Intelligent Bridges—Adaptive Systems for Information and Holistic Evaluation in Real Time

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ABSTRACT

The German highway network has to face new challenges in the near future, e.g. increasing traffic density and loads, climate change effects and new quality requirements regarding sustainability. It is necessary to come up with foresighted concepts in the present to be prepared for these challenges. Therefore it is important to adapt and enhance innovative attempts, which take changing impacts into account. One goal of these efforts is the development of adaptive systems for the provision of information and a holistic evaluation in real time.

The paper describes the recent research and developments on a system for information and holistic evaluation in real time, taking into account sensor networks, evaluation procedures and their implementation in existing maintenance and inspection strategies.

INTRODUCTION

The federal road network includes 38,806 bridges with a bridge deck area of approx. 30 million m^2 [1] as well as a large number of additional engineering structures such as tunnels, noise protection devices and support walls. The total assets of all engineering structures are valued at approx. 50 billion euros. The largest component are the bridge structures (approx. 90% of the asset value), which are mainly concrete bridges (approx. 90% of the bridge structures).

A large part of these bridge structures has had a service life of 40 to 50 years and increasingly requires thorough maintenance and repair measures (see Fig. 1).

Continuous observation and inspection of the assets is an important service that the road-building 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 information database SIB-Structures has been used since 1998 by the road administrations to register and evaluate structure data and the results of regular inspections. Condition rating results from regular inspections according to DIN 1076 [3] and considers 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 in a considerable percentage of the engineering structures, which leads to appropriate maintenance measures.

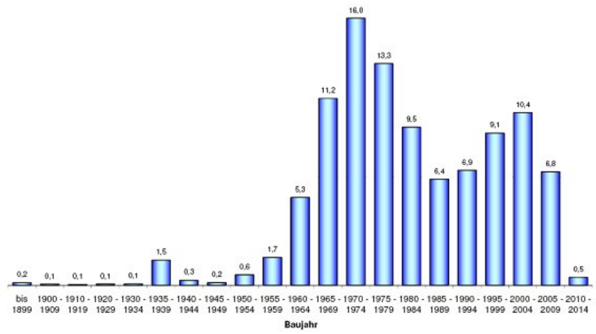

Figure 1. Age distribution of Federal road bridges in Germany [1].

Approx. 350 million euros were invested in 2008 for maintaining the engineering structure assets. This amounts to only approx. 50% of what would have been required according to the prediction of the federal traffic route plan. The situation was similar during the two previous years, which explains that the condition index distribution has deteriorated over time (see Fig. 2).

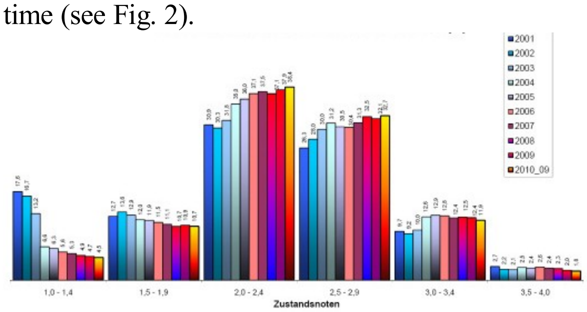

Figure 2. Condition index [% of bridges] of federal road bridges in Germany [1].

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.

The damage mechanisms are largely known and usually result from the penetration of moisture and pollutants as well as from temperature effects, traffic loads and their interactions. Material faults reduce the carrying capacity and service life. 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 expired. Besides this, bridge structures in Germany differ with regard to their carrying capacity. This is due to changes in the load models and design rules, which have developed over time. Future effects, e.g. the development of heavy traffic or climate change effects, are not taken into account in maintenance management.

Current maintenance management is damage-based and reactive. However, this approach 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.

INTELLIGENT BRIDGE – AN ADAPTIVE SYSTEM FOR INFORMATION AND HOLISTIC EVALUATION IN REAL TIME

Introduction

It is generally known that the financial means used so far are insufficient to reach the maintenance goals according to this method. Bridge structures require a high effort to provide the availability, the transport safety and the guarantee of the expected service life. 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.

