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First bridge with aspects of the "Smart Bridge" released for traffic

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Abstract

The current German maintenance management system 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 information and holistic evaluation in real time is developed. The adaptive system consists of suitable sensors, a sensor network, analytical structural models and evaluation methods. A newly constructed prestressed concrete bridge positioned in the highway interchange Nuremberg is the first bridge in Germany consisting of aspects of the Smart Bridge, which is released for traffic. The impact of traffic loads and climatic effects are identified. Reactions of the bridge structure and relevant bridge components are detected locally with regard to their functionality. By using analytical bridge models and evaluation methods the condition and the reliability of the overall bridge construction and its components as well as the remaining service life will be determined in the future.

Keywords: Smart Bridge; sensors; bridge assessment; remaining service life

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1. Introduction

The federal highway network includes 39,500 bridges with a bridge deck area of about 30.6 million m² (BASt (2016)). A majority of Germany's bridge structures has been built in the 1960s and 70s. In addition to ageing structures, bridges have to face further challenges such as climatic changes and increasing traffic loads. High traffic loads are caused by increasing entire traffic and disproportionately high increasing freight traffic. A further increasing in traffic loads is 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 and Ensle (2012)). The current maintenance management system for bridges is preliminary based on regular bridge inspections, which consists largely of visual assessments of the bridge structure. Many damages occur in the interior of the bridge structure and become only visible when the damage has progressed. The procedure in the current maintenance management system for bridges can therefore be described as reactive.

Currently, monitoring methods are mainly used in order to monitor a defect of the bridge structure which is determined by re-assessment or bridge inspection. This procedure supports the reactive maintenance management system for bridges well. The aim of the project cluster “Intelligente Brücke” (hereafter “Smart Bridge”) is to take full advantage of the potential of monitoring methods by creating an adaptive system for providing all relevant information for the holistic assessment of the condition and behaviour of a bridge structure in real time. The system “Smart Bridge” is modularly designed, 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: smart sensor technology, smart evaluation methods as well as smart maintenance and inspection strategies (Neumann and Haardt (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 system for bridges 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 system for bridges, 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. The Smart Bridge is supposed to support a predictive maintenance management system for bridges. Fig. 1shows a schema of the Smart Bridge.

