39th IABSE Symposium – *Engineering the Future*
September 21-23 2017, Vancouver, Canada

Decision support for maintenance and upgrading of existing bridges

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Abstract

Maintenance of transportation infrastructure assets can be relatively expensive, since it does not only include the direct cost of interventions, but also the indirect consequences of traffic disruptions. To make optimal decisions about maintenance actions, including rehabilitation and upgrading, reliable information about the performance of existing structures is needed. However, obtaining such information might require significant efforts and can be done in various ways. The purpose of an ongoing Swedish research project BIG BRO is to develop a framework for a decision support methodology that can be used for implementing maintenance strategies for bridges on a rational basis. The present paper provides a brief overview about the project as well as describes some of the ongoing work.

Keywords: maintenance; rehabilitation; upgrading; infrastructure; bridges; decision support.

1 Introduction

Transportation infrastructure is subjected to several types of exposures (e.g. weather events), loading (e.g. traffic) as well as material deterioration/degradation processes (e.g. corrosion and fatigue). Structural codes intend to ensure that despite these effects the safety and serviceability requirements are satisfied with a given level of reliability during the design life-time of the structure. For economic reasons, however, the reliability targets are often determined in a way that regular maintenance of the assets is required to uphold their serviceability. Furthermore, exceptional situations may also call for interventions and assessments of existing bridges e.g. in cases where:

- Rehabilitation of the asset involve changes in the existing loadbearing system;
- Significant changes in operation or the environment affect the anticipated loads;
- Evidence of deterioration or damage is found;
- Unusual incidents occur during use;
- Discovery of design and/or construction errors;
- Changes or amendments are made in the codes;
- Expiration of residual service life is achieved based on an earlier assessment.

Maintenance of infrastructure assets can be relatively expensive, since it does not only include the direct cost of interventions, but also the indirect consequences of traffic disruptions due to closing down the asset. Furthermore, transportation infrastructure assets are often critical for maintaining essential societal functions and need to be functional for effective crisis management, e.g., after disastrous events. Thus it is necessary that:

1. Technologies should be applied that minimize traffic disturbances (e.g. non-invasive inspections, non-destructive testing, monitoring systems);
2. Interventions should be applied only if necessary, i.e. reliable methods are needed to predict the actual performance of the structure;
3. Criticality, importance and interdependencies of the asset within the transportation network should be taken into account when decisions about maintenance actions are made.

Obviously, to consider all these aforementioned issues is rather complex and maintenance planning of infrastructure assets is often carried out intuitively rather than systematically, which might lead to sub-optimal decisions about interventions. However, in the past decades significant scientific knowledge and experience has been developed in various fields that can support a more rational decision making about maintaining and upgrading existing infrastructure, see e.g. [1],[2],[3],[4].

To utilise this scientific potential in practice, knowledge from several fields related to structural engineering needs to be implemented in a common framework. An ongoing research project, BIG BRO (Decision support for maintenance and upgrading of existing transportation infrastructure) in Sweden aims to develop such a framework. The project team includes representatives from a research institute, academia as well as the industry and works in collaboration with the Swedish Transport Administration, the owner and operator of the majority of Sweden's bridges. The present paper provides an overview of this project.

2 Concept

The main idea in BIG BRO is to combine knowledge from different areas of expertise in structural engineering and develop a common methodology that could be implemented by practitioners. Thus the methodological framework should reflect the scientific state-of-the-art while also adhering with the current state-of-the-practice.

The concept to be developed rests on 4 main pillars as shown in Figure 1.

