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Smart Bridge – Way into practice

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ABSTRACT: The current maintenance management for bridges is mainly based on visual inspection and aims at the repair of identified damages. In the project cluster “Smart Bridge” an adaptive system for holistic evaluation in real time is developed. The following pilot studies show significant aspects of the Smart Bridge.

Within the research project “Digital Test Area Autobahn” a new constructed pre-stressed concrete bridge is implemented with instrumented expansion joints and bearings, a “RTMS©” and a sensor network. By using analytical bridge models and evaluation methods the condition and reliability of the bridge as well as the remaining service life is determined.

In the pilot study “duraBASt” sensors for the detection of durability and structural safety as well as data analyzing and evaluation procedures are investigated. The aim of this study is the partial implementation of the aspects: data collection, data processing and model development for condition assessment of the bridge.

1 SMART BRIDGE

1.1 Background

The federal highway network includes 39,499 bridges with a bridge deck area of about 30.6 million m² (BASt, 2016). Approximately 90 % of these bridges are concrete bridges. A large quantity of these bridge structures has been built in the 1960’s and 70’s. In addition to the ageing structures, bridges have to face further challenges such as increasing traffic load and climatic changes. High traffic loads are caused by increasing entire traffic and disproportionately high increasing freight traffic. A further increasing in traffic loads are predicted for the coming decades (BMVI, 2015). In addition, the effects of the climate change such as rising temperatures and extreme weather events affect the usability, durability and in long term the sustainability of bridge structures (Novák et al., 2012). The mentioned future effects are not taken into account in current maintenance management. At present, maintenance management of bridge structures is primarily based on regular building inspections, so that damage is only discovered when it is obvious. This procedure is damage-based and reactive.

1.2 Concept

Recently, monitoring methods have been used in order to support the maintenance management of bridge structures. Theses monitoring systems are mostly used to monitor defects of existing bridge structures that are determined by recalculation or in the course of bridge inspections. The aim of the project cluster “Intelligente Brücke” (hereafter “Smart Bridge”) is to overcome the limitations of monitoring by using an adaptive system for providing all relevant information for the holistic evaluation of the condition of a bridge structure in real time. The system “Smart Bridge” is modular, so that it can be individually adapted to the needs of the bridge structure. Most components of the system “Smart Bridge” can be classified in the following groups: intelligent sensor technology, intelligent evaluation methods as well as intelligent maintenance and inspection strategies (Neumann et al., 2012).

By using analytical bridge models and evaluation models the condition and the reliability of the overall bridge construction and its components as well as the remaining service life is determined. Reliable maintenance management for real-time applications is realized by linking prognostic models and available information from existing databases. In the context of a network-oriented maintenance management, the condition of bridges of the same bridge type and period of construction can be derived from the condition of the Smart Bridge. Therefore, only a few bridges selected as Smart Bridge are sufficient to monitor bridges across the network. Collected information is made available online to the responsible road administration. The Smart Bridge enables reliability-oriented analyzes for quality assurance of safety-relevant components. This results in a safety gain by early detection of safety-relevant changes.

In Germany, the Federal Ministry of Transport and Digital Infrastructure is the responsible authority for federal highways but the road administrations of the 16 federal states carry out the planning, construction and operation of infrastructures. In order to transfer new, unregulated developments into practice, pilot studies are necessary in order to demonstrate the efficiency and the benefits of the development and to promote the interest of the road administration. With regard to the topic Smart Bridge, two pilot studies “Digitales Testfeld Autobahn” (hereafter “Digital Test Area Autobahn”) and “DuraBASt” are carried out to make the development available for practice and to recommend the Smart Bridge to the road administrations.

2 PILOT STUDY “DIGITAL TEST AREA AUTOBAHN”

2.1 General description of the Smart Bridge in the “Digital Test Area Autobahn”

Within the scope of the “Digital Test Area Autobahn” innovations related to mobility 4.0 on the highway “A9” in Bavaria are tested and further developed. The research project “Digital Test Area Autobahn” has two main focuses: automated and networked driving and intelligent road equipment. Smart Bridge is an innovation of the focus “intelligent road equipment”. Research projects, which dealt, inter alia, with the development of new concepts and technologies of the "Smart Bridge" with the main focus on "monitoring of loads", "instrumented joints and bearings" and "sensor networks" were funded by the Federal Ministry of Transport and Digital Infrastructure’s Innovation Program. Within the scope of the "Digital Test Area Autobahn", these developments are presented at the new constructed pre-stressed concrete bridge BW 402e in the highway interchange Nuremberg (BAB A3/A9) and made accessible nationwide. The bridge structure BW 402e was completed in September 2016. Before the bridge was released for traffic in October 2016, calibrating drives with vehicles of known geometries and weights were carried out for the entire sensor system. Further information is shown in Figure 1.