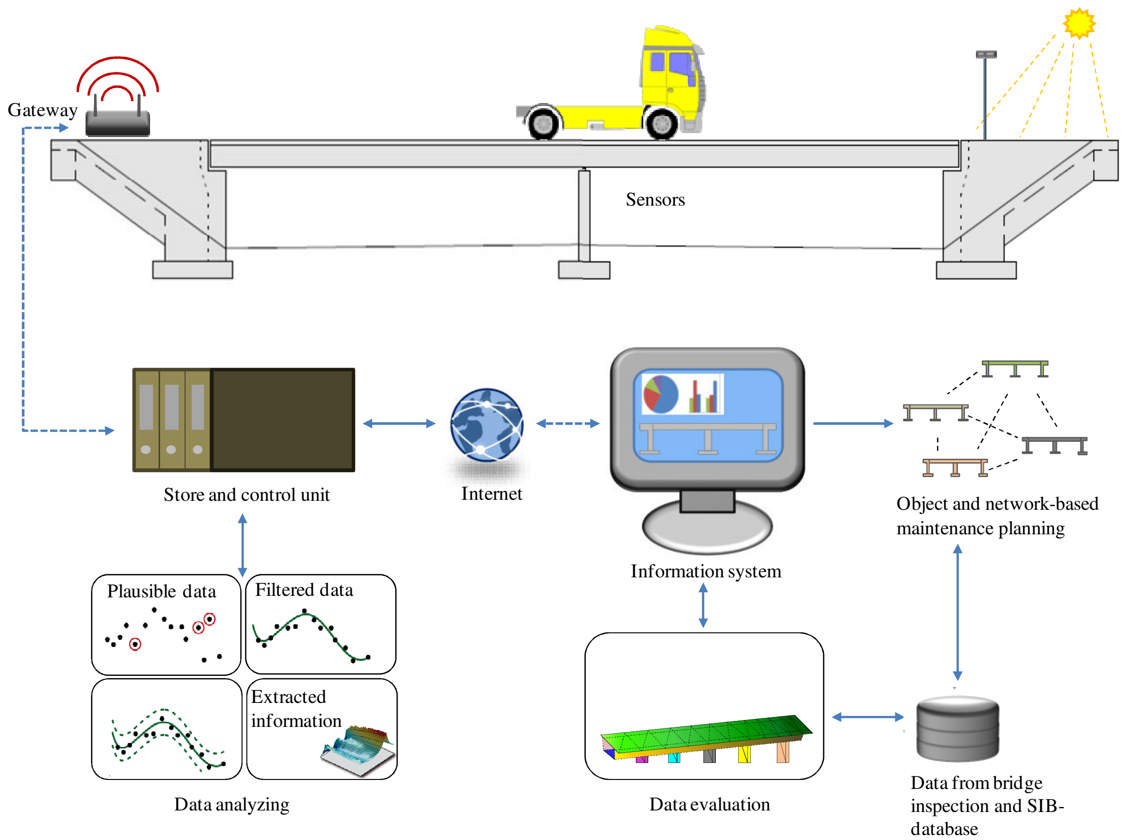

Fig. 1 Schema of the Smart Bridge

The first bridge structure equipped with some relevant aspects of the Smart Bridge and released for traffic was realized in the “Digitales Testfeld Autobahn” (hereafter “Digital Test Area Autobahn”). The “Digital Test Area Autobahn” is a test area on the German highway A 9 in Bavaria, Germany, provided by the Federal Ministry of Transport and Digital Infrastructure. Within the scope of this test area innovations related to the topic “mobility 4.0” are tested, assessed and further developed. The research project “Digital Test Area Autobahn” has two focuses: automated and networked driving and intelligent infrastructures. Smart Bridge is an innovation of the focus “intelligent infrastructures”. The newly constructed prestressed concrete bridge positioned in the highway interchange Nuremberg consists of the following aspects of the Smart Bridge: an instrumented expansion joint and two instrumented bearings, an information system for detecting loads on the bridge and a wireless sensor network. The goal of this pilot study is to demonstrate the developed aspects on a bridge structure, which is released for traffic, to show the functionality of the whole system and to develop single aspects further. By using analytical bridge models and evaluation methods the condition and the reliability of the overall bridge construction and its components as well as the remaining service life will be determined. The collected information will be made available online to the responsible road administration (Haardt et al. (2017)).

In addition to the Federal Research Institute the following institutes are involved in this pilot study: Federal Ministry of Transport and Digital Infrastructure, Bavarian Ministry of the Interior, for Building and Transport, Highway administration of northern Bavaria, Engineering Consultant Freundt (IBF), Maurer SE, Institute of Telematics (University of Lübeck), Institute for Steel Structures (Universität der Bundeswehr München).

2. Bridge construction BW 402e

The bridge BW 402e, a 155.75 m prestressed concrete structure, was built in 1970 and is part of the highway A 9 from Frankfurt to Munich. The bridge is placed in the interchange Nuremberg. Because of the fatigue affected steel the bridge had to be removed. Therefore, a new bridge structure was built according to the old structure in 2015/2016 and released for traffic in October 2016. The most important data of the bridge are shown in Fig. 2 Technical data (Autobahndirektion Nordbayern, 2016)

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Length [m]	155.75
Road width [m]	12
Spans [m]	37.75 45.00 44.00 29.00
Bridge deck area [m²]	2,445.30
Superstructure	Single-celled box girder, longitudinally pre-stressed
Construction	Timed shifting

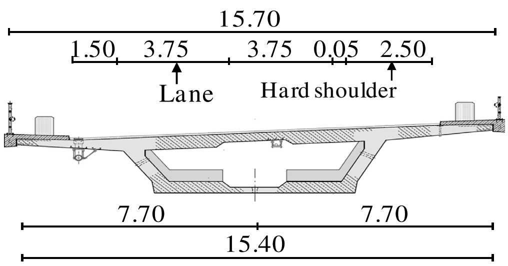


Fig. 2 Technical data (Autobahndirektion Nordbayern, 2016)

Fig. 3 shows the Smart Bridge in the "Digital Test Area Autobahn".