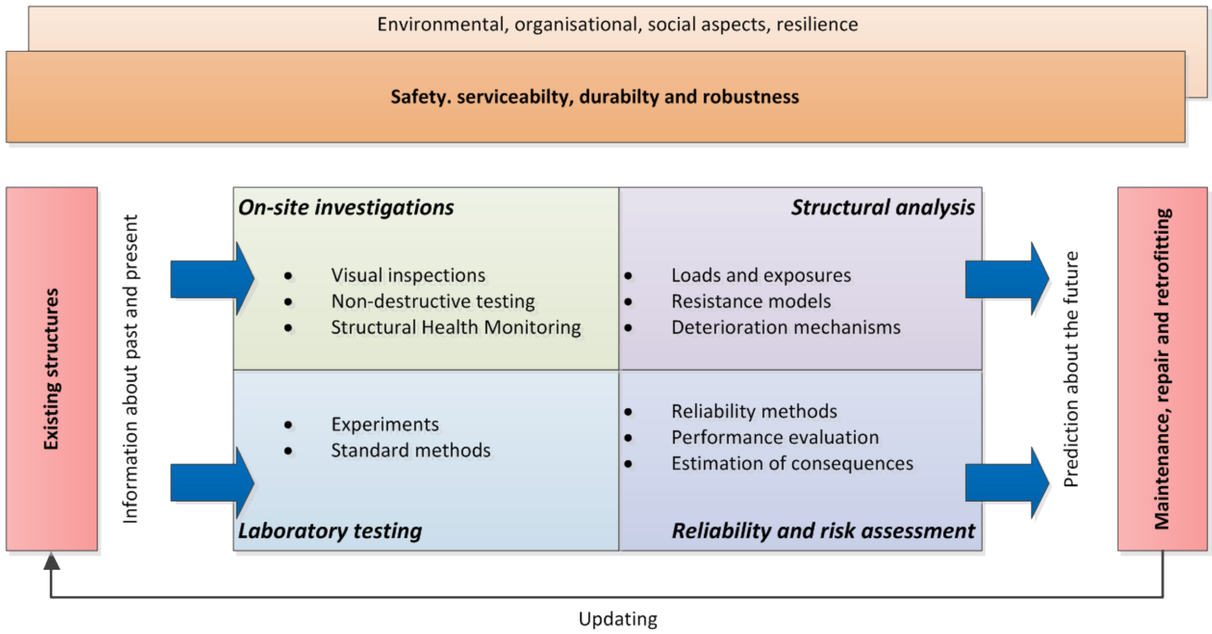

Figure 1. The BIG BRO concept

Pillar 1: On-site investigations

To be able to assess the current level of structural performance it is essential to collect data on-site without (or with as low as possible) traffic disturbances. This could be carried out e.g. by the implementation of continuous structural health monitoring (SHM) systems or planned inspections including non-destructive and destructive testing. The data collected could relate to e.g. loading, strains, deformations, stresses, accelerations and modal responses.

Pillar 2: Laboratory testing

It is not always possible to collect the required information on site, thus experimental investigations are required to determine relevant material or obtain accurate information about structural parameters. These laboratory tests could be standardized tests or tailor-made to mimic special conditions given at the structure in question. It could involve properties such as the compressive strength of concrete, yield stress, material composition, and fracture toughness of steel, etc.

Pillar 3: Structural analysis

Since one can only experience (and measure) certain aspects of physical reality, there is a need to create models to understand structural behaviour and predict future performance. Modelling could be carried out at different levels (material, structural component, structural system etc.) and might consider different aspects, e.g. loading, resistance and deterioration.

Pillar 4: Reliability and risk

By knowing the expected loads and the expected structural response it is possible to estimate the structural reliability; which could also be expressed as the expected remaining service life. It is important to note that if new information is available the reliability prediction can be updated. Furthermore, the accepted level of reliability should reflect the expected consequences of potential damages or failure to the structure.

Pillars 1 and 2 focus on collecting information concerning the past and present state of the structure, while Pillars 3 and 4 intend to predict what is expected to happen in the future; see Figure 1. Thus an important aspect of a decision making framework relates to how the available information could be best utilised and at what cost further information should be collected considering the value it brings. The primary aspects to be considered in the framework under development relate to safety and serviceability of bridges with due consideration of long-term performance (durability) and system effects (robustness). However, environmental consequences, organisational issues (to provide effective maintenance), societal aspects (the effects of the service the bridge provide to the community), considerations of timely and resource-efficient recovery after damage (resilience) etc. might also play an important role in the decision making framework.

2.1 On-site investigations

With regard to investigations on-site, monitoring and measurement technology is an extensive field covering different applications and techniques. The condition of the structure is typically the main question for most assessments, but it is rarely possible to monitor or measure the structural health directly. In deciding on what should be inspected or monitored, it is important to understand how the bridge might behave considering e.g. its structural system and materials used. Concerning structural materials typical deterioration mechanisms need to be identified to be able to select the right indicators of performance and predict remaining service life.

For *concrete bridges*, corrosion of the reinforcement has a crucial influence on the service life. The corrosion causes cracking and ultimately spalling of the concrete cover. Monitoring systems can be designed to quantify the risk of reinforcement corrosion due to carbonation or chloride ingress [5]. However, the connection between the monitoring and the assessment of the remaining service life is not evident and many models for strength degradation are strictly theoretical [6]. Nevertheless, it is possible to develop strategies for incorporating measured corrosion rate data in a reliability model [7].

Corrosion is of major concern also for *steel bridges*. The corrosion process is complex and the effects can vary from non-structural maintenance problems to a local failure or an overall collapse [8]. In most theoretical assessments, only the material loss due to uniform corrosion is considered. Reliability models considering the initial time and the corrosion rate are available [8], where the input is based on empirical data which can be updated by inspection or test results.

Fatigue is also a significant reason for limiting the service life of steel bridges. Cracks are initiated and propagated at critical locations such as welded connections or other abrupt geometry changes. These cracks may grow at an accelerated rate which can result in a critical crack depth before they are detected. The use of monitoring for a direct assessment of the fatigue is therefore questionable. Monitoring can, however, be useful for measuring the stresses close to the critical locations for fatigue cracking; these results can then be incorporated in a reliability analysis [9].

Monitoring of structural condition is also important for *timber bridges* where the main focus may be on relative humidity, temperature and moisture content of the wood at different depths. The purpose of the measurements is often to verify models for prediction of long-term durability based on periods of surface wetting, on moisture conditions related to climatic loads, coatings, wood processing etc. [10].

