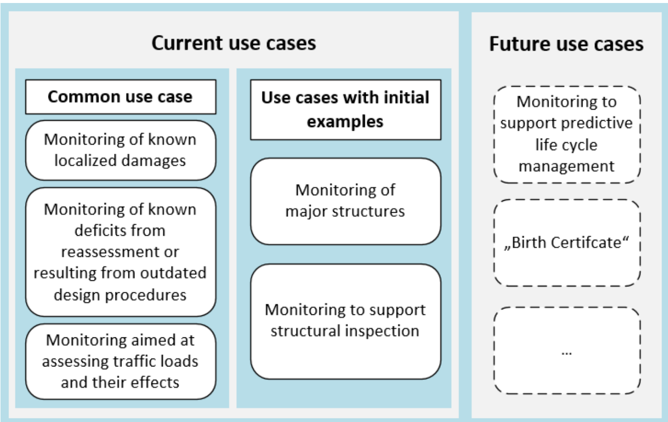

Figure 1. Monitoring use cases.

3.1 Common use cases

The use cases of monitoring of known localized damages, of known deficits from reassessment or resulting from outdated design procedures and using monitoring to determine loads and loads effects representing the most common use cases in Germany. These use cases are employed to address specific questions regarding the civil engineering structures, their condition, and its development over time. Starting from known damages or deficits, a monitoring concept is developed that is tailored to the structure and the specific question at hand.

Monitoring of known localized damages:

In this case, a local monitoring system is typically deployed. This local monitoring provides a good opportunity for monitoring the progression of damage. By monitoring the local condition, an estimation of further local developments can be made. This approach serves to extend the remaining service life and increase safety.

Figure 2. Bridge over the DB AG facilities along the B1 in Brandenburg an der Havel.

This use case is implemented on the bridge over the facilities of the Deutsche Bahn AG (DB AG) along the B1 in Brandenburg a der Havel (Figure 2). The structure was built in 1971 and is a single-span bridge with a span length of 47 meters. Separate, parallel superstructures carry the two traffic lanes. Their cross-sections are nearly identical and consist of two steel box girders and an orthotropic deck plate.

Numerous damages were identified on the structure during the structural inspection. These include, among others, cross-sectional reductions due to corrosion, fatigue cracks in the deck, and an abnormal positioning of the roller bearings. An object-specific damage analysis (OSA) demonstrated that the bearing positions are due to misalignment of the abutments caused by settlement. Geodetic measurements of the abutments showed that this process has not yet stabilized, indicating that further tilting is to be expected. Since the deformation capacity of the roller bearings is already highly stressed, permanent monitoring of the bearing movements is required.

Figure 3. Monitoring system on the bridge bearing.

This monitoring task is realized by installing inductive displacement transducers on each roller bearing (Figure 3) [9]. This allows for the monitoring of the remaining available bearing travel to ensure it is not exceeded. To identify long-

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term trends, the measurement data from the temperature monitoring system of the superstructure are also used. Over the years, a nearly linear relationship between bearing movement and temperature has been observed (Figure 4). Changes in the regression relationship between temperature and bearing movement can serve as an indicator of a system change.

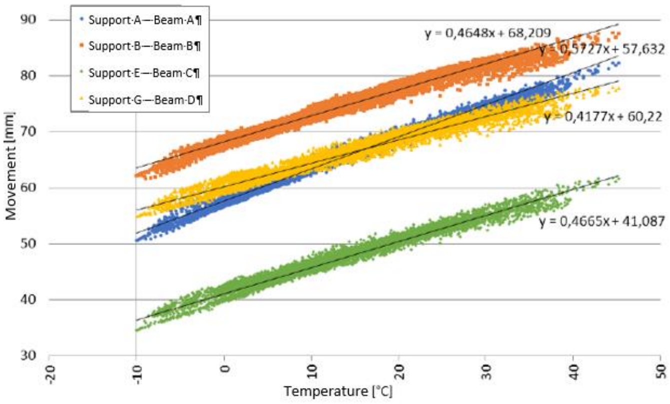

Figure 4. Evaluation of measurement data for one year.