Fig. 3 Smart Bridge in the “Digital Test Area Autobahn”

3. Equipment of the Smart Bridge in the "Digital Test Area Autobahn"

The Smart Bridge in the "Digital Test Area Autobahn" is the first new with measuring systems equipped bridge in Germany that is released for traffic. An important advantage of equipping a new bridge with measuring systems is that the load-bearing behaviour and the condition of the new bridge as well as its components are detected precisely and reliably. The bridge in the "Digital Test Area Autobahn" is equipped with five information systems that collect relevant loads and reactions of the bridge structure. Traffic data have a big impact on bridge structures. In order to ensure the reliability of measured data as well as to optimize the measuring systems, three measuring systems for determining traffic data were installed. Not all aspects of the traffic data are recorded by all 3 systems. Fig. 4 shows the scheme of the network structure of the Smart Bridge in the "Digital Test Area Autobahn". Some measuring systems have their own measuring computers, on which sensor data are stored temporarily. There is a network attached storage (NAS) for storing all sensor data for the whole project duration. A switch ensures the connection of different components with the NAS. The uninterrupted power supply ensures that the NAS shuts down in case of power interruption and restarts automatically after the power interruption in order to minimize not collected data. Furthermore, the Smart Bridge has an internet access which is important for the wireless sensor network and for remote monitoring in the future.

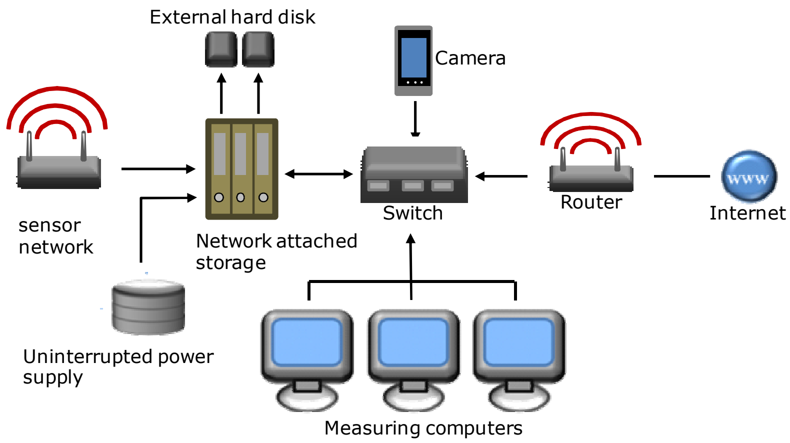


Fig. 4 Scheme of the network structure, based on (Fischer et al., 2017)

3.1. Information system for detecting effects on the bridge structure

This information system, also called Road Traffic Management System (RTMS), is a system for determining all relevant loads and reactions as well as the condition of a bridge structure (Freundt et al. (2014)). The system consists of the following sensors, shown in Table 1.

Table 1. Sensors of RTMS.

Sensors	Number	Location	What is measured?
Foil strain gauges	16	Below the bridge deck	Concrete strain
	4	In concrete	Reinforcement strains, displacements
	6	Expansion joint	Strains
Inductive displacement sensors	2	Below the pavement	Displacements
	4	Bearing	Rotation of the bearing -> Deduction of the deformation of the superstructure
Temperature sensors	2	In concrete	Temperature of bridge components
Acceleration sensors	4	External tendons	Acceleration -> Deduction of tension force progression

Fig. 5 shows a foil strain gauge and an inductive displacement sensor that are glued on the of the bridge deck.

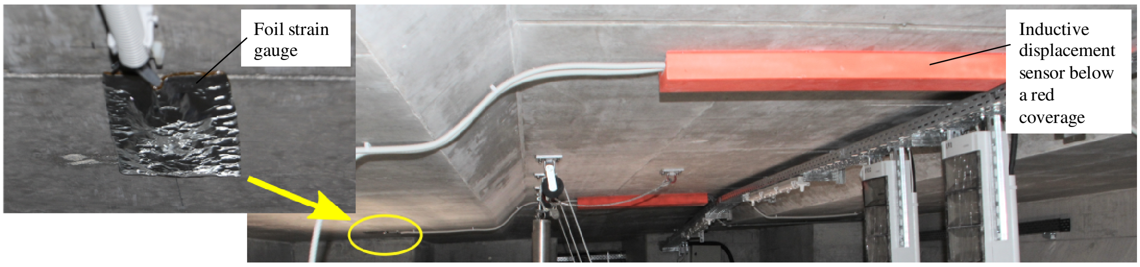


Fig. 5 Foil strain gauges and inductive displacement sensor on the bottom of the bridge deck slab (IBF)