Length [m]	155.75			
Road width [m]	12			
Spans [m]	37.75	45.00	44.00	29.00
Bridge area	2,445.30 m²			
Superstructure	Single-celled hollow box, longitudinally pre-stressed			
Construction	Place and thrust method			

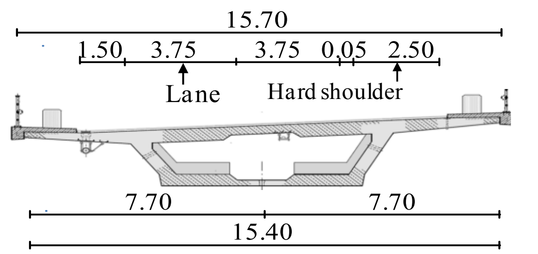

Figure 1: Technical data (Autobahndirektion Nordbayern, 2016)

2.2 *Components of the Smart Bridge in the "Digital Test Area Autobahn"*

Within the scope of the Smart Bridge in the "Digital Test Area Autobahn" the following partial aspects of the Smart Bridge are realized: Roadtraffic Management System (RTMS©), instrumented bearings and expansion joints, intelligent sensor networks and analytical structural models and evaluation methods.

2.2.1 Roadtraffic Management System

RTMS©, developed by engineering office Prof. Freundt, is a modular system for determining the effects, resistances and the condition as well as the prognosis of the condition of a bridge structure. The following aspects can be determined by RTMS©:

- Traffic data: the number of vehicles, vehicle speeds, axis distances, dynamic axis loads per single axis and the total vehicle weight.
- Climate data: Shadow temperature, wind speed and moisture.
- Bridge parameters: Deformation, displacement and elongation of concrete and steel.

The data is collected by traffic sensors, inductive displacement transducers, foil strain gauges and resistance thermometers. Within the framework of data processing, the degree of damage due to fatigue and the time course of the global stiffness of the bridge are determined. (Freundt et al., 2014)

2.2.2 Instrumented bearings and expansion joints

Bridge bearings are one of the basic components of a bridge, since these allow displacements, rotations and defined load transfer between bridge components. Usual displacements of bridge structures are due to effects such as traffic and temperature. Permissible displacements, rotations and load transfer of the bearing for certain directions can be realized by the choice of the bearing type (Mehlhorn et al., 2014). Modified MSM® spherical bearings, developed by Maurer SE, which are used in the Smart Bridge, were equipped with pressure and displacement sensors.

Expansion joints are components of a bridge construction which are used between the bridge and the adjoining roadway in order to compensate the bridge movements due to temperature and traffic loads. They are wear parts of a bridge because they are exposed to high dynamic effects by direct crossing by vehicles (Mehlhorn et al., 2014). For the Smart Bridge, a modified Swivel Joist-Expansion Joint developed by Maurer SE was equipped with strain gauges and force sensors. The following aspects are determined by the instrumented bearings and expansion joints:

- Monitoring the functions of the bearing by detecting the bearing paths and sliding gaps.
- Detection of the static load, bearing rotation and displacement.

- Distribution of the load, bearing rotation and displacement in temperature- and traffic-induced shares.
- Monitoring the functions of the expansion joints by detecting the gap width.
- Collection of relevant traffic data by the expansion joints: number of vehicles, vehicle speeds, axis distances, dynamic axis loads per single axis and the vehicle weight.

Figure 2 shows an instrumented bearing and an expansion joint of the bridge structure.

Figure 2: Instrumented bearing (left), instrumented expansion joint (right)

2.2.3 Sensor network

A sensor network consists of different motes, which communicate wireless or wire-based (Krüger et al., 2010). The sensor network passes on the acquired data to a central computer unit for further processing. In the central computer the data are evaluated and integrated into a bridge model. The collected information is made available online. Due to high energy consumption during remote transmissions, a sleep-wake system was developed (Fischer et al., 2015), in which energy is consumed significantly only during data exchange. Climate data and some relevant bridge parameters such as incline are determined by different sensors. Time synchronization for the different sensors is a significant task.

2.3 Current projects

Subsequently to the opening for traffic, three projects were started and another one was launched. The aim of these projects is to show the functionality of the system "Smart Bridge", to evaluate not yet tested aspects and to develop the system further.

