

Structural Health Monitoring (SHM) of transport infrastructure - challenges, solutions, trends

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ABSTRACT: Today, the national guidelines allow a comprehensive assessment of the state of the transport infrastructure. Analyses based on measured data can significantly improve the condition statements. Today monitoring is only carried out on the basis of special tasks – an example shows that also reality sometimes beats all expectations. There is a big need to reliably manage the entire process from the task definition to the final recommendations. In order to meet the future requirements of infrastructure operators and to benefit from digitisation, monitoring activities should be extended to bridge clusters by defining simple, but meaningful KPI. This can be a target of future research.

1 BRIDGE MANAGEMENT TODAY

Inspection of bridge structures is regulated throughout Europe by national guidelines - in Germany DIN1076, DIN e.V. (1999). Visual (and manual) inspections are recommended or prescribed at regular intervals and different levels. These are carried out by certified specialists, supplemented by photos and documented in software programs (SIB Bauwerke 1.0). Based on this data pool, the responsible operators and authorities plan maintenance activities, create construction-based observations or generate statistics. Essential weaknesses of this procedure are

- a) the subjective view of the construction inspectors, which can lead to deviations in the partial and overall ratings of ultimate limit state (ULS), serviceability limit state (SLS), or fatigue limit state (FLS).
- b) the large number of free text fields in the “SIB Bauwerke” software, which limits the evaluability and the informational value.

The challenges getting bigger – the fleet of large civil works is getting older, the unrestricted availability decreases rapidly, bridge collapses bring the topic into the public eye, and skills shortage limits engineering resources – but the development of digital tool kits gives measurement solutions the advanced performance needed to become a problem solver.

The use of objectifying test and measurement technologies, which provides standardized measurement results, should increasingly supplement the visual inspections! Thus the inspectors get important additional information "from the inside" of the constructions, while the measuring technology and the evaluating monitoring service providers can show their expertise.

Measurements on bridges are carried out for various reasons - during planning, construction phases, or operation. Usually they are ordered on a basis of a specified task. Typical applications are monitoring of damages like coupling joints or stress corrosion cracking, support of



recalculation regarding Eurocode part 3 (load reserves) or monitoring of temporary construction stages.

The cause is always an acute lack of information (e.g. proof of limit states impossible or control of traffic restrictions). The analysis of the recorded data usually is realised manually or PC-supported in post-processing on a basis of known physical contexts and algorithms.

2 SHM REQUIREMENTS

The acquisition of measurement values on civil structures is state of the art. The main challenge is the definition of meaningful Key Performance Indicators (KPI) extracted from the raw data. The analysis is usually based on comparative assumptions for one or more models. These models deliver the limit values, which finally evaluate the KPI. With this information, corresponding recommendations or actions can be made.

Furthermore, it is important to integrate economic aspects already in the design phase of the measurement system. This restricts the number of possible measurement methods and ultimately leads to more comparable bids.

Long-term measuring systems should be designed to work trouble-free over long periods. Easy access is needed for maintenance and service reasons (avoidance of traffic limitations). The requirements to the measurement must be defined as precisely as possible in the tender. Disregarding this can lead to considerable price differences and miss the monitoring target. Auto-supervising functions are essential. Faults must initiate automatically procedures to maintain or restore operation (restart, messages, usage of "substitute values"... if signal is faulty, set value to 10,000).

The main requirements, the tendering process and economical aspects now are aggregated in the guideline "Bridge Monitoring – Design, Tender and Implementation", DBV e.V. (2018).

2.1 *Example: Bridge monitoring in a non-public industrial area, Ebert (2015)*

This project shows very well that a good measurement conception leads to valid measurement values and to reliable recommendations for action.

Wölfel managed the complete process here - conception (system design), realisation of the measurement (installation and operation), presentation of the results (problems) and recommendation of actions (solutions).

The bridge is located in an industrial area and spans a river (Figure 14). It was built in 1960 and is used for internal traffic including heavy goods vehicles, forklifts and fire brigades. The largest span is 130m, the river piers are monolithically connected to the superstructure, on both sides 20m long cantilevers (four bar tee-beam) are connected to the foreland bridges. The river bridge is designed as a three-cell box girder, with an (untypical) joint in the middle (transmission of shear forces and torsional moments). Because of the cantilever construction method the structure was anchored back on both riversides.