<u>Monitoring of known deficits from reassessment or resulting from outdated design procedures:</u>

This use case is relevant when deficits in structures are identified during reassessment or when similar deficits are found in comparable constructions. Often, there are no visible damages yet, and the type or location of potential damage is unknown. Global monitoring enables the monitoring of the deficient structure. Global monitoring is designed to capture and evaluate global parameters of a structure that may indicate damage. A significant change in the global stiffness of the structure is generally required to enable precise system response measurements via global monitoring.

These parameters can be determined from the system response, for example, by measuring acceleration or deformation. The measurements serve to capture changes that develop in the structure over time. Provided the structure behaves in a ductile manner with failure warning signs, the basis for global monitoring of system reactions is that impacts and damages significantly affect the system stiffness, thereby having a direct influence on the load-bearing behavior of the structure. The various methods of global structural monitoring are based on the assumption that damages in the structure can be detected by changes in its global load-bearing behavior. Through measurements of these parameters and subsequent evaluation, conclusions can be drawn about the nature and location of the damage [10; 11].

Alternatively, global monitoring can be designed to detect the cause of the damage. For this, an acoustic emission monitoring system could be used, for example, to detect strand wire fractures in pre-stressed concrete structures [12] or fatigue crack formation in orthotropic deck slabs [13]. With a sufficiently large monitoring system, all areas where the deficit was identified can be monitored. The monitoring system detects and localizes any damage that occurs from the start of the monitoring.

The use of local monitoring can be applied, for example, in the case of fatigue in the coupling joint during recalculation deficits or shear force recalculation deficits, such as in the local monitoring of shear areas to detect the formation of shear cracks.

Figure 5. Bridge over the Havel along the B96 in Fürstenberg/Havel.

The measure for the bridge over the Havel River along the B96 in Fürstenberg/Havel serves as an example of this use case (Figure 5). The structure was built in 1968 as a single-span pre-stressed concrete slab with a span of approximately 16 meters. Hennigsdorf pre-stressing steel was used, which is now classified as being at risk of stress corrosion cracking. As part of the object-specific investigations to verify the failure warning behavior, samples of the pre-stressing tendons were taken. Broken tendons were already identified during the sample extraction. Laboratory tests confirmed that the tendons did not meet the required fracture elongation or tensile strength. The fracture patterns show significant initial cracks due to stress corrosion cracking.

Due to the importance of the structure for traffic, closure to traffic is only permissible in extreme cases. Therefore, a monitoring system using acoustic emission was installed on-site. The measurement system consists of 12 acoustic emission sensors, each positioned outside the navigation channel of the Havel River. Since its commissioning, a total of 10 tendon fractures have been recorded at the structure by the end of 2022. Each tendon fracture triggered an event-based structural inspection.

<u>Monitoring aimed at assessing traffic loads and their effects</u>

The actions on the structure can include direct effects from external loads (e.g. dead loads, traffic loads, wind or snow loads) and indirect effects due to restrained deformations (thermal stresses) caused by climatic influences (temperature) or settlement differences.

Climatic influences such as humidity and temperature can be measured through weather stations. The impact of temperature on the structure is measured using temperature sensors within and on the structure. Determining the temperature plays an important role in compensating for the temperature effect on measurements. In certain use cases (e.g., monitoring of coupling joints), temperature is a significant influencing factor for the assessment. Traffic and the composition of traffic are also of great importance for capturing the relevant effects on bridge structures. The use of Bridge Weigh-in-Motion (B-WIM) systems can, for example, determine the actual current traffic loads [14].

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Figure 6. Bridge over the Spree along the L35 in Fürstenwalde/Spree.

In the State Road Agency, a study was conducted to realistically capture object-specific target load levels. Monitoring systems were installed on individual structures to accurately record the respective boundary conditions [15]. One example is the bridge over the Spree River along the L35 in Fürstenwalde/Spree. The Spree crossing consists of a main bridge and a bridge over a side branch of the river (Archen arm) (Figure 6). The main bridge is a pre-stressed arch bridge with a span of 67 meters. The bridge over the Archen arm was constructed as a composite structure with a steel girder deck and concrete deck plate. It has individual spans of 25.5 meters, 28 meters, and 29 meters.

