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Permanent Structural Health Monitoring of a new prestressed concrete bridge

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Abstract

The digitization of processes and methods has been in the focus of construction industry in recent years. Whereas in the automotive industry predictive maintenance is state of the art, the prediction of the service lifetime for bridges is not standardized due to missing sufficient data to develop and train machine learning algorithms. Structural Health Monitoring (SHM) for bridges is used, e.g., to monitor a local damage trend or a structure's response to external influence. Because of the typical SHM tasks, sensors are often built to be attached temporarily to the structure and to be removed afterwards. For predictive maintenance, there is a demand for data from the beginning of the lifetime. In this paper we show challenges and solutions to implement sensors during construction like the integration in the construction planning, the geo-localization of the sensors, and durability of the sensors to obtain data from first day of lifetime.

All these aspects are shown in a practical example for the newly built Isen bridge in Schwindegg, Germany, where a sensory SHM-system has been installed to measure the bridge's condition starting from day one of its service lifetime. The results show that with a flexible installation team, the installation does not lead to delay in construction.

Keywords

Bridge Construction, Sensors, Structural Health Monitoring, Installation, 3D-Laserscan, Digital Twin, Ab Initio Monitoring

1 Introduction

In countries all around the world, bridges do oftentimes not reach their planned service life. Reasons for that are e.g., the increase of traffic [1], heavier trucks or mistakes in planning or construction [2]. But also, natural hazards come into play, as the German flood catastrophe in Ahrtal 2021 shows. The bridges were swept away and will be rebuilt [3]. Where disasters like flood, earthquakes or else are difficult to predict due to force majeure, human made damages or changes in the material behaviour of the bridge can be localized, reported, and tracked over many years. The deterioration of a bridge's condition is currently tracked in Germany with the bridge's inspection. The main bridge inspection is carried out every six years in accordance with DIN 1076 [4]. If damage is detected there, it is recorded in the structure log. The structure thus receives a condition grade. Austria also has a similar regulation with RVS 13.03.11 [5], while Switzerland uses SIA 469 [6]. The intervals between inspections are several years. Internal damage such as pretensioned steel fractures often cannot be detected by eye. In the worst case, overlooking such damage or the missing possibility of inspection can lead to the collapse of the bridge, as the Morandi Bridge in Genoa has shown [7].

In Germany, when damage is severely advanced and the condition grade is poor, bridge recalculation is needed. The recalculation guideline (Nachrechnungsrichtlinie - NRR [8; 9]) defines 4 stages for this:

- Stage 1: Recalculation according to current codes (Eurocode, DIN Fachbericht)
- Stage 2: Recalculation with additional codes (NRR)
- Stage 3: Recalculation including measurement results on the structure
- Stage 4: Application of scientific methods

For the last two stages, measurements are carried out on the structure. These can result from non-destructive testing (NDT), test loading or structural health monitoring (SHM). With NDTs and SHM, condition states are recorded more frequently, and the specific condition is monitored.

In manufacturing industry, the condition of machines such

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as robots is already monitored. In this way, wear progress can be detected, and maintenance periods can be scheduled. This eliminates long waiting times for spare parts. Digital twins take this one step further. The machines often communicate with each other and exchange information in the sense of the Internet of Things.

For structures, a permanent surveillance from the beginning to the end of the lifetime is not common. Monitoring is mostly used as a so-called emergency monitoring to secure the usability and until the bridge can be repaired or replaced. There are well-known projects in Germany like the Gänstor Bridge in Ulm [10] and the railroad bridge in Waren [11] where an SHM-system has been applied later. The monitored details are those where the damage occurred.

Also, when SHM starts from the first minute of a structure's lifetime, the measuring task mostly clear. For example, at the Austrian Huyck bridge, the load-bearing behaviour of pretensioned concrete hinges are investigated [12]. Therefore, several sensors to measure concrete strain, deformations and earth pressure are attached and integrated in the structure. Another example of measurements from nearly the beginning is the III[rd] Millennium Bridge in Gdansk, on which a monitoring system has been installed less than one year after the opening to monitor the influence of traffic and wind on the swinging behaviour of the bridge [13].

One can find more information about life cycle management and decision-making processes in the lifetime of a structure in [14].