2.3.1 Investigation program

The system of the Smart Bridge is operated and analyzed in a five-year investigation program in cooperation with the responsible road construction administration. The aim of the investigation program is to demonstrate the functionality and applicability of the Smart Bridge for reliability-oriented condition assessments and prognoses. For reference, traffic data are determined both by RTMS© and by an expansion joint. Relevant climatic data such as shadow temperature, wind speed and moisture are measured by a weather station. On the basis of the load model, climatic data and bridge parameters, the global safety of the bridge is determined in form of a reliability index and the remaining service life of the structure is determined.

2.3.2 Synchronization of sensors and automatic evaluation of measurement data

The System "Smart Bridge" consists of a sensor network and an information system for analyzing and evaluating data. Both conventional and smart sensors are used in this sensor network. The measuring frequencies of the implemented sensors vary between 1 Hz and

20,000 Hz and currently there are no data collection strategies and evaluation methods for this wide range available. Therefore data collection strategies and evaluation methods and a time synchronization method are to develop for systems with different measuring frequencies. Existing bridge models are to extend to measurement-based probabilistic models and an automatic evaluation of the data is to realize.

2.3.3 Data acquisition and processing strategies for instrumented bearings and expansion joints

Within the scope of these projects, data acquisition and processing strategies for instrumented bearings and expansion joints are developed to evaluate the sensor signals with regard to environmental influences and dynamic properties of bridges. Already developed algorithms for the manual evaluation of the measured data are further developed so that data evaluation can be carried out automatically in the future. The data collected automatically should be included in the bridge model to give the user information about the condition of the bridge structure relating to the traffic data, load and temperature movements of the bridge as well as the stress on the instrumented bearings and expansion joints. Furthermore, a concept for quality assurance has to be developed which also includes calibration of the bearings and expansion joints in order to ensure reliable data.

3 PILOT STUDY "DURABAST"

3.1 General description of the test area "duraBASt"

The situation of the road infrastructure in the Federal Republic of Germany will change in the coming years caused by globalization, increasing mobility, climate change und aging infrastructure. To find ways to respond these changes the duraBASt is built. The duraBASt is a demonstration, investigation and reference area of the Federal Highway Research Institute (BASt). The duraBASt gives the possibility for testing research findings on realistic, large-scale studies before its standard implementation in the road network. The site is located on a previously unused area at the highway interchange Cologne East (BAB A3/A4).

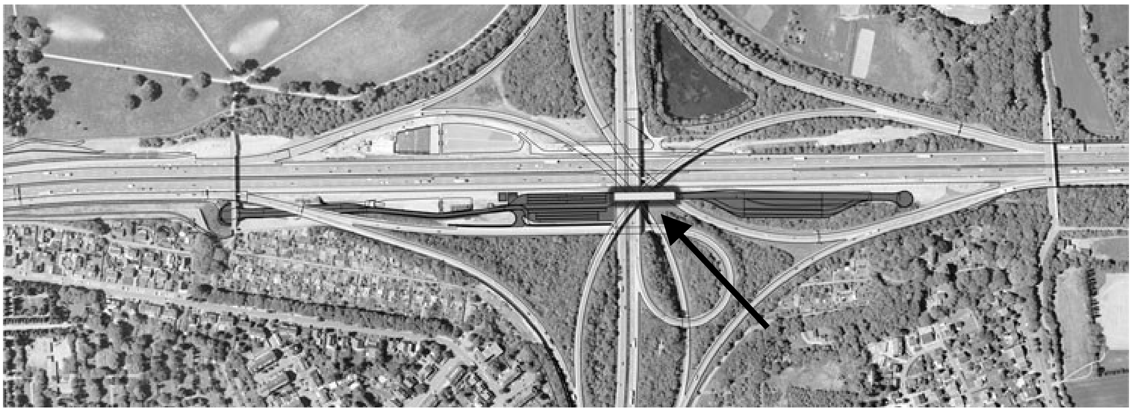

Figure 3: Location of the Smart Bridge at the duraBASt site (www.durabast.de)

At the duraBASt a two-span pre-stressed concrete bridge is located (Figure 3). The oblique bridge (45 gon) was built in 1972 but never put into operation. The bridge is 66 m long, 14 m wide and the total bridge area is about 950 m^2.

During the construction of the duraBASt the bridge was maintained. The seals and parapets were renewed and a Polyflex expansion joint was built-in at the transition. During the repair the bridge was instrumented. Sensors for the detection of durability and structural comprehensively parameters were installed.