Monitoring methods have increasingly been used in recent years in national and international applications to support the maintenance management of engineering structures. In most cases these monitoring systems are set up, because a potential danger had already been determined: for example either by a recalculation with adjusted load assumptions or in the course of bridge inspections. However, these efforts mainly involve mere recording of data, according to defined criteria.

The objective 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 (see Fig. 3).

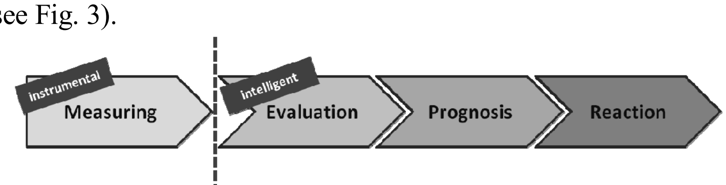

Figure 3. From an instrumental to an intelligent bridge.

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 intelligent 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. Fig. 4 shows the integration of intelligent bridges into maintenance management.

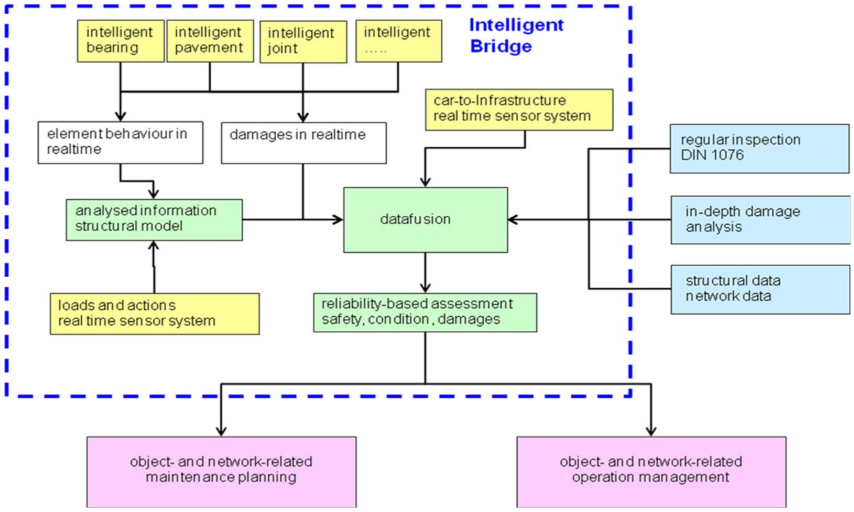

Figure 4. Intelligent bridges in the course of maintenance management.

Within the complex structure of the adaptive system of an intelligent 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: Intelligent sensor technology, intelligent evaluation models and intelligent maintenance and inspection strategies (see Fig. 5).

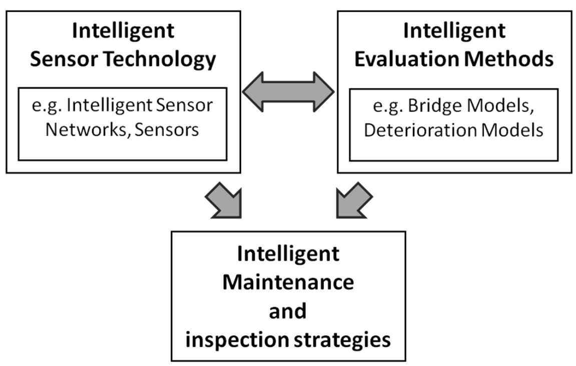

Figure 5. Component groups within the adaptive system of an intelligent bridge.

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 an intelligent 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 intelligent bridge 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.

Sensor Technology

The sensor technology is needed to derive the information in real time. While the individual sensor is decisive for the local, very selective measurement of impacts or structural responses, it is as important to install a sensor network with user interfaces to deliver the data to the owner or responsible engineer and compose a holistic overview over the whole structure.

Focusing on bridges, the use of sensor technology itself is a sensible subject, since the special application on bridge structures asks for increased requirements. The first task is to define, which parameters have to be measured to represent impacts or first indicator for deterioration appropriately. This input is basically given by an analysis of the damages and problems occurring in practice and the corresponding evaluation models.