The determination of the target load level is relevant because there is a comparatively high traffic load and congestion due to junctions before and after the structure.

Figure 7. Measuring system on the bearing shelf/seat of the abutment.

To capture the effect, strain gauges were used, and temperature sensors were deployed to compensate for the measurement values' temperature influence. Temperature compensation in this use case is carried out in two steps: first, real-time compensation during measurement using a Wheatstone bridge; second, calibration of the recorded values by determining a baseline load level for a specific time series.

The measurement system was installed on the bearing shelf of the abutment (Measurement system on the bearing shelf/seat of the abutment, Figure 7). The verification of the measurement results was carried out through camera recordings of the ongoing traffic. The measurement took approximately two years. As a result, it was demonstrated that the target load level BK30/30 can be justified for the structure. The subsequent recalculation revealed deficits in the fatigue performance. However, the available measurement data allows for the derivation of an object-specific fatigue load model to optimize the verification process. This step is still pending.

3.2 Use cases with initial practical examples

"Monitoring to support structural inspection" and "Monitoring of major structures" are use cases where initial implementations are present in practice, but further research and support for implementation are still necessary.

Monitoring to support the structural inspection:

As part of the structural inspection according to [8], monitoring can be used to provide supplementary information that cannot be obtained through conventional inspections. The use of monitoring is possible at various stages in the structural inspection process. One option is the use of instrumented components to assess the behavior. For example, instrumenting bridge deck expansion joints and measuring performance parameters offers the advantage that these components are repaired based on actual loading. Instrumented components provide information on existing damage to the relevant parts and, if necessary, allow the prediction of future developments [16]. By now this use case is not aligned with DIN 1076 and is currently under discussion in the relevant standardization committees.

An alternative is the use of image-based monitoring, where structural images are automatically captured, and the georeferenced 3D geometry of the structure is subsequently determined. This allows the identification of areas of the structure that should be further examined during the structural inspection.

The image data can also be used for AI-supported analysis to automate the detection of cracks, spalling, or changes [17; 18]. Extracting damage information and locations, such as cracks from the captured image datasets, parallels the system identification methods of sensor-based monitoring [19]. Parts of traditional hands-on inspections can be enhanced and improved through digital tools.

Alternatively, Virtual and Augmented Reality (VR/AR) can also be used in the context of structural inspections. In this case, image-based techniques are also applied, where image data is georeferenced and linked to an existing 3D model.

Monitoring of major structures:

Monitoring of major structures refers to structures whose failure would have a large impact on the transportation network. Examples of such structures include major viaducts or river crossings. For these structures, the use of monitoring can be a useful addition to ensuring availability, even when no damage or deficits are currently known. To implement this use case, identification of the relevant structures is necessary. Their significance can stem from traffic-related or structural reasons. Traffic-related reasons include the importance of the structure for network availability or high traffic volumes. Structural reasons arise from the size and location of the structure, considering any limited options for providing short-term replacement. For this use case, global monitoring is relevant. In contrast to the use case "Monitoring with known deficits," no

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deficits need to be known in this case. This use case can apply to both new and existing structures.

Monitoring of major structures is more widespread abroad, as demonstrated by the monitoring of the Ponte da Lezíria bridge built in Portugal in 2007 [20]. The bridge was equipped with an extensive monitoring system to measure static and dynamic parameters. This system supports the structural inspections, and the asset owner has continuous access to an assessment of the structure's condition [20].

Similarly, at the bridge in the Digital Test Field Highway, the embedded sensors and the aggregation of the measured data provide the asset owner with continuous access to the current condition of the bridge, allowing for quick and effective decision-making when changes in the condition are detected [21]. The benefits of using preventive monitoring for bridges without existing damage have been demonstrated in [22].

3.3 Potential future use cases

The use case "Monitoring to support a Predictive Lifecycle Management" will gain significant importance in the context of implementing Digital Twins, which are announced in the BIM Master Plan [23]. Initial steps and ideas for implementing this use case were outlined in [19].

The potential of monitoring arises from the ability to monitor structures over long periods and detect changes. The potential lies in determining the structural condition and quantifying the reliability of the structure, characterizing the behavior of the structure with the goal of anomaly detection, and securing the remaining service life [19].