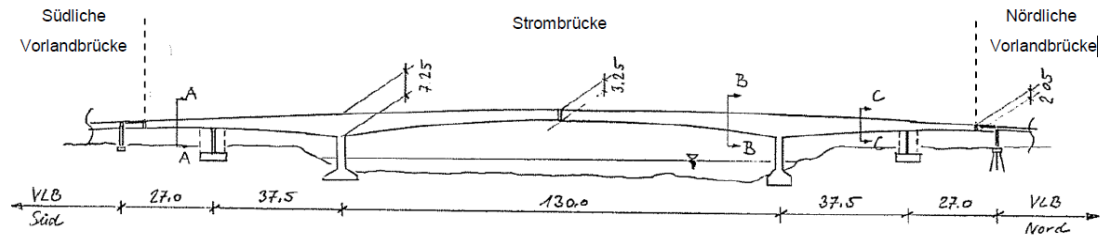


Figure 1. General bridge design

The bridge was renovated in 1990 and a replacement planned for 2010. In 2010 the bridge was checked again and a move of the replacement desired. The inspection showed that inadequate covering with salt destroyed tendons and damaged the bridge in a way that the dynamic load capacity had to be checked. With the results the planning office evaluated the design assumptions.

Wölfel was asked to measure the dynamic loads on the structure and to give recommendations for action. The measuring plan was designed in two phases.

1. two-day test measurements (crossing of test vehicles) with different sensor layouts to determine a representative layout for long-term monitoring.

It was measured with 16 accelerometers in different sensor layouts. 4 sensors were installed at fixed measuring locations (for signal calibration).

A fire brigade unit (5 vehicles), a forklift truck with trailers, an articulated bus and a three-axle truck passed the bridge at different speeds.

It was assumed that the strongest stresses occur in the main field. At the end Wölfel measured the natural frequencies and modal damping for different modes (Table 1, Figure 2 and 3).

Table 1. Measurement results phase 1

Mode	description	frequency	modal damping
01	1. bending main field	1.26 Hz	3.3 ... 3.6 %
02	bending cantilever south	2.99 Hz	≈2.2 %
03	bending cantilever north	3.11 Hz	2.0 ... 3.0 %
04	2. bending main field and bending cantilevers	3.43 Hz	3.5 ... 4.7 %
05	torsion cantilevers and 3. bending main field	4.58 Hz	1.6 ... 1.9 %
06	torsion main field	7.76 Hz	3.9 ... 4.8 %

