Innovative Monitoring and Evaluation of Aging Infrastructure

Tabea NEUMANN*, Juergen KRIEGER*
*Bundesanstalt fuer Straßenwesen, Bergisch Gladbach

Abstract. The German highway network is facing new challenges in the near future. The structures have to deal with increasing traffic loads, climate change effects and new requirements regarding sustainability while they are getting older and budget cuts can be expected. To guarantee a reliable highway network, it will be vital to adapt and enhance innovative approaches. Current bridge management relies on the results of conventional bridge inspections and thus has certain limitations when it comes to insufficient load bearing capacity and other systematic weaknesses. Therefore, new approaches for real time condition assessment of critical road infrastructure elements are to be developed.

1. Bridge Structures in Germany

With 39,039 bridges and a bridge deck area of approx. 30 million m^2 [1] the federal road network includes a noticeable asset of bridges. Along with the bridge structures a large number of additional engineering structures such as tunnels, noise protection devices and support walls build up the total asset of engineering structures. The total assets of all engineering structures are valued at approx. 50 billion euros. Approximately 90 % of this asset value comes from bridge structures, which are mainly concrete bridges (approx. 90% of the bridge structures). A large quantity of these bridge structures has been built in the 1960's and 1970's (see Fig. 1).

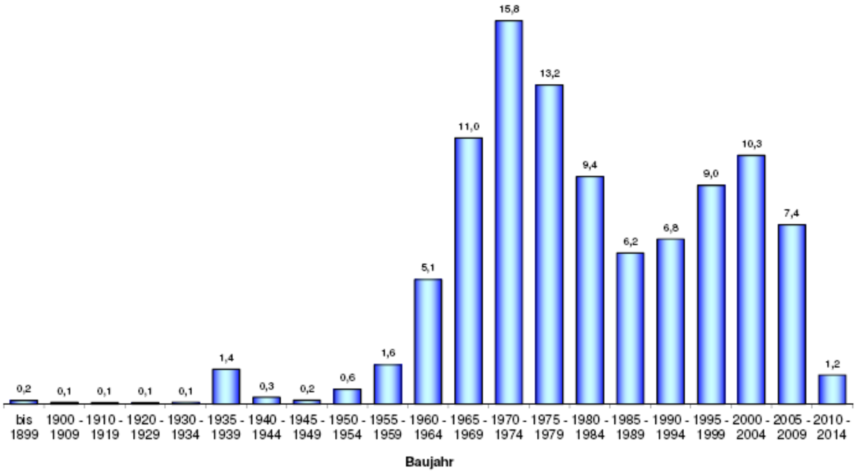

Fig. 1: Age distribution of federal road bridges in Germany [1]

Road bridges are planned for a service life of 100 years. A service life of approx. 50 years for the superstructures and substructures is assumed before substantial repair measures are required. Since a significant number of bridges are in service for 40 to 50 years, they increasingly require thorough maintenance and repair measures.

Continuous observation and inspection of the assets is an important service that the road administrations provide as part of the maintenance of bridge and engineering structures. Standardised databases according to the guideline ASB-ING [2] are implemented at state level. The road administrations register and evaluate structure data and the results of regular inspections using the road information database SIB-Structures, which has been used since 1998. Condition ratings are the results from regular inspections according to DIN 1076 [3] and consider damage evaluations regarding stability, durability and traffic safety. According to RI-EBW-PRÜF [4], the distribution of the condition index indicates that there is a need for action on a considerable percentage of the engineering structures, which leads to appropriate maintenance measures.

Nevertheless the condition index distribution has deteriorated over time (see Fig. 2). That is basically due to the fact that the invested budget was insufficient. In 2010 approx. 470 million euros were invested for maintaining the engineering structure assets - this amounts to only approx. 60% of what would have been required according to the prediction of the federal traffic route plan.