The following traffic data are determined by the measurements of the foil strain gauges and the inductive displacement sensors: Vehicle type, velocity, gross weight, static and dynamic axle load, distance of axles and the number of axles of a vehicle. The vehicle velocity is determined by strain measurements of two foil strain gauges located in succession. The numbers of vehicle axles and axle distances are determined by the evaluation of local measuring points with regard to the measurement signal peaks and allocation of a vehicle. By comparing determined measuring curves due to traffic with calculated curves, vehicle weights are derived (Haardt et al. (2017)). The RTMS has two measuring cabinets with media converters, measuring amplifiers, a network technology and a power supply in order to keep the signal paths short. All measuring data are stored on the measuring computer of the measuring cabinet 1 which is connected to measuring cabinet 2 by glass fibre.

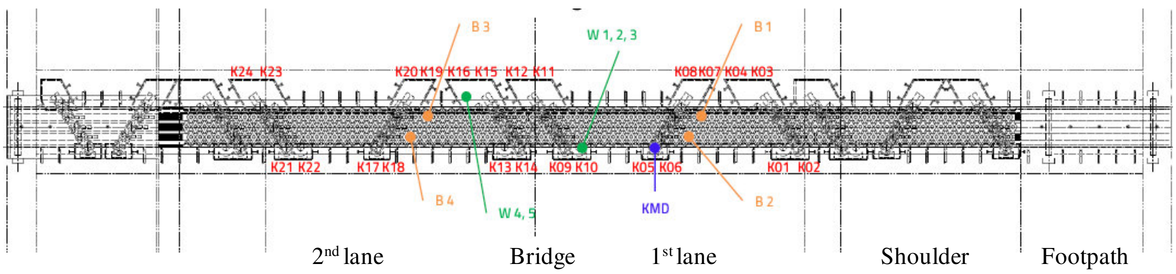
3.2. Instrumented expansion joint

Expansion joints are components of a bridge structure 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 resulting from direct crossing by vehicles (Mehlhorn and Curbach (2014)). The Smart Bridge in the "Digital Test Area Autobahn" is equipped with a modified Swivel Joist-Expansion Joint, DS 320 GO, developed by Maurer SE. The equipment of the expansion joint is shown in Table 2.

Table 2. Equipment of the expansion joint.

Sensors	Number	What is measured?
Force sensors	24	Load
Load cell	1	Spring pre-load (as reference for the force sensors)
Draw wire sensors	5	Total joint gap Distance between 1st and 3rd beam
Acceleration sensors	4	Vibration frequency Time when the wheel hits the beam

Fig. 6 shows the position of the sensors, mentioned in Table 2, in the top view of the expansion joint.



B: Acceleration sensor; W: Draw wire sensor; K: Force sensor; KMD: Load cell

Fig. 6 Position of the sensors in the expansion joint (Butz, 2017)

Fig. 7 shows the instrumented expansion joint of the Smart Bridge in the “Digital Test Area Autobahn”. The sensors listed in Table 2 are not visible because they are in the inside of the expansion joint. Cables for powering sensors and forwarding data to the measuring computer are protected by blue protective tubes against damage. The foil strain gauges of the RTMS, compare Table 1, are highlighted in the picture. They were glued on the surface of the beams of the expansion joint. Cables in the white protective tubes connect the foil strain gauges with the measuring cabinet of the RTMS.

Fig. 7 Instrumented expansion joint

By determining the total joint gap and the distance between the 1st and 3rd beam the condition of the expansion joint is monitored. The following traffic data are determined by the measuring values of the instrumented expansion joint: number, velocity and weight of vehicles, axles of vehicles, distance between axles and axle load.

3.3. Instrumented bearings

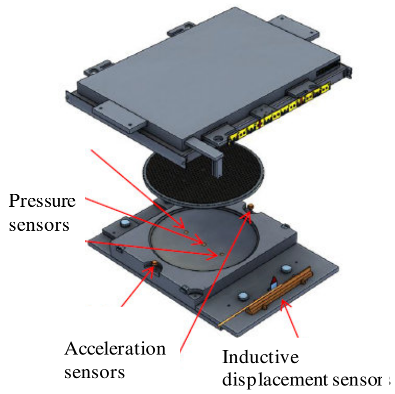
Bridge bearings are one of the basic components of a bridge, since these allow displacements, rotations and defined load transfers between bridge components. Usual displacements of bridge structures are due to effects such as traffic and temperature. Permissible displacements, rotations and load transfers of the bearing for certain directions can be realized by the choice of the bearing type (Mehlhorn and Curbach (2014)). The Smart Bridge has two modified and instrumented MSM® spherical bearings type KGA 18436 kN, developed by Maurer SE. The equipment of the two bearings is shown in Table 3.