Within the research project RISK.twin [15], digital twins are developed to create intelligent critical infrastructure. In cooperation with a bridge's replacement of the district administration of Mühldorf am Inn, Germany, an SHM system was installed to monitor a bridge from the first passing car. In the following chapters, the bridge and its instrumentation are shown.

2 The Isen bridge in Schwindegg

2.1 General information

In the German district of Mühldorf am Inn, the bridge of the district road MÜ22 in Schwindegg was hardly damaged during the Second World War. After renewing the superstructure in 1956 the bridge's condition was bad in the beginning of the 2020s. Therefore, the district administration decided to rebuild the connection road between Schwindegg and Buchbach at the same place. The replaced bridge's static system was a two single spans steel beam with a top concrete layer as superstructure. The supporting pile had been placed in the river.

Unlike the old structure, the new bridge is planned as a single-span frame bridge. The exact design is a four T-girder superstructure made of precast prestressed concrete elements with cast-in-place concrete supplement. The abutments are founded on bored piles with a diameter of 120 cm. The backfilling is done with lightweight material. Compared to its predecessor, the bridge is wider and has a sidewalk and cycle path. The clear span is approximately 19.8 m, the width between the outer edges of the caps is approximately 10.8 m. Figure 1 shows the new bridge underneath the old one. In Table 1, the main changes between the old bridge and its replacement are summarized.

Figure 1 Sideview of the demolished bridge (top) and the new bridge (bottom).

Table 1 Comparison between old and new Isen bridge Schwindegg.

attribute	old bridge	new bridge
number of spans	2	1
material	steel concrete compound	prestressed concrete
width between handrail	approx. 9.0 m	approx. 10.3 m
bridge area	178 m²	222 m²
clear height	approx. 2.2 m	approx. 2.5 m
span	approx. 19.3 m	approx. 21.7 m

2.2 Monitoring concept

The Isen bridge is common in its size, its construction material and its geometry and exists many times in Germany. Regarding the static system of the bridge, the following static effects and their origin are from interest:

- Stiffness of the rigid frame corners.
- Moment distribution of field and corners.
- Interaction between the bored piles and the abutment.
- Influence of temperature daily and seasonally.
- Tracking of all passing vehicles.

The main concept of the lifetime long monitoring is to monitor these effects that are also shown in Figure 2. In the following subchapters, these points are explained more in detail.

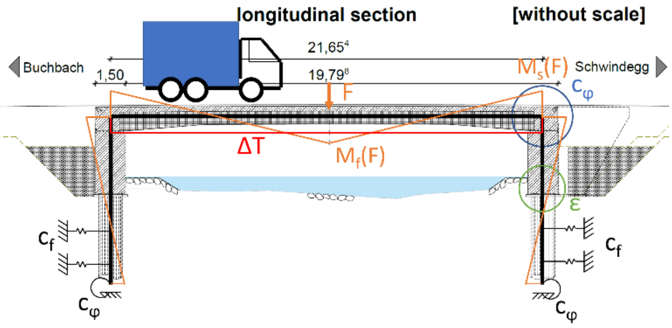

Figure 2 Examples for details of a single-span frame bridge to monitor in a SHM.

2.2.1 *Stiffness of the rigid frame corners*

In the structural calculations for a frame bridge structure, different approaches are chosen for the frame corner. In a manual calculation, completely rigid connections are assumed as a rough estimate. In the more detailed calculation using the finite element method (FEM) or framework models, the behaviour can be modelled more precisely with springs. The assumptions for the springs stiffnesses can be verified or improved by a test. In this way, conservative assumptions can be identified, and more resource-efficient constructions can be carried out in the future. For this, strain measurement in the corner area to compare with the assumptions of the calculation are needed.

2.2.2 *Moment distribution of field and corners*

The stiffness differences of the abutments and the precast girders depend, among other things, on the bond behaviour of the cast-in-place concrete supplement. These are shaped by the connection reinforcement, the roughness of the precast elements surface and the thickness of the supplement. Time-dependent prestressing losses of the precast girders due to creep, shrinkage and relaxation contribute to a shift of the neutral axis. Strain measurements in the centre of the field and in the frame, corner can be used to record initial properties as well as the typical changes in state of the bridge.