2.2 Laboratory testing

Not all information related to the performance of an existing structure can be obtained on-site nor is always economical to do so. For example it might be beneficial to take material samples to test off-site in a laboratory in accordance with relevant testing standards. These tests can help provide valuable data for structural analysis (e.g. model updating) and/or statistical analysis (e.g. Bayesian updating of the basic stochastic variables in a probabilistic model). Furthermore if there is doubt about the performance of a structural model, laboratory testing can be useful to verify the model or parts of it under controlled conditions. Typical examples include testing of certain components/connections or scaled wind tunnel testing.

2.3 Structural analysis

As shown earlier, various monitoring and inspection options are available for the condition assessment of assets within transport infrastructure. However, even the most advanced technology is inefficient if it is unclear how the obtained data is to be used. Furthermore, it may be difficult to determine effective strategies for data collection; i.e. in terms of what information should be collected, at which location and how frequently. To make a decision about inspection, maintenance activities or structural changes due to e.g. repair, strengthening or rehabilitation a structural response model is usually used to represent a given bridge. In general, the response of a structure to real loads will always have a major influence on the degradation.

Besides reliable methods for measurements and data collection a good structural model, reflecting the real response of the structure, is crucial for evaluation of the structural capacity. Modelling of the structural response usually involves uncertainties that are not directly measurable. However, model updating based on tests and measurements (structural identification) can be used to reduce these uncertainties and improve the structural model [11],[12]. This has been demonstrated by some bridge monitoring campaigns in Sweden [13],[14]. A well calibrated structural model is also important in order to be able to evaluate changes in structural response based on e.g. structural health monitoring.

2.4 Reliability and risk

From a structural point of view the performance of an existing infrastructure asset is characterized by the probability of failure (for a given reference period, usually 1 year) and the associated consequences (or more generally, the utility). These factors can be quantified by the use of reliability and risk based methods. Moreover, they can be used for updating current load and resistance models and as a means for making more rational decisions concerning maintenance strategies. Reliability-based evaluation methods can be classified into different categories according to the level of evaluation and the input information [15]. The reliability index of a structural system is evaluated based on demand (loading effect) and capacity (resistance); both of which will vary during the structures lifetime. Therefore, the reliability index β also varies with time and usually decreases, as shown in Figure 2.a. The efforts to maintain the performance of a system above a prescribed target reliability level β_t can include inspection, maintenance and rehabilitation or upgrading, see Figure 2.b.

Two important questions in reliability-based management of structural systems are [16]:

1. How to evaluate the effects of various maintenance interventions that may be applied during the lifetime of a system and;
2. How to select the next maintenance intervention from a set of available interventions.

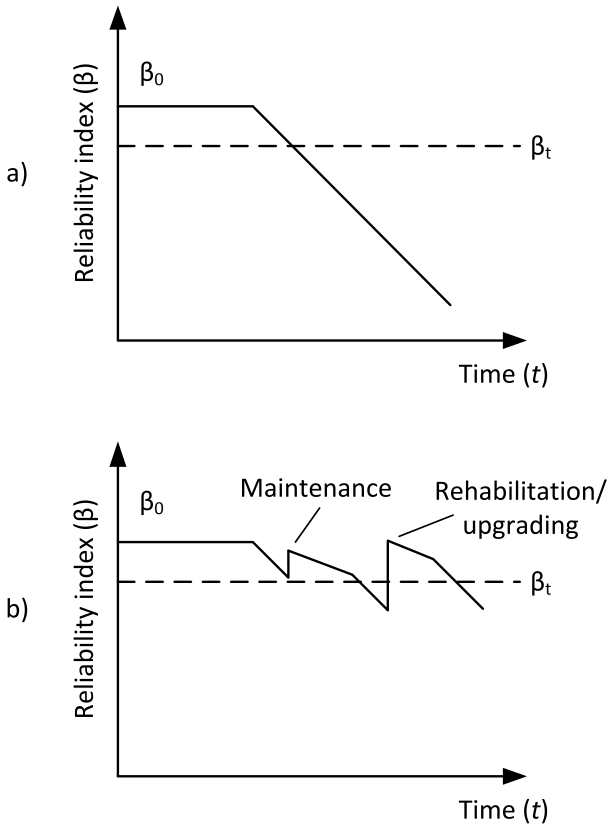

Figure 2. Effect of maintenance and rehabilitation on reliability

Reliability based assessment methods combined with measurements of real loads and structural health monitoring have a great potential for answering these questions. An example of reliability based assessment methods with measurements of vehicle loads is presented in [17]; the bridge owners managed to avoid a large scale strengthening of the Öland Bridge in Sweden based on these types of assessments. Further developments in this area include SHM and other measuring techniques which could lead to further understanding of the safety level in our bridges in real-time.

2.5 Decision theory

Substantial research has been devoted to the development of monitoring and measurement techniques to reduce the various uncertainties associated with different structural characteristics and performances [18]. However, there is comparatively little research available on how to