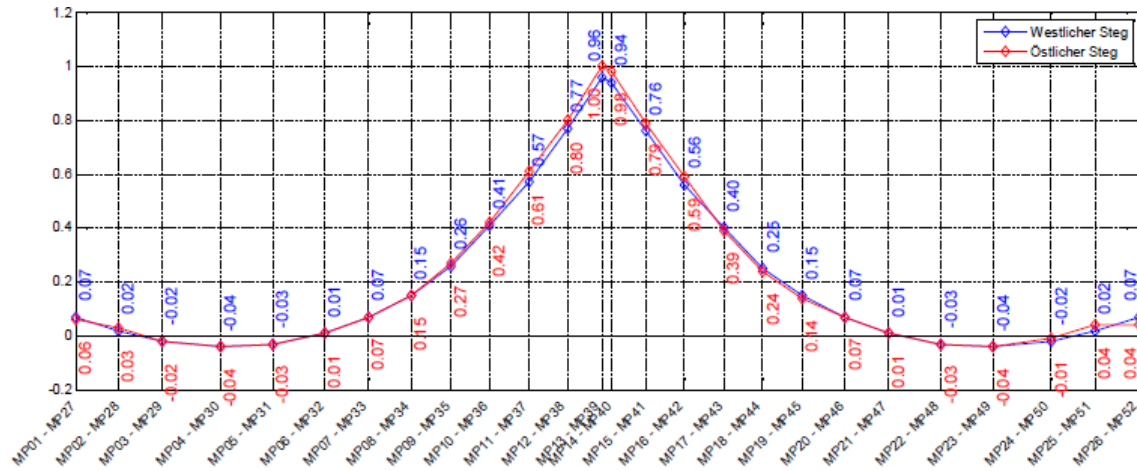


Figure 2. Rel. amplitude mode 01 – 1.26 Hz

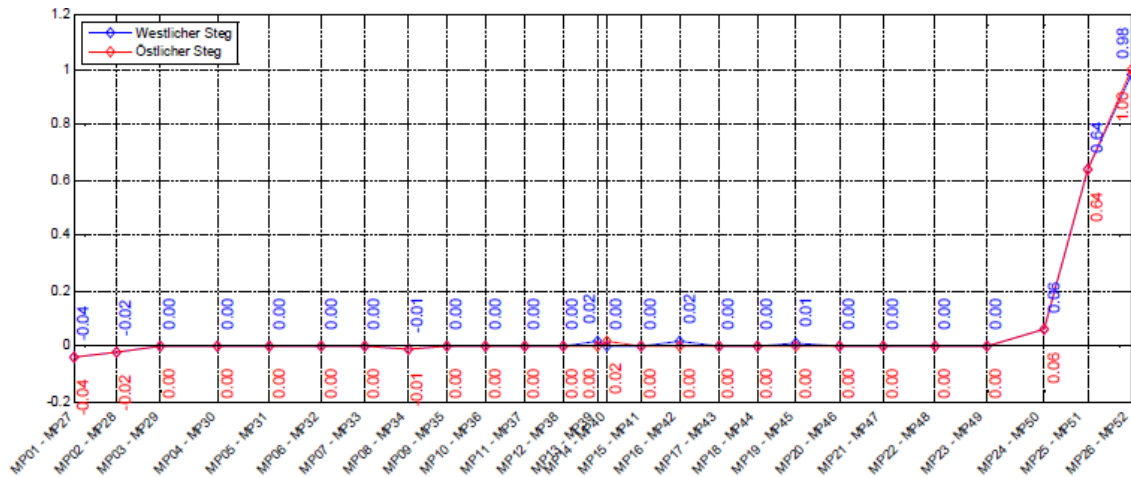


Figure 3. Rel. amplitude mode 02 – 2.99 Hz

Contrary to all expectations, the strongest stresses occurred on the cantilevers (instead of main field). The reason for this behavior may be found in the passage between the stiff foreland bridges and the weak bridge cantilevers. The eigenmodes of the cantilevers were excited very well, large amplitudes were generated with low damping.

Based on the results of the dynamic analyses, a measurement design for continuous monitoring was derived.

2. Equipping the bridge with a continuous monitoring system according to the results of the test measurements (figure 4), handing over the results to the structural engineer, give recommendations for further proceedings.

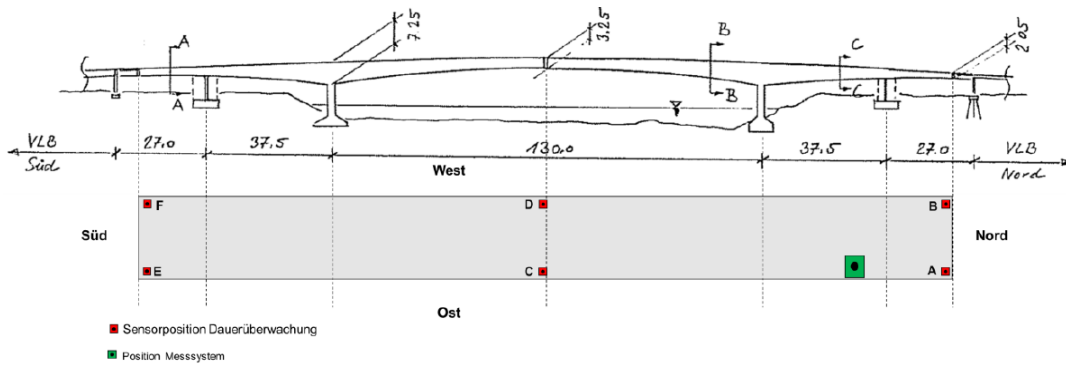


Figure 4. Sensor conception for SHM system

The following vehicle classes generated high dynamic loads (Figure 5):

Excavators, wheel loaders, tractors, forklifts, trucks > 12tons.

The highest bending loads were measured at about 3Hz, the highest torsion loads at 4.5Hz.