Table 3. Equipment of the bearings.

Sensor	Bearing 40/1	Bearing 40/3	Location	What is measured?
Pressure sensor	3	3	In the bearing transverse to the longitudinal axis of the bridge	Pressure -> Deduction of bearing load by calibration curves
Distance sensor	2	0	In the bearing in the direction of the longitudinal axis of the bridge	Distance between two bearing surfaces -> Rotation of the bearing
Inductive displacement sensor	1	0	Below the bearing scale in the direction of the longitudinal axis of the bridge	Bearing path and gap

The collected data permit a self-monitoring of the bearings and a determination of the number of vehicles. Fig. 8 shows an instrumented bearing of the Smart Bridge.

a



b

Fig. 8 (a) Position of the sensors of the bearing A 40/3; (b) Bearing A 40/3 of the Smart Bridge (Butz, 2017)

3.4. Sensor network

A sensor network (Sk) consists of different sensor knots, which communicate wireless or wire-based (Krüger and Große (2010)). The Smart Bridge in the "Digital Test Area Autobahn" is equipped with a wireless sensor network. It passes on acquired data to network attached storage for further processing. Long distances between sensors are bridged by repeaters. Due to high energy consumption during remote transmissions, a sleep-wake system was developed, in which energy is consumed significantly only during data exchange (Fischer and Boldt (2015)). A gateway is a special sensor knot that ensures a connection between the sensor network and the network attached storage. Table 4 shows the different sensors used in the Smart Bridge.

Table 4. Sensor knots of the sensor network.

Sensors	Acronym	Number	What is measured?
Weather station	Sk 1, 2	1	Wind direction, wind velocity, rainfall, air temperature, humidity
Temperature sensor	Sk 3, 4	2	Surface temperature of bridge components
Extension sensor	Sk 5	1	Crack development, heat-conditioned material extension
Force sensor with encoder	Sk 6, 7, 9, 10	4	Crack development
Inclination sensor	Sk 8	1	Inclination

Fig. 9 shows the schema of the sensor network of the Smart Bridge. The connections with the strongest signals are represented by arrows.

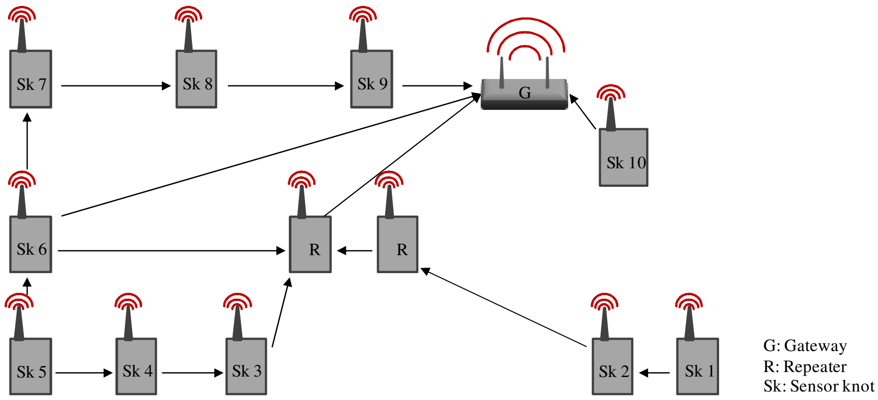


Fig. 9 Schema of the sensor network of the Smart Bridge in the "Digital Test Area Autobahn", based on (Fischer et al., 2017)

Fig. 10 shows a force sensor with encoder and an inclination sensor used in the Smart Bridge.