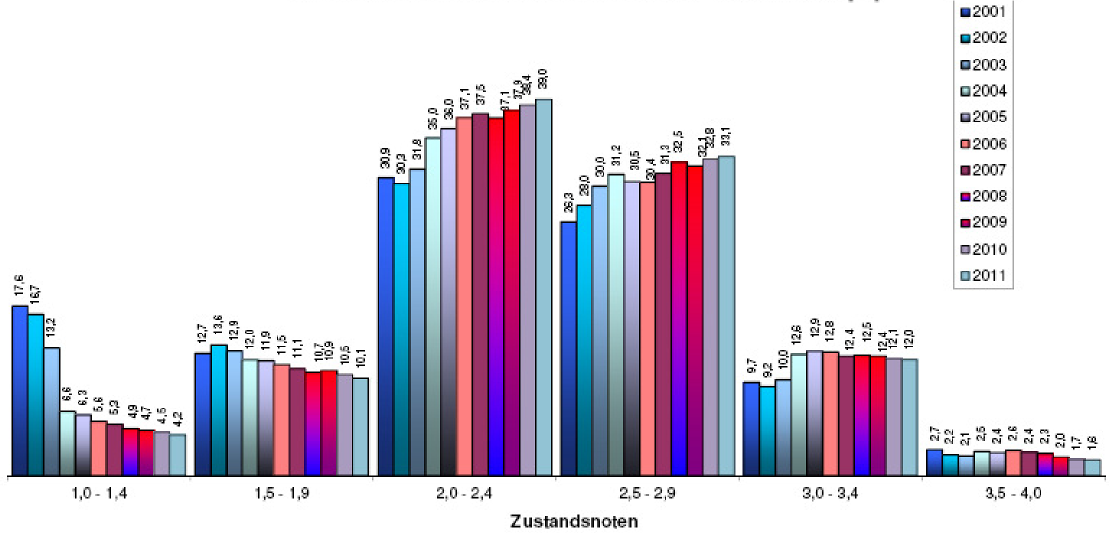

Fig. 2: Condition index [% of bridges] of federal road bridges in Germany [1]

The challenges bridges have to deal with are largely known: deterioration, deficiencies and increasing traffic. The damage mechanisms usually result from the penetration of moisture and pollutants as well as from temperature effects, traffic loads and their interactions. Besides this, material faults reduce the load carrying capacity and service life while the development of damages is accelerated by construction faults, insufficient workmanship, structural shortcomings and inappropriate maintenance and repair. In such cases, damage may occur before the planned service life has been achieved. Another significant aspect is that bridge structures in Germany differ with regard to their load carrying capacity. Load models and design rules have changed over time and have been adapted to the increasing traffic as well as to advanced material and construction knowledge. That means the older the structures within the federal road network are, the less they are prepared to future effects, e.g. the development of heavy traffic or climate change effects. So far these effects are not been taken into account in the maintenance management.

A damage-based and reactive maintenance management, as it currently undertaken, is only useful when the structure indicates that it is about to fail, when the load situation does not change over time and when sufficient maintenance funds are available.

2. Monitoring and Evaluation of Aging Infrastructure

2.1 Approach and Background

Due to the fact, that the overall asset of bridge structures is getting older, thorough maintenance, repair or strengthening has to be undertaken. Above all, the analysis of current traffic volume on Germany's "Autobahns" has shown that the former planned capacity of older bridges is almost exceeded [5]. To guarantee serviceability and safety, a proper evaluation of the remaining service life is crucial in this context. In a priority list a significant amount of bridges has been determined which have to be reassessed.

The DIN standards (DIN Fachberichte [6-9]) are basically destined for the design and construction of new bridge structures. Therefore the DIN standards cannot be transferred one-to-one to the recalculation of existing structures [10]. The required input parameters are unrelated to former standards and the construction materials and their characteristics have changed. Above all the applied structures, their material and their resistances have changed over time.

The need for an appropriate way to evaluate older bridge structures, led to the recalculation guideline (Nachrechnungsrichtlinie [11]), which has been introduced in May 2011 and supplements the DIN standards 101-104 [6-9]. The scheme for recalculation provides different detail levels depending on what is needed to come to a conclusive evaluation [11].

If the needed safety level cannot be verified, the options are limited. The structure can either be subject to compensation measures, refurbished/strengthened or replaced. The fact that Germany has an appreciable asset of bridges derives one major application field for smart monitoring. In all three cases, application of compensation measures, strengthening and replacement, structural health monitoring systems and sensor technology in general can thereby gain particular importance. The objective is to implement the smart data processing, which evaluates the monitored structure in real time.