2.2.3 *Interaction between the bored piles and the abutment*

The transition of the bored piles to the abutment wall is called the bored pile head. Normal force, shear forces and moments can be transmitted there by the connecting reinforcement. These internal forces result from, for instance, from dead weight, traffic, or temperature. Since the abutment is solid, but the backfill is made of lightweight materials, the interaction between the structure and the ground is not unique. Soil samples taken through boreholes only give an indication of the subsoil at certain points. Strain sensors at the bored pile head can be used to measure the strain absorbed by the bored pile.

2.2.4 *Influence of temperature – daily and seasonally*

For integral structures such as the Isen bridge in Schwindegg, temperature changes have a major influence on the structure due to restraint stresses. Temperature fluctuations are given both by the daily course and over the seasonal course. Due to day and night changes, the difference between the upper and lower sides of the bridge generates internal forces in the structure. The heating on the upper side is caused by solar radiation, for example. Over the course of the year, the bridge expands due to higher temperatures in summer - this is referred to as the summer position. The counterpart is the winter position, in which the bridge contracts. Depending on the climatological boundary conditions, these temperature changes can be larger or smaller over the year. EN 1991-1-5 [16] and its national annexes provide calculation approaches for temperature - these approaches can be checked by measuring the temperature of the structure and the interaction with the surrounding ground and strains in the bridge.

2.2.5 *Tracking of passing vehicles*

For the design of road bridges, EN 1991-2 [17] specifies the design actions. In the LM1 load model, heavy traffic is assumed. In the fatigue load model LM3, four axes of 120 kN each are assumed. This is plausible for highly frequented highways, but for subordinate district roads, traffic flows of this type are reached only in extreme cases. By measuring the actual traffic impact, the adjustment factors can be modified in the NRR or the Eurocode. If the actual traffic on the structure is recorded over the entire life cycle, this information can be used for the life cycle management and damage and its consequences can be assessed more realistically and quickly. Otherwise, for this reason the traffic is measured afterwards, like at the Heinrichs Bridge in Bamberg, Germany [18]. Bridge Weigh in Motion (B-WiM) is another application of monitoring traffic load, and speed. In this method, the bridge is used as an axle scale. This allows, e.g., the axle loads to be measured and thus overloading of vehicles to be detected. The speed of the crossing can also be measured. More detailed information about B-WiM is given in [19], which will not be discussed further here.

2.3 Boundary conditions

To determine the possible dimension of a monitoring measure, the prevailing conditions must be considered. Often bridges are in an area without electricity connection. Therefore, a power supply cannot be taken for granted. The measured data should also be available online. For this reason, a data connection, at least via LTE, is desirable. Local network providers run their lines over the Isen bridge. Discussions with the suppliers and the district led to the planning of the connection for the measurement technology. In the process of the construction work, these supply lines were laid to the measurement units for the creation of the field test for this purpose. The last mile was installed for the bridge to use electricity and internet. For effective planning, the involvement of all stakeholders is important. Due to the connections, the extent of the monitoring for the bridge is largely unlimited.

2.4 Conception

2.4.1 Sensor concept

Based on the conditions on site and the chosen monitoring approaches, the measured variables to be recorded were selected, and corresponding sensors were picked.

At first, the decision had to be made between sensors to be pre-installed before pouring the concrete and post-installed sensors. To develop a robust sensor constellation, different systems came into play to figure out the usability, the robustness, and the accuracy of the different sensor types.

For temperature sensors and strain sensors, solutions exist for a long lifetime in the concrete. Cast-in-place strain sensors were planned in the centre of the field and the support area of the precast elements, in the frame corner and the area of the bored pile head. Temperature sensors were installed evenly over the entire southern structure - in the direction of Schwindegg - to monitor the temperature development of the structure. Figure 3 pictures the sensors' distribution over the cross-section and the longitudinal section.

Pressure sensors that were planned for earth pressure measurement at the abutment rear wall are bonded to the finished stripped abutment on the Schwindegg side with injection mortar before the geotextile is attached. Thus, the sensors are not concreted in, but the backfill makes them inaccessible for later replacement or maintenance work. In Figure 3, those sensors are placed behind the abutment in the direction of Schwindegg.

No applications for embedding can be found in literature for the other sensor types. Thus, the following sensors were anchored to the bottom surface of the completed structure.

In addition to the embedded strain gauges, strain is also to be measured on the outside of the t-beams. For this purpose, one sensor per beam will be provided in the tension zone and one in the compression zone in the middle of the span. In the cross-section of Figure 3 those sensors are shown at the side surface of the t-beams.