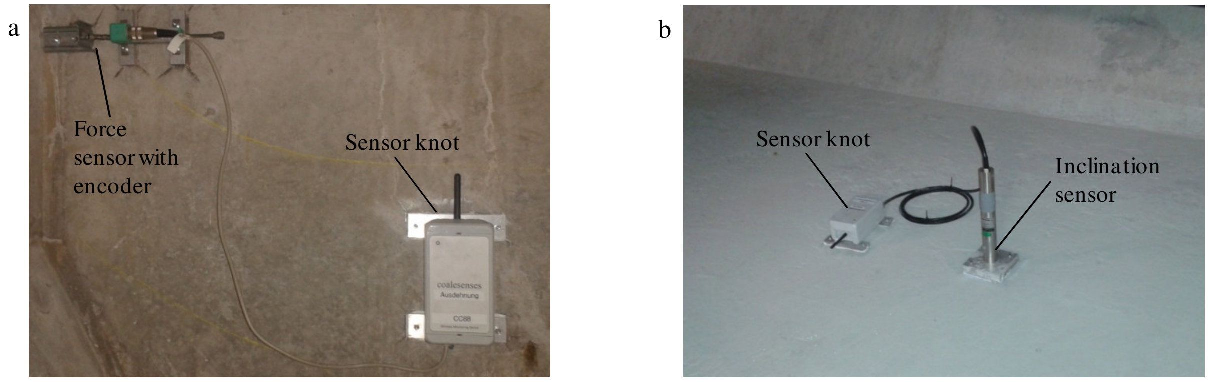


Fig. 10 (a) Force sensor with encoder, (b) Inclination sensor of the wireless sensor network

3.5. Camera

Collecting traffic data by a camera serves as a reference for the RTMS and the measuring system of the instrumented expansion joint. The optical measurement system consists of two cameras with infrared lighting. By means of a calibration 3d camera pictures are generated of 2d pictures. Aspects such as the number of vehicles, the vehicle type and the number of axles can be determined by the camera system and are compared to the results of the measurement systems.

4. Operation of the Smart Bridge in the "Digital Test Area Autobahn"

The operation of the Smart Bridge in the "Digital Test Area Autobahn" is subdivided into three steps. During the first evaluation steps the measuring data are carried to the laboratories manually and are evaluated in the laboratories. The final expansion stage includes an automatic evaluation of the measuring data on-site. By the means of the internet access evaluations can be made available online in the future.

4.1. Step 1 – Calibration and commissioning

The first step includes an offline evaluation of the calibration measurement data, the adaption of the evaluation algorithms in relation to local conditions and a quality control for the collected and evaluated data. The data evaluation is based on a load-bearing model. Because mechanical properties of the bridge are not known with sufficient reliability, calibration runs are carried out in order to adapt the load-bearing model to the real state so that reliable evaluations are generated. Before the bridge was completed for traffic in October 2016, 36 calibration runs were carried out with a three axle truck and a five axle semitrailer by inter alia varying the vehicle velocity. The axle loads of the calibration vehicles were measured by a mobile axle load weighing machine and the distance of the axles were measured on site.

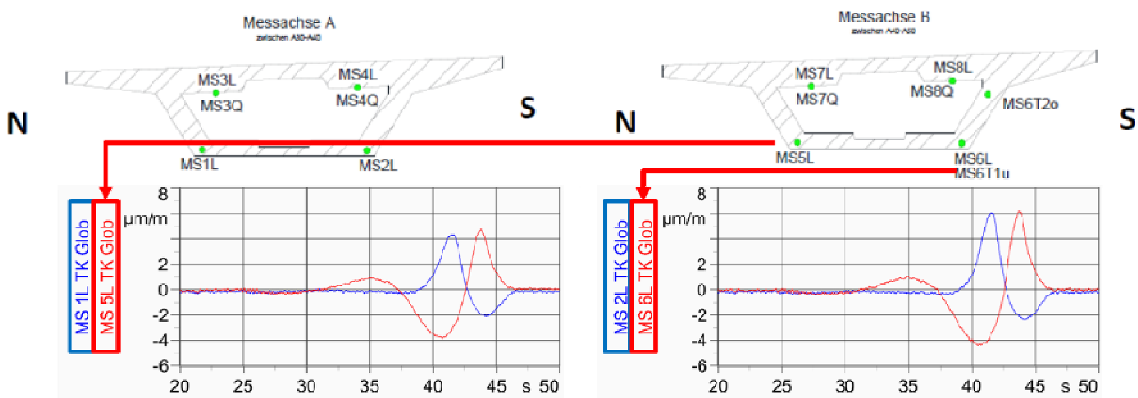


Fig. 11 Relevant measuring section for the calibration runs (Haardt et al., 2017)

The strain is measured by strain gauges on two embedded steel reinforcement bars on the right and left side of the bridge. By comparing the strain of the right and the left side of one measuring section the identification of the lane is possible. The two graphs show that the strain on the right side is higher than on the left side. This means that the vehicle is driving on the right lane (Haardt et al. (2017)).