2.2. Monitoring as Compensation Measures

In case of severe structural deficits and the need of prompt intervention, compensation measures are needed. Those compensation measures can be traffic restrictions such as load or velocity limits or even the blocking of a lane. Although it depends on how serious the restrictions are, they go along with intervention into the traffic flow. Another less intervening possibility could be a permanent health monitoring in real-time. The recalculation guideline (Nachrechnungsrichtlinie) considers the application of compensations measures for additive safety in case of a calculative reduction of the reliability level [11]. Smart monitoring systems customized to the specific needs might help to guarantee the needed safety level. One can also take into consideration to use the structural health monitoring to bridge a time gap before a recalculation or strengthening is undertaken.

Since these bridges are already critical in the sense of load bearing capacity and/or serviceability, it is highly important to have a well working alarming system in case of measured irregularities, in order to not endanger safety.

2.3 Monitoring of Strengthening Measures

Compensation measures are usually temporary and therefore limited interventions. Sooner or later those bridges have to be either replaced or strengthened. Several strengthening measures are possible, such as an addition of in-situ concrete (to enlarge the compression zone) or external prestressings. The success and reliability of strengthening measures are so far difficult to be verified or even quantified. Usually they are only undertaken visual and manual inspection within the regular intervals. Since strengthening has a great effect on the load bearing capacity and the serviceability of the primary structure, it is crucial to know how they perform. There are various possible approaches towards the monitoring tasks. This is not only because there are different measures to improve the primary structure but also because the monitoring concept can either envisage to monitor the entire structure or only the strengthening application itself. Nevertheless, what is true for the compensations measure is valid here as well, the data interpretation and evaluation in real-time grants an important role.

3. Adaptive Systems for Information and Holistic Evaluation in Real Time

3.1 Approach and Background

Although the amount of newly build bridges will be further reduced in the upcoming years, new replacement bridge structures will be needed. That offers new opportunities towards an enhanced maintenance management and the development of adaptive systems for the provision of information together with a holistic evaluation in real time – especially for notable bridges within the road network.

The objective is to build smart bridges of the 21st century, which should be designed in a way that various sensors can be integrated into the structure and thus feeding interrelated prognosis and condition models constantly with data in real-time. The corresponding expert system derives intelligently warning messages for the user, which might lead to self-organized reaction.

The already mentioned changing conditions call for new standards in performance, efficiency and effectiveness of maintenance management. A key function is the provision of information for effective decision-making, criteria and methods for optimisation as well as methods for the implementation of plans. Preventative maintenance strategies, which are applied before the occurrence of severe damage, are useful. However, they require more detailed knowledge of the actual condition and more reliable predictions of future developments than previously available.

In most cases these monitoring systems are set up, because a potential danger had already been determined for example as a consequence of re-assessments as shown before. One characteristic of the presented possible monitoring application fields is their reactive nature. Often deficiencies are only getting apparent when they are not only obvious but also intricate to be cured and repaired. The optimal point for intervention in terms of economic maintenance or refurbishing has already passed by. Most monitoring measures concerning older structures therefore focus on the load bearing capacity and serviceability.

The objective of the approach presented in the following is to go further than the monitoring does so far, and set the starting point before a potential danger is manifested. Therefore it is planned to implement an adaptive system that provides not only information but also a holistic evaluation in real time. Besides the load bearing capacity, durability and fatigue should also be taken into consideration, since they have a great impact on the service life and load capacity respectively.

3.2 Structure and Approach

The development from an instrumental to a smart structure is described in the Fig. 3. The instrumented bridge, measuring impacts/ resistance or reactions and providing the data needed, is the first step within this adaptive system and constitutes the basis for the smart bridge. The objective is to evaluate the data with regard to for example preventative maintenance measures. In combination with the implementation of life cycle or deterioration models, life cycle predictions can be generated, especially regarding the development of condition and damage. The corresponding software system - the expert system - derives intelligently warning messages for the user or owner, which might even lead us to self-organized reaction in the future. [12]