Starting from the parameters needed, it is necessary to draw up an overview on the sensors available on the market, being able to provide the required measurements. Although there has been a lot of development, there is still not only a potential of improving, adapting and modifying existing sensors has but also the demand for new sensor developments and inventions. The focus of sensors coming into consideration is laid on wireless and energy self-sufficient sensors. Wires and cables, especially in combination with sensors integrated in structural elements evoke vulnerable points in the structure. In addition, integrated sensors have the advantage of being protected by the structure itself to a certain extent. The risk of external damages and vandalism can be reduced. The energy supply on the other hand cannot be provided everywhere. Besides, the running costs should be reduced to a minimum.

Longstanding experience and knowledge on operating wireless sensors in bridge structures are currently not available, since the technology is still fairly young and monitored lifecycle periods of structural elements endure decades. The question whether the sensors available on the market are designated for the operation in bridge structures, is not yet examined sufficiently, although is it most important to ensure the sensor’s utilization and its data reliability in bridge structures. Therefore it turned out, that it is necessary to analyze, which sensors are reasonable concerning their manageability, durability and reliability within the special field. The objective is to derive a catalogue of criteria, which the sensors have to fulfill in terms of their utilization in bridge structures. The first criterion is the manageability and availability of sensors. The second point is the measurement precision and reliability of sensor data taking the dynamic load effects on bridge structures into account. The third criterion deals with the complex around the topic on durability of sensors.

All sensors have to be unified in one sensor system, which measures constantly or occurrence based, verifies and consolidates the data and communicates intelligently. Being able to build up an intelligent sensor network is a crucial step from the instrumented to the intelligent structure. Regarding sensor networks some major aspects have to be taken into account (see Fig. 6).

One of the necessary aspects is the hardware – sensors, motes, basis stations etc. The arrangement of the sensors within the network has to be considered thoroughly. The knowledge about the representative measuring points is brought in by the evaluation models in particular by system analyses and bridge models which help to identify hotspots or redundancies within the system. Statistic modeling provides the information how many data is required.

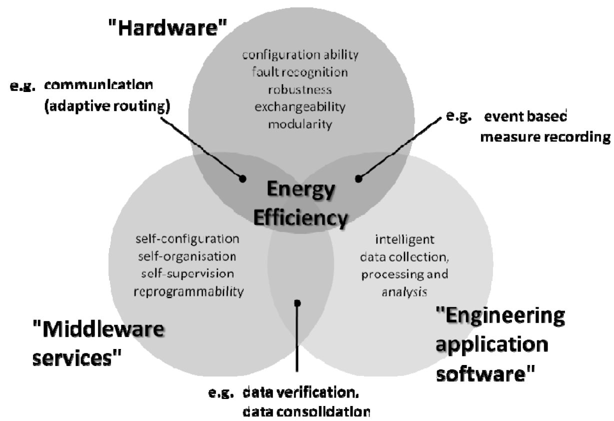

Figure 6. Components of an intelligent sensor and data network [5].

That way the sensor application can assure reasonable results. The data has not only to be collected, but also consolidated and analyzed. Self-organization of the network is needed, since the sensor network should be able to configure and control itself and be reprogrammable. The system itself has to be reliable and therefore redundant. Some further issues, such as sensor communication, data verification event based measures, are affected by at least two of the preliminarily mentioned aspects. The sensors within the network have to interact with each other and trigger for example sensors, which are only needed if a certain impact occurs. In the center of interest and influencing each aspect is the energy efficiency that has to be taken into account [5].

Evaluation Methods

The derived, evaluated and compromised data is giving the input into the evaluation models needed, to predict damage and condition effects as well as future demands due to changing conditions.

Because of the randomness of most of the parameters, a probabilistic approach is appropriate. Basic idea is that both actions (E_i) and resistance (R_i) of structures are time-dependent and random parameters. Typically probabilistic analyses result in failure probabilities (P_{fi}), which should not increase a pre-defined target failure probability ($P_{target\ i}$). Risk assessment broadens this approach by introducing the risk of failure for a given structure or component, which can be computed by multiplying the failure probability by the consequences of failure. Consequences of inadequate performance can be transferred into owner, user and environmental costs (C_o C_u and C_e). Based on these costs, the vulnerability of a structural component experiencing failure due to a given load can be defined. An example is given in [6], where the vulnerability assessment of road infrastructure subjected to natural hazards is presented.