4.2. Step 2- Operation

The second step includes a quality control and a continuous collecting of the measuring data and an online evaluation. The evaluation algorithms are adapted to the lane set up of the bridge. Furthermore, the results of different measurement systems are compared continuously in order to ensure a reliable quality of measuring data. Step 2 shall be finished at the end of 2017 (Haardt et al. (2017)).

4.3. Step 3 - Further development

The third step of this pilot study is the automatic data collection and evaluation. Three projects were started in 2017 within the scope of a research program of the Federal Ministry of Transport and Digital Infrastructure. The project "Data acquisition and processing strategies for expansion joints" is not assigned yet.

- 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 assessment and prognoses. The measured data are compared to determined thresholds. If the measured value exceeds the determined thresholds, a warning shall be issued by the system. Furthermore, single measuring systems of the Smart Bridge are maintained at least every year. The project includes a data management which includes the data processing for online presentation. In this project the automatic evaluation of data in relation to load models, climatic data and bridge parameters is done. Furthermore, the global safety of the bridge in form of a reliability index and the remaining service life of the structure is expected to be determined after 2 years after operation of the bridge.

- Synchronization of sensors and automatic evaluation of measurement data

  The Smart Bridge in the "Digital Test Area Autobahn" is equipped with different measuring systems in order to determine the condition of the bridge and its components. Both conventional and smart sensors are used. 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 as well as a time synchronization method are to develop for systems with different measuring frequencies. With the help of the measuring systems the traffic load and the behaviour of the bridge is determined. Algorithms for an automatic evaluation are developed in order to determine the load level and the reliability index of the bridge. Existing bridge models are to extend to measurement-based probabilistic models.

- 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 shall 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 the expansion joint. 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. For determining the accuracy of the load measurement the measured traffic induced bearing influences are checked by simulating the real traffic with a FEM simulation model.

5. Benefits

With a view to the mentioned tight budget and increasing expenditures, a sustainable and preventive maintenance management system for bridges is becoming increasingly important. The concept of the Smart Bridge is based on collecting and evaluating holistically relevant information about a bridge structure and it might play an important role in maintenance management system for bridges in the future. However, it should be noted that the Smart Bridge serves as a support and not as a substitute for bridge inspection. It is also necessary to take into account that there are additional costs for purchasing, operating and maintaining the Smart Bridge.
Nevertheless, there are significant advantages for users and operators of bridges. The most important benefit of the Smart Bridge is the gain in safety. Safety-relevant changes are recognized by determining all relevant information of the bridge structure in real time. With the concept of the Smart Bridge, the current maintenance management system for bridges can be optimized in the future. Due to the early recognition of developing damages, repair and maintenance measures can be planned in the long term. On the basis of reliability assessments, it is possible to secure the availability of bridge structures. In the context of a network-oriented maintenance management system for bridges, 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. A further benefit is that data of the bridge condition are available for further analyzes such as re-assessment or crack tests because of permanent collecting relevant information since construction of the bridge. In addition, the road administration could be able to control the condition of use by evaluating traffic effects on the bridge. In this pilot study, individual aspects of the concept "Smart Bridge" are tested and further developed in order to put the concept "Smart Bridge" into practice. Different measuring systems are used for the collection of traffic data in order to optimize the measuring systems by comparing reference traffic data. In addition to traffic and climate data, relevant reactions of the bridge and components are collected. The self-monitoring of instrumented bearings and expansion joint permits a function control and a quality assurance of wear components. The monitoring of the reactions of the bridge structure and its components can lead to a better understanding of the structure and component behaviour. The reliability index and the remaining service life of the bridge will be determined within an ongoing project.

6. Conclusion

For the first time, relevant aspects of the concept "Smart Bridge" are used in a new bridge. The functionality of the system is tested and further developed. Ongoing research projects include the development of sensor synchronization, data acquisition and analyzing strategies, the development of determining the reliability index and the remaining lifetime of the bridge. The main benefits of the "Smart Bridge" are the safety gain and the possibility to optimize the current maintenance management system for bridges. Future tasks are the transferability of the results and the development of conceptual approaches for different bridge types.

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