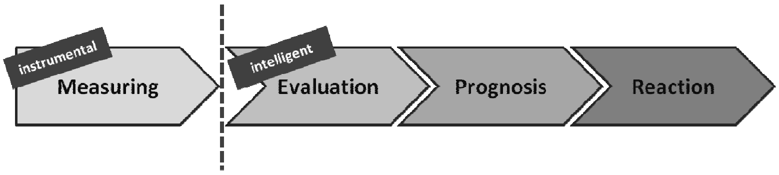

Fig. 3: From an instrumental to a smart bridge structure

The smart bridge structure is supposed to be integrated into the existing maintenance management. Therefore, not only the regular inspections- according to DIN 1076 [3]- find their way into the adaptive systems for smart structures, but also in-depth damage analysis and the structural data. Fig. 4 shows the integration of smart bridges into the maintenance management in detail taking the expected output in terms of object- and network related maintenance planning and operation management into account.

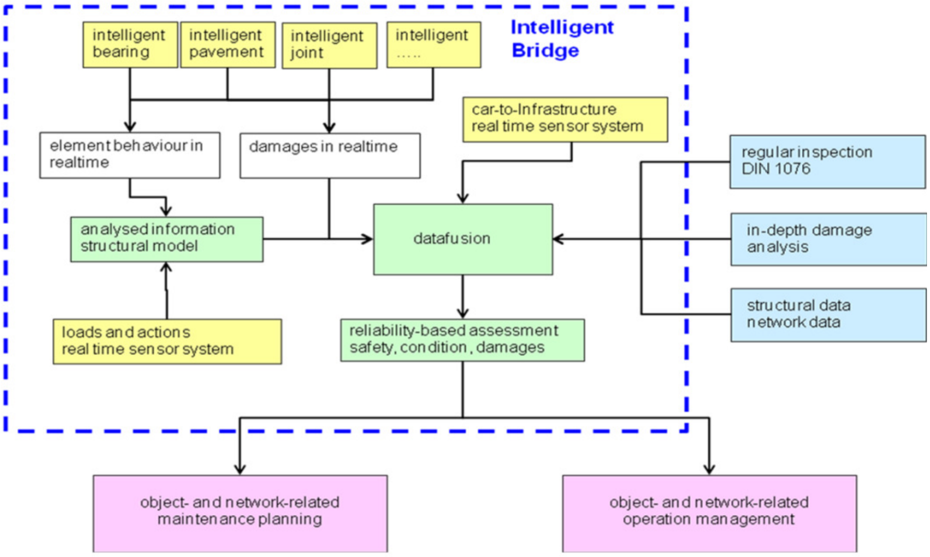

Fig. 4: Smart bridges in the course of maintenance management

Within the complex structure of the adaptive system of a smart bridge, the variety of components and aspects affect each other decisively. Most of these components and aspects can be classified into one of the three following component groups: Smart sensor technology, smart evaluation models and smart maintenance and inspection strategies. All these decisive elements have to be considered and developed precisely within the system, since they are mutually depended in one or the other way. The three outlined component groups undertake different tasks and functions.

The hard- and software retrieves the required information: sensors and sensor networks with a smart data management and a sufficient energy supply are existential. The measured data feeds the evaluation models, which on the other hand indicate the catalogue of requirements regarding e. g. measured parameters or sampling rates. Both component groups have to be implemented into one adaptive system, which is to be integrated in the progressive management and inspection strategies. The objective is to support the existing (mostly deterministic) strategies by the input of the smart bridge structure especially by probabilistic and statistic means. The modular system, which can be extended or reduced according to the individual needs, advances the evaluation in respect of the development of condition and damage. [13]

4. Outlook and Conclusion - Technology Requirements and Research Needs

Compared to monitoring tasks in mechanical engineering or aeronautics, the conditions for (structural) health monitoring of bridges are more difficult.

Bridges structures are highly individual. Although we have specific construction types, they differ very much not only in dimensions but also in construction details and material. Therefore it is not appropriate to develop standardized solutions, since that is not promising. Each individual bridge has its deficiencies and complicated details with have to be taken into account. It might be easier to develop standardized solutions to monitor strengthening measures, but although they might be more similar to each other, they still differ from bridge to bridge due to the individual shortcomings of the structure.