The extent of failure consequences is influenced by indication effects. If a failure could occur without indication, e.g. the sudden collapse of a bridge, the consequences could be enormous. Even in cases with low failure probability, the risk of failure could be comparatively high. As a consequence high priority regarding repair should be allocated to these bridges.

If resistance and action parameters are recorded sufficiently by monitoring, optimized maintenance strategies including well balanced protective measures could be derived, which may lead to decreasing maintenance costs and an increase in service life (see Fig. 7).

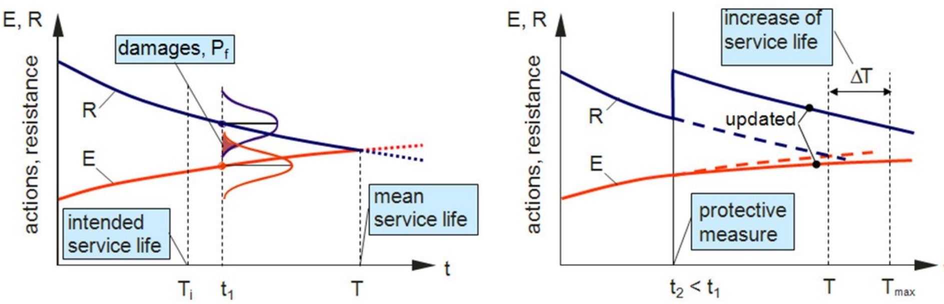

Figure 7. Deterioration, damage and increase of service life without (left) and with (right) protective measures [7].

The proposed reliability based maintenance management consists of three essential steps. First of all as a basis for the following steps a comprehensive reliability analysis of the given structures has to be performed. The probability of potential damages and the probable consequences have to be derived, which forms the basis for the second step, reliability based monitoring regime, in which frequency and extent of measurements is variable and adapted. The common inspection procedures will be enhanced by application of adapted sensors, for an in-depth investigation of critical structural elements. Thirdly, a procedure for optimization of maintenance strategies will be derived, regarding the development of costs as a function of failure probability (see Fig. 8).

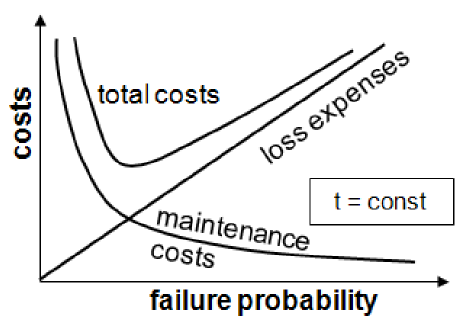

Figure 8. Cost optimization [8].

Decreasing maintenance expenses lead to both increasing failure probability and loss expenses. If maintenance costs and loss expenses do not compensate each other, a cost minimum can be expected which represents an optimized strategy if the failure probability at cost minimum is lower than the target failure probability. This simple approach has to be extended by taking the individual risks, possible maintenance strategies and their lifecycle costs into account. In addition to owner costs a full cost approach would consider user, climate and environmental cost aspects, too. Besides the probabilistic deterioration models, which are a central issue within the evaluation, it is important to develop bridge models which help to analyze the support structure, system redundancies and hotspots with a higher risk potential. An efficient and solid system analysis is not only important to understand the structure's condition and response but also to know where the crucial condition and impact/resistance parameters can be detected and measured. Since the bridge structures are often very different from each other, it is difficult to find one universally valid system. In current research projects it is strived to find a way to model bridges in general in a modular way, which can be adapted individually.

CONCLUSION AND OUTLOOK

The maintenance and inspection of bridge structures will take a high priority in the future. To be prepared in the future it is necessary to have detailed knowledge of conditions and damages of the individual bridges structures. Therefore probabilistic evaluation models and sensor technology have to implemented and added on the existing management systems which are generally deterministic and damage based so far. The Bundesanstalt fuer Straßenwesen has drawn up a research program around the topic of the so-called Intelligent Bridge, which is an adaptive system for information and holistic evaluation in real time. The planned modularity of the Intelligent Bridge guarantees the flexibility and openness to improve and upgrade the system. Further research regarding sensor technology or evaluation models can be taken into account and be implemented that way and a basis and a promising starting point for further R&D projects is set.

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