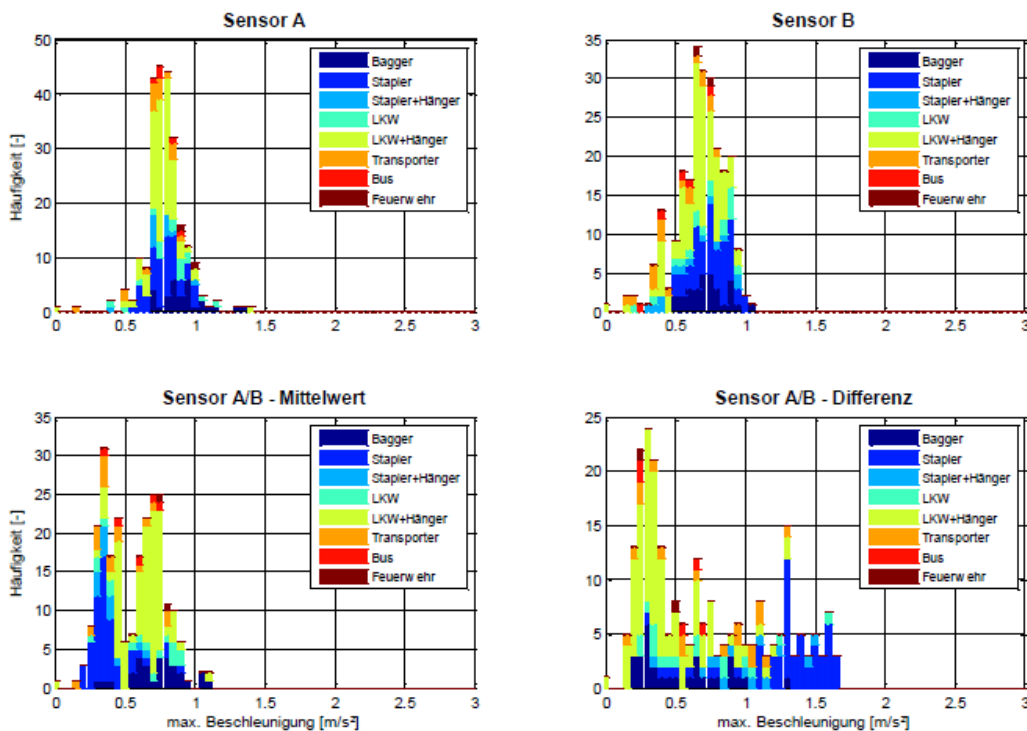


Figure 5. Example of classification of vehicle classes as function of vibration amplitudes

This design was later supplemented by stress sensors (monitoring of bending moments).

Besides the measurements were supplemented by video recordings (determination of the vehicle classes in case of exceeding the limit value (0.7 m/s^2), see Figure 6).