To exclude the twisting influence of the structure, deformation measurement will take place at the edges of the abutments in the form of hose scales. With four measuring points, precise displacements can thus be recorded in the vertical direction. Figure 3 shows the positioning of the measurement points in the longitudinal section.

Various approaches exist to use changes in modal shapes to infer changes in the condition of the structure and to detect and locate damage. Methods of statistical damage detection (e.g. [20]) are mentioned. To perform investigations in this field, three-dimensional accelerometers are placed in the deflection points of the first three eigenmodes that were calculated in a simulation using FEM. The chosen points are shown qualitatively in Figure 3.

In addition to the accelerations, inclinations are logged in two directions. It is to be examined whether the sensitive inclination sensors are also suitable for modal investigations. Their positioning is also shown in Figure 3.

To place the measured values in a global context and to check the plausibility of the temperature values, the following environmental conditions are recorded by a weather station:

- Air temperature
- Humidity
- Wind speed and direction
- Sun intensity
- Precipitation
- Air pressure

The weather station is not shown in Figure 3, because it is not positioned on the bridge, but on a technical block next to it. Due to a better overview, only plenty sensors are depicted.

2.4.2 Measuring concept

To achieve the research objective and to obtain the best possible redundancy of systems and values used, a total of over 170 different measured values are received. These come from approximately 130 different installed physical sensors.