3.2 Durability monitoring

3.2.1 Damage mechanism

Durability means in this regard that components made of concrete are sufficiently resistant over the intended service life against all influence with sufficient maintenance and repair (Stark et al., 1997).The durability of concrete can be influenced by physical, mechanical, or chemical effects. The main physical effect is frost which can destroy the concrete if a critical degree of water saturation exists. Abrasion is the main mechanical effect. Chemical effects are shown, when substance infiltrate in the concrete and react with the components of the concrete. For example the infiltration of chloride can be mentioned (Bergmeister et al., 2016). Chloride infiltration is the main cause for damages on the concrete surface of bridges (Schnellenbach-Held et al., 2015). The main source of chlorides on bridges is de-icing salt-solution. The infiltration of dissolved chlorides leads to the depassivation in the concrete and subsequently to the corrosion of the reinforced steel (Bergmeister et al., 2016).

3.2.2 Durability sensor

The main parameters to monitor the durability are moisture, temperature and corrosion effects. The temperature is important, because all corrosion processes are temperature sensitive. These parameters are monitored at the Smart Bridge on the duraBASt. The sensors which were implemented in the bridge parapets and the road deck are shown in table 1.

Table 1. Corrosion, moisture and temperature sensors in the smart bridge at the duraBASt

parameter	sensor	Tech nique	Measurement principle
moisture	CorroTec moisture sensor (BS2 GmbH)	RFID	The sensor detects electrical conductivity and temperature in concrete. Recalculation of the measured data in percent by weight moisture is possible by using concrete-specific calibration curves.
moisture	Multiring Electrode (Sensortec)	wired	Moisture sensor consisting of stainless steel rings at staggered depths to determine the moisture distribution. The AC resistance between two adjacent rings is measured and information can be converted into moisture profile by using concrete-specific calibration curves.
moisture	moisture sensor (BAM*)	RFID	The relative humidity in the concrete is measured by moisture sensors. These sensors are encapsulated to protect them.
corrosion	CorroTec corrosion sensor (BS2 GmbH)	RFID	The sensors have two special wires fixed at the outside of the sensor. If these wires are corroded, it will be detected by the RFID technology.
corrosion	Anode ladder (Sensortec)	wired	The sensor consisting of single steel anodes at different depths for the monitoring of the time-dependent chloride ingress or carbonation progress. Corrosion potential and corrosion current between anodes and the titanium oxide cathode and the

			temperature is measured.
corrosion	corrosion sensor (BAM)	RFID	The sensor detects the electrochemical potential between the reinforcement and the reference electrode.

* Federal institute for material testing

3.2.3 Experiments

Experiments for the detection of corrosion at the Smart Bridge are planned. Caused by the fact that there is no winter service at the duraBASt chlorides are not infiltrated by de-icing salt-solution. To simulate the normal infiltration of chlorides an impact pool on the surface of the bridge parapets will be realized. This impact pool will be covered and filled with a NaCl solution. The aim if these experiments are to get information about handling of the sensors, data collection, data evaluation and different measurement principles.

3.3 Structural safety parameters

3.3.1 Structural safety

Structural safety consists of static load safety, fatigue resistance, dynamic load safety and seismic safety. Relevant parameters on structural safety are loads and effects like traffic load, wind load, dead load, attached load or temperature effects (Mehlhorn et al., 2014).

The parameter of structural safety can be measured in many ways. The traffic load for example can be determined directly by special weighing equipment or indirectly by the expansion of the bridge (Schnellenbach-Held et al., 2015).

3.3.2 Recalculation of bridges and development of FE-models

To analyze the structural safety of bridges in Germany the “directive for the reassessment on existing bridges” (2011) is used. The bridge at the duraBASt will be reassessed by using this directive. The aim of the recalculation is to find the deficits of the bridge. If the deficits are known a concept to monitor these deficits can be developed.

During the repair of the bridge a first instrumentation for detecting of the structural safety was performed. Two different techniques for the strain measurement in concrete were installed: electrical strain gauges and temperature sensors and fiber-optic strain gauges and temperature sensors. The deformation is detected at three webs of the box grider and the deck slab.

Also the development of a FE-model is planned. Following the results of reassessment, further instrumentation will be designed.

3.3.3 Experiments

In the future experimental evaluation of the structural safety is planned. Load tests with defined vehicle weight and speed will be performed. Additional instrumentation of the bridge is necessary for these load tests. The load tests are needed for the recalculation of the FE-model and the analysis of the implemented monitoring system.

4 CONCLUSIONS

Within the scope of the pilot studies “Digital Test Area Autobahn” and “DuraBASt”, significant aspects of the adaptive system “Smart Bridge” for relevant information and holistic evaluation of the condition of the bridge structure were realized for the first time and are further developed. With regard to current challenges for bridge structures, the Smart Bridge shall enable the optimization of maintenance and inspection management and the quality assurance of the function of safety-relevant components. A safety gain can be achieved by reliability analyzes and remaining service life considerations. Future tasks are the transferability of the results and the development of conceptual approaches for different bridge types.

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