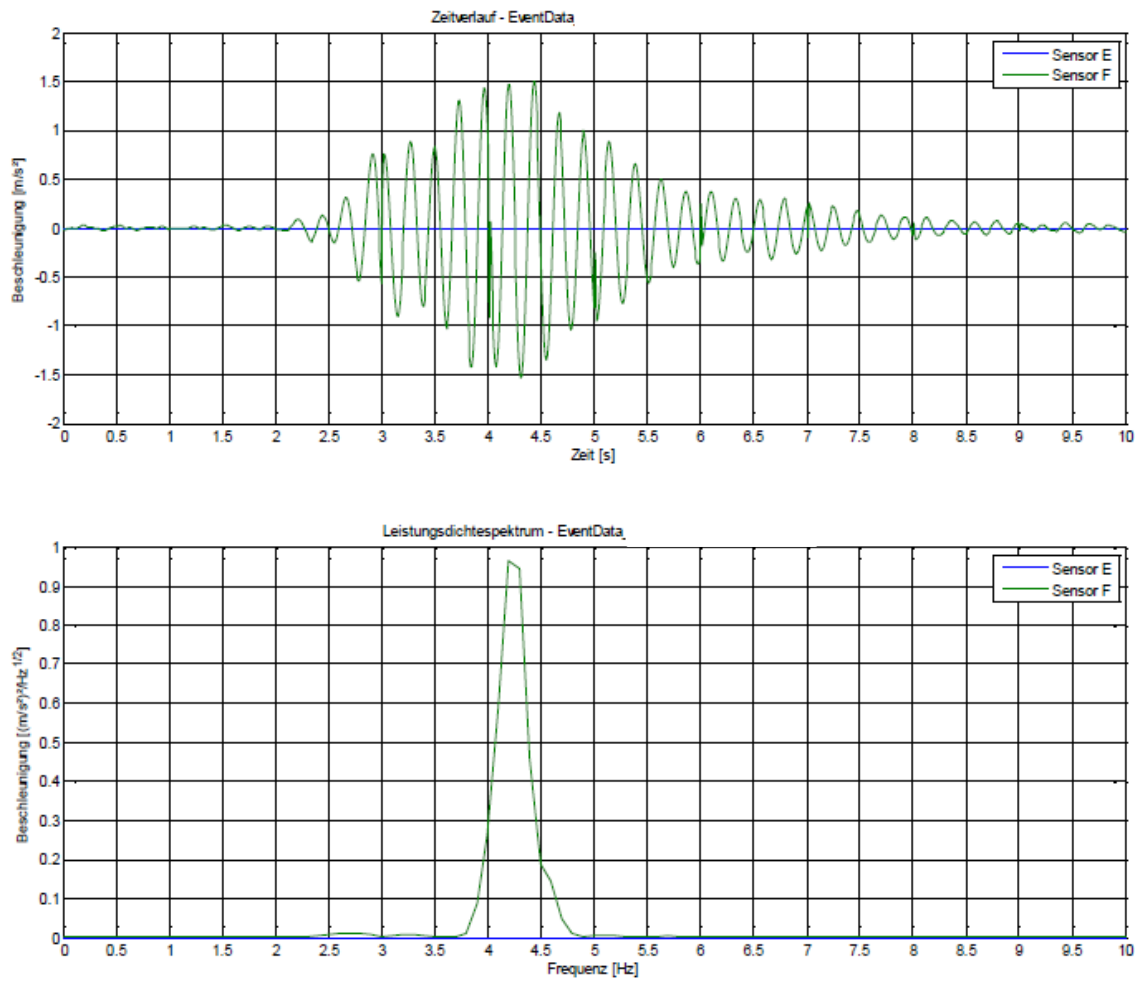


Figure 6. Documentation of vehicles exceeding the limit value

Two recommendations were made:

1. use of absorbers to reduce vibrations in the measured frequency ranges – without any impact to the traffic or
2. Reduction of fatigue stresses due to traffic control (rerouting of vehicles of certain vehicle classes).

The project shows how measurement solutions can be optimised by test measurements and how clear recommendations can be derived from the results, which lead to a significant extension of the remaining service life.

3 CHALLENGES & TRENDS

The results of individual monitoring projects are valid for the respective structure, and for the period investigated under the given conditions. This means, they are not transferable to or valid for other structures.

The future main concerns of the bridge operators for increased safety, a plus in availability, focused investments, efficiency in Asset Management, and additional information, Promobilität e.V. (2019) can be fulfilled collecting standardised information based on measurements in bigger bridge clusters. This complements the visual inspections and allows a comprehensive analysis of the asset network, managing all activities needed.

Projects showing the transferability and comparability of the data within (comparable) bridge clusters do not exist yet. Despite extensive research funding by the Ministry of Transport and Digital Infrastructure (BMVI) in Germany, digitisation or machine learning and artificial intelligence (AI) play almost no role. The reasons are often the low standardization rate for bridges, the large number of different states of regulations adapted over the years (or their absence), and the short service life of the measuring systems compared with the calculated lifetime of the bridges.

Tendering monitoring solutions for bridge clusters would generate important experiences and increase knowledge rapidly. All market actors would benefit - the operators, the inspectors, the monitoring service providers, their suppliers as well as the AI-related research institutions and start-up's.

3.1 Market trends

The market of *measurement technologies* is driven by reduction of energy consumption, wireless data communication/power supply, and smart networks.

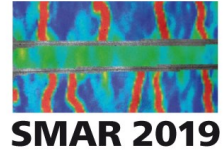
All aspects of digitization (cloud-based applications, machine learning and AI, Building Information Modelling (BIM), and the development of Digital Twins) influence *data analysis*.

A huge *technical challenge* is standardization. This includes measurement systems, meaningful KPI's, and interoperable, intelligent, *and* certified algorithms.

Another important aspect is data security (protection against unauthorized access and against loss).

4 CONCLUSION

The path from inspection-based bridge monitoring to data-driven, preventive Asset Management is irreversible and necessary! The essential strategies and technologies are available. Guidelines simplify the use of standardized solutions in the market. Digitization acts as a catalyst and sets new momentum with new approaches. Government and operators should courageously and



innovatively take the lead in this change. Cost-effectiveness and helpful results should take precedence over price and minimum equipment.

5 REFERENCE LIST

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