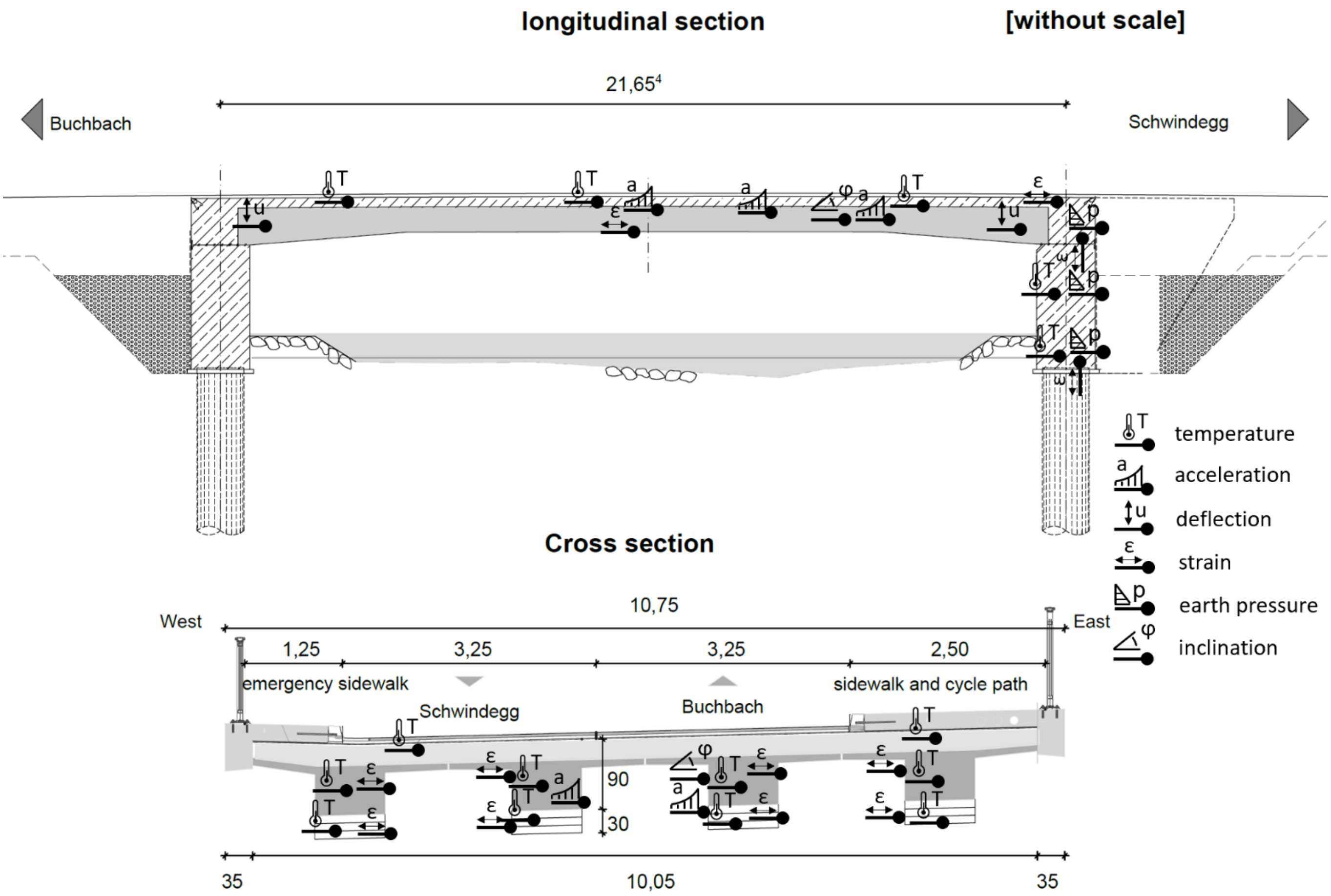

Figure 3 Sensors of the Isen bridge in Schwindegg in longitudinal and cross-section – principal sketch.

The main challenges here are, on the one hand, the laying of the cables attached to the bridge and through the bridge structure to make them invisible from the outside and to protect them from the weather. On the other hand, logical data management is required to avoid generating an unnecessary large amount of data. For this purpose, the ambient conditions of the bridge were used to set the sampling rates for each sensor individually. Important general conditions were, for example, the expected crossing speed of the vehicles of max. 50 km/h for passenger cars - due to the routing, lower speeds are to be expected for trucks. The first expected eigenfrequencies of the bridge were also determined in advance using the finite element method. In some cases, sensors were used whose measuring principle specifies a maximum sampling rate. For example, a sensor based on the vibrating wire principle requires an excitation time, so the measurement process takes several seconds. Sensors of this type are understandably not suitable for dynamic measurements. In Table 2, the selected sampling rates per sensor are summarised.

A technical block was planned to secure all data loggers and measuring devices safely against environmental influences, vandalism, and theft. All sensor cables run underground to this block.

2.4.3 *Involving stakeholders*

When such a comparatively large project is conducted on a small bridge, all those involved in the project must exchange information on a permanent basis. The district, as the owner of the structure, must approve all planned measures. There exist measures, such as the laying of cables, require slight changes to the bridge planning. The planning design engineer must, for example, adapt the formwork and reinforcement planning to the sensor planning. Time slots for sensor installation must be planned with the construction company. Otherwise, considerable delays can occur in the construction process. For the timely provision of power supply and telecommunications, the utility companies must be involved in a timely manner. A lot of working tasks can already be done during construction of the structure, in which case unnecessary excavation work can be avoided.

Table 2 Chosen sampling rate per sensor and measurement principle.

measurement variable	principle	frequency [Hz]
strain	strain gauge	10
strain	vibrating wire	0.1
temperature	PT100	0.003
acceleration	MEMS	200
inclination	MEMS	200
deflection	water level hose	0.003
weather	weather station	0.003
earth pressure	pressure sensors	10

Another point that should not be underestimated is the constant information and involvement of residents. Especially when work must be carried out at weekends and on public holidays, understanding is not a matter of course. In this project, for example, the residents were continuously informed about the progress of the construction site through the municipal newspaper. Inquisitive people were also able to ask their questions on site or via e-mail to those carrying out the sensory measures. News was spread in the local and national newspapers (e.g. [21–23]).

2.4.4 Data processing and data model

At the end of the data chain of the monitoring, the data must become processable for evaluation. The manufacturers of the measurement systems used supply evaluation software and cloud solutions for dashboards. By using different manufacturers, it is easy to lose track of the origin and plausibility of the data. To standardize the monitoring to a certain extent, the Asset Administration Shell (AAS) BBox is used. An AAS is an approach of the "Platform Industry 4.0" to create digital twins. It makes use of the already existing methods of the manufacturing industry, which are applied to bridge construction. Further information is provided by [18]. Through a unified data model, the data is neatly fed into BBox.