The environmental conditions can be rough. The sensor technology is exposed to the weather extremes during the course of the year. Nevertheless, technology needs to be durable for a long time. As already explained before, bridges have a planned service life of 100 years. Although external sensors could be exchanged as opposed to in structural elements integrated sensors, the replacement of sensors is never easy and always comes along with expenses and interruption of traffic flow. The hardware and technical support on the bridge site has to be of low energy consumption or even energy self-sufficient. Bridge structures in not developed rural areas do not have access to electricity. Besides that constant energy consumption leads to high monthly fix costs, which increase the overall price significantly. For a similar reason the sensor technology should be wireless. Cables are not only vulnerable points in a structural element; they also need regular inspections and manual data retrieval on site or long and expensive cables.

Besides the technical solution for the hardware components, the software is of high priority. The crucial aspect especially for the monitoring applications for older bridges is, that not only the data transfer has to be in real time but also the data processing. Collected sensor data has to be evaluated concerning the bearing capacity and serviceability of the entire structure in nearly real time (and maybe even on site). If an irregularity is detected, reaction is needed as soon as possible, since those monitoring tasks have to determine indicators for bearing capacity and/or serviceability of already critical old bridge structures. The reliability of the sensor hard- and software is very significant for the same reason. The technology has to report technical problems itself and would be completely redundant at the best. It is essential that the bridge structure and its reliability are on the safe and conservative side at any time.

Above all, economic solutions are needed. In most cases structural health monitoring as presented before will only be commonly used in future if the application is economically convincing. To increase the acceptance of monitoring of federal highway bridges, it is advisable to involve the road authorities as well as responsible civil engineers, who have to be involved to find the right evaluation procedures and parameters needed.

There is still a lack of experience with smart monitoring and evaluation of aging infrastructure but it is a forward-looking topic, which requires further R&D.

References

[1] Internal evaluation by Bundesanstalt fuer Straßenwesen, March 2012

[2] ASB-ING 2004. Anweisung Straßeninformationsbank, Teilsystem Bauwerksdaten. BMVBS (www.sib-bauwerke.de)

[3] DIN 1076 1999. Ingenieurbauwerke im Zuge von Straßen und Wegen; Überwachung und Prüfung, Berlin: Beuth Verlag

[4] RI-EBW-PRUEF 2007. Richtlinie zur einheitlichen Erfassung, Bewertung, Aufzeichnung und Auswertung von Ergebnissen der Bauwerksprüfung nach DIN 1076. BMVBS (www.bast.de)

[5] Benning, H., Goj, K., Marzahn, G., Mertzsch, O.:Richtlinie zur Nachrechnung von Straßenbrücken im Bestand – Veranlassung und Grundsätze. Bauingenieur, Band 87, January 2012

[6] DIN Fachbericht 101: Einwirkungen auf Brücken. Beuth Verlag, Berlin, March 2009

[7] DIN Fachbericht 102: Betonbrücken. Beuth Verlag, Berlin, March 2009

[8] DIN Fachbericht 103: Stahlbrücken. Beuth Verlag, Berlin, March 2009

[9] DIN Fachbericht 104: Verbundbrücken. Beuth Verlag, Berlin, March 2009

[10] Maurer, R., Zilch, K., Hegger, J., Zichner, T., Dunkelberg, D., Karakas, A., Kolodziejczyk, A.: Erläuterungen und Hintergründe zur Nachrechnungsrichtlinie – Betonbrücken. Bauingenieur, Band 87, January 2012

[11] Bundesverkehrsministerium für Verkehr, Bau und Stadtentwicklung: Richtlinie zur Nachrechnung von Straßenbrücken im Bestand, May 2011

[12] Neumann, T., Haardt, P.: Intelligent bridges – Adaptive systems for information and holistic evaluation in real time. In: Proceeding of the Sixth International Conference on Bridge Maintenance, Safety and Management, IABMAS 2012, 8-12 July 2012, Stresa, Italy, ISBN 978-0-415-62124-3. CD-ROM.

[13] Neumann, T., Haardt, P.: Intelligent bridges – Adaptive systems for information and holistic evaluation in real time. In: Proceedings of the Sixth European Workshop on Structural Health Monitoring, EWSHM 2012, 3-6 July 2012, Dresden, Germany, ISBN 978-3-940283-41-2. CD-ROM