Monitoring data can provide information, for example, about damage mechanisms. This information can then serve as the basis for determining performance indicators in combination with other data. This approach aims to reduce uncertainties in the condition assessment and identify appropriate maintenance measures [19].

The use case "Birth Certificate" aims to establish a reference condition of the structure before commissioning, providing a basis for interpreting the impact of later changes and making statements about the expected behavior of the structural and equipment components. This reference condition can be compared with subsequent measurements, thus providing a decision-making foundation for determining the timing of necessary measures, such as permanent monitoring. For clarification the single measurement as mentioned above does not constitute monitoring in the classical sense, which generally implies continuous data acquisition.

The performance of a baseline measurement, including a proof load test, is mandatory in Switzerland, Italy, and France [24–26]. In [17], the performance of a baseline measurement at the Hochmosel Bridge is described. Here, in addition to vibration and strain measurements to determine the behavior of the bridge, imaging techniques were also used, among other things, to determine the 3D geometry.

4 INTEGRATION OF USE CASES

The interaction of the individual use cases can be envisioned through the implementation of Digital Twins. A Digital Twin can be understood as a digital representation of the real road infrastructure, which interacts with the real structure, records all properties throughout the entire lifecycle, and generates information for decision support from the data [27]. Figure 8 provides a schematic representation of a bridge's digital twin, highlighting the various data sources and the role of monitoring within the system.

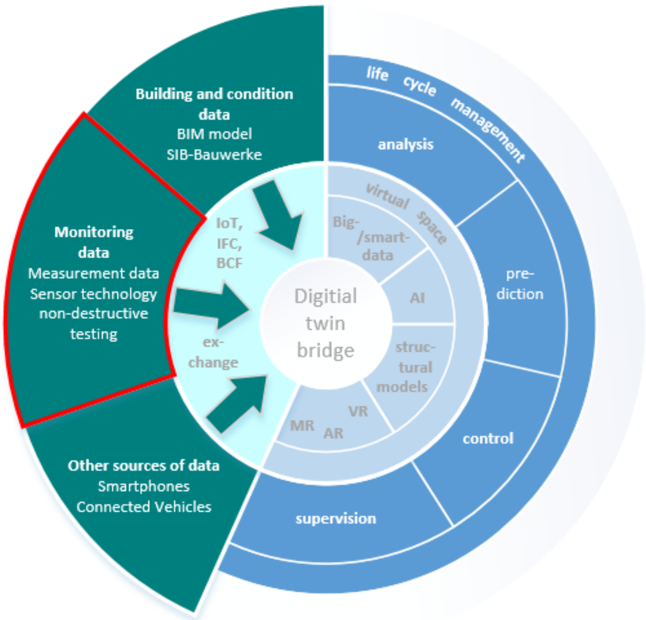

Figure 8. Monitoring as part of the digital twin according to [28].

Monitoring and the information and insights gained from it are essential foundations for the development and use of Digital Twins. The monitoring data provides insight into the current condition of the structure and serves as input data for determining future behavior. Therefore, the use of monitoring is fundamental to the processes of monitoring, analysis, prediction, and control that occur within the Digital Twin.

5 CONCLUSION

The use of monitoring on engineering structures of the federal highways is still not widely spread, but it is gaining in importance. Through the use cases, there is the opportunity to demonstrate the potential of monitoring and overcome barriers to its implementation. Currently, monitoring is of great importance in supporting the availability of engineering structures and, in particular, ensuring the remaining service life. A wealth of experience is already being gathered in these use cases today, which can be beneficial in the long term for the introduction of Digital Twins. Initial results, within the framework of Digital Shadows, can already demonstrate the potential on a smaller scale.

The benefits resulting from the application of monitoring measures can be quantified in monetary terms – for example, through savings on inspections, extended service life or early damage detection. In contrast, the benefits of the digital twin cannot yet be expressed in concrete figures, but they can be described qualitatively – such as improved decision-making, increased transparency regarding the structural condition and long-term potential for process optimization.

In conclusion, monitoring and the demonstrated use cases help bridge the gap between the physical structure and its digital representation.

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