Figure 4 shows an engineering flow model for this process on the bridge. The real twin with the sensors is shown on the top left. After passing through the individual measuring chains, the data is pre-processed at the bridge. This serves on the one hand for data reduction, and on the other hand for checking whether the real twin's sensors are still intact. From the edge pre-processing, alarms can already be triggered via telecommunication, e.g., by setting threshold values. The sensor data can be transferred to the BBox via Internet, other networks, but also classically via hard disks. The data is enriched with metadata and assigned to the AAS of the bridge. Long-term storage takes place in the data lake, from which visualizations are derived, and diagnostic tools are applied. All stakeholders use the AAS to evaluate the data. The model can also be supplemented with further information and documents such as construction models, plans, data sheets or even images of the construction work and the installed sensors. Coupled with a powerful computing unit, the data lake forms a breeding ground for virtual experimentation rooms in which data scientists develop new diagnostic tools for the AAS, but also for edge processing [18].

2.5 Installation

Before the installation was conducted, tests were performed in the laboratory at University of the Bundeswehr in Munich to ensure a smooth process. Using a reinforced concrete beam, sensors were embedded in and attached to the beam. The sensors tested were distributed fibre optic sensors (DFOS), strain gauges, displacement transducers, temperature sensors, and accelerometers. The advantages and disadvantages of each system were summarised in [24].

The installation of the sensors took place over a period of five months, during which installation work was repeatedly carried out daily to accompany the progress of the construction work. In total, the sensors were installed in the precast elements on four days, as the reinforcement for each beam was produced just in time. Because of the ergonomic working conditions in the precast plant, cable ducts were mounted on the precast elements there. Installing them underneath the bridge on site would have taken many more time and would have been not in accordance with safety rules (e.g., working time on ladders).

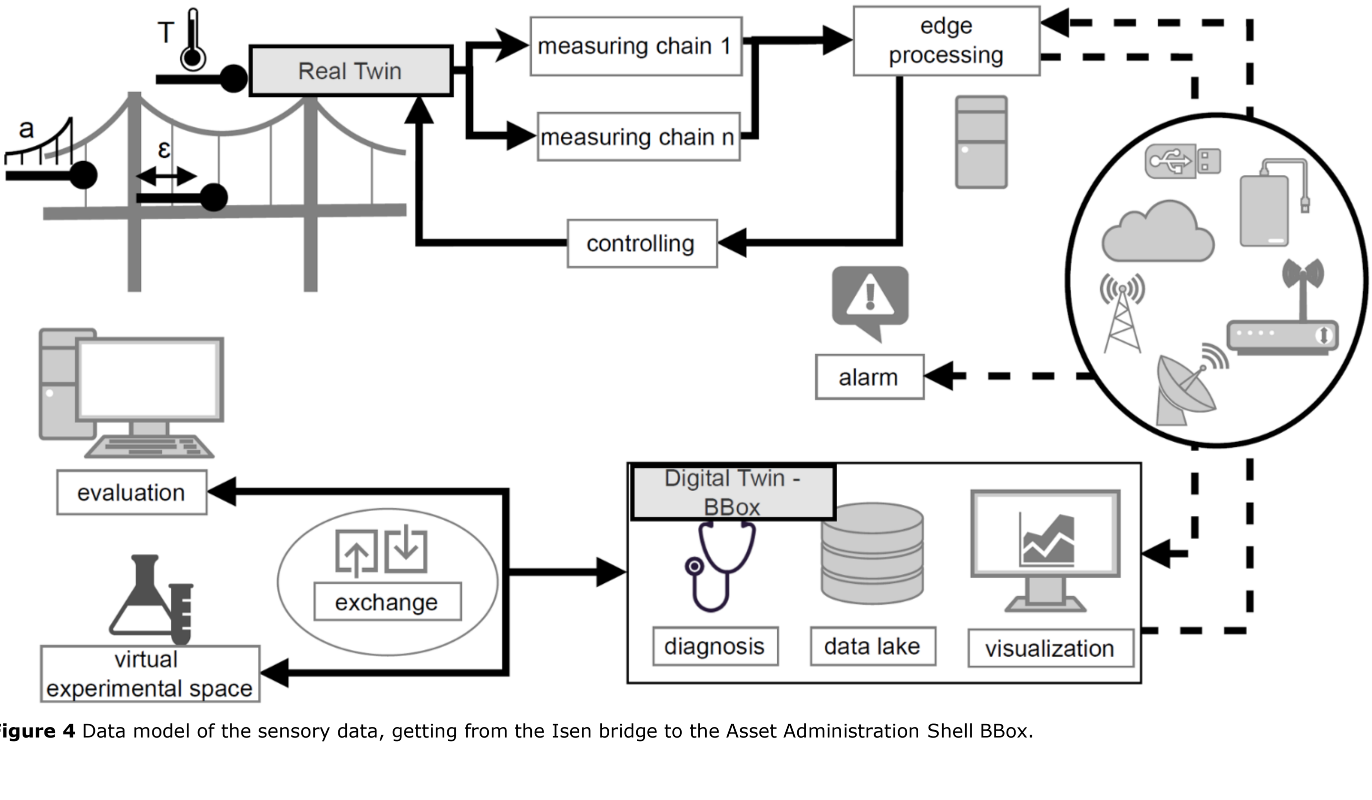

Figure 4 Data model of the sensory data, getting from the Isen bridge to the Asset Administration Shell BBox.

To pre-install the sensors before pouring the concrete, assembly events took place in the concreting sections on the structure itself. In addition, the sensors had to be aligned with the bridge. While the installation of the sensors at the bored pile head could be carried out in one day with two people due to the location in one plane of reinforcement, the reinforcement sequence in the frame corner was extremely complex. The net time spent on installation and measuring was approximately eight hours. However, these were spread over five days. Good cooperation with the construction company is important, as otherwise installation points can become inaccessible, or it becomes complicated to route the cables. The reinforcement ratio of the reinforced frame corner was high in the end, as can be seen in Figure 5. In addition to the sensor cabling, conduits were installed routing the cables of the sensors installed at the bottom of the bridge.

The installation of the sensors on the finished structure took three days. Since the clear height between the river Isen and the lower edge of the bridge is less than 2 m, bridge under sight devices cannot be used. The contracted monitoring company provided a pontoon with a footprint of approximately 2 m x 2 m for this purpose. In addition, ladders were used. Scaffolding was erected at the abutment. This additional working space was indispensable, especially for inserting the cables. The assembly was conducted efficiently with these aids.

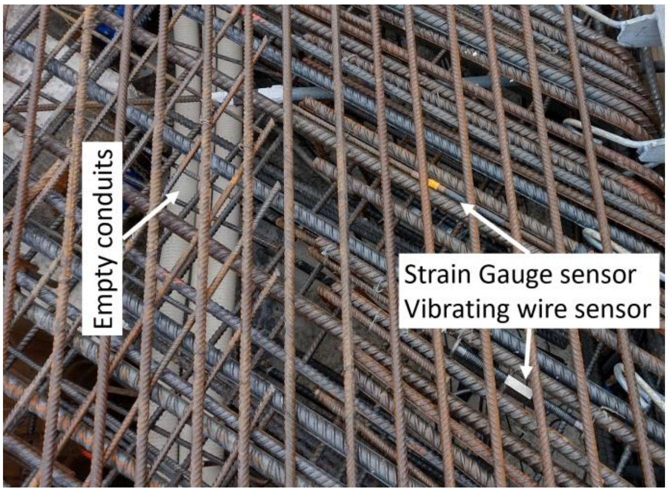

Figure 5 Sensors and conduits in densely reinforced concrete corner section.

3 Experiences

3.1 Introduction in phases of performing experiments.

As a structure for this chapter, the installation steps are separated into phases. According to [25], performing experiments was divided into the following phases:

- Phase 1: Feasibility Study
- Phase 2: Measuring Concept
- Phase 3: Implementation Planning
- Phase 4: Installation
- Phase 5: Processing of Measured Data
- Phase 6: Evaluation of Results
- Phase 7: Maintenance and Dismantling

In addition, the phases "tender" (between phase 2 and phase 3) and "calibration" (between phase 4 and phase 5) are useful. In this paper we deal with the phases "feasibility study" to "installation" and the point "documentation" and show the gained experiences based on the instrumentation of the Isen bridge in Schwindegg.

3.2 Feasibility study, measuring concept and tendering.

It has been shown that the clear definition of the project goal in the feasibility study sets the direction for the further phases. Thereby, the requirements of power and internet supply to operate the measuring chains and the timeline of installation need to be defined. To avoid scheduling problems, the measurement concept should be defined at an early stage with details of the measured variables to be recorded, the number of sensors and their installation position. Sketches on the construction plans are indispensable to put the possible services out to tender. The time of tendering should be at least five to six months before the installation of the first sensors. At the Isen Bridge, the lead time from the tender to the start of construction was too short, at approx. three months. Only thanks to the prioritization by the administration and the commitment of all bidders, at least three offers could be obtained.

Unfortunately, there are no sample tenders for bridge monitoring of new bridge construction yet. [25] provides a good overview as a checklist, but unfortunately there is still far too little coverage of tender texts. One of the essential findings was to define in advance regulations for work on weekends and public holidays, as it may be necessary to work there in the construction process to avoid construction delays.

3.3 Implementation planning

After completion of the contract award phase, the installation planning was started. Based on the design plans of the construction company, own plans were derived to specify each sensor to be installed and to determine its position. The cable routing was planned in a plan view and in the sections. The cable lengths were also determined on this basis. The essential experience here was that cable reserves due to unforeseeable rescheduling after the cables had been assembled ensure a more flexible construction process. A cable reserve of 15% of the cable length was always selected, but at least five meters.

The cable reserve can be reduced using Building Information Modelling (BIM). Reason is, that while planning the cables in respective concreting sections, collisions between breakthroughs and formwork could be better mitigated in advance. The rescheduling conducted on the bridge during construction could thus have been avoided. Likewise, by modelling the cable's length can be determined without uncertainties and thus cable reserves can be avoided.

3.4 Installation

Since the installation took place in parallel with the construction of the structure, the installation schedule was linked to the construction schedule. As construction progress is not always linear, weekly coordination is important. An example of the different framework conditions is given with the installations at the bored pile head and in the frame corner. At the bored pile head, 36 sensors were installed in one day (eight hours), while in the frame corner and in-situ concrete plate, 24 sensors and empty pipes were installed in a period of seven days with less than eight hours of net working time. The reason for this was that the reinforcement sequences determined the installation order of the sensors. Consideration for process orders in the construction flow is essential.

Site personnel must also be made aware of the sensitivity of the sensors. Heavy construction equipment can cause major damage to sensors and their positioning. Figure 6 shows the broken screws of an earth pressure sensor demolished by an excavator. This was torn down after installation and calibration. Luckily, the sensor's calibration was not destroyed, and therefore, it only had to be reattached and repositioned.

Figure 6 Destroyed screws of an earth pressure sensor.

3.5 Documentation

3D laser scans are suitable for determining the position of sensors in retrospect. Figure 7 shows a laser scan of the underside of a bridge next to a photographic image. If this is geo-referenced and the structure is also scanned, this can be coupled with a structure model, e.g., as a 3D model or BIM model, after alignment. With this, the model coordinates can be classified as well globally. This visual method is unsuitable for sensors that cannot be viewed later. Manual measurement on formwork or on fixed points in the concreting section is indispensable. For this purpose, fixed points were concreted into the precast elements to transfer inner points to the surface. The sensors were then calibrated to the precast elements. Geo-referencing is thus possible via the two steps. The sensors embedded in the cast-in-place concrete were calibrated by triangulation to measuring points in the formwork and at the bond areas. It would not have been possible to measure the sensors' location optically using a total station due to the shading caused by a high degree of reinforcement and the formwork.

The location information is stored together with sensor information such as calibration certificates, data sheets and serial numbers. It has been proven that these are ideally linked to the root of the sensory data source of the measurement system, so that there are no misunderstandings.

Figure 7 Photography (top) and a 3D laser scan (bottom) of the bridges bottom view.

4 Conclusion and Outlook

The paper pointed out the necessity of monitoring measures as a data basis for predictive maintenance algorithm, not only for emergency monitoring. The example of the Isen bridge in Schwindegg was used to show the implementation of the installation of a monitoring system from the feasibility study to the installation of the sensors. Since the monitoring is only in its first months in operation, the first measurement results would not be very meaningful at this point of time. However, the sensors used are running after the installation and especially after the concreting. Problems during the feasibility study, the creation of the measurement concept, the tendering, the execution planning, the installation, and the documentation were shown and can thus be considered in the following project and are helpful for others.

The lack of standardization is noticeable in the execution of the next work steps on the way to the digital twin. Non-uniform data transmission structures, a lack of standards for intelligent data formats and the inadequate expansion of broadband in Germany pose further problems. These points will be pursued further based on the research project and solutions will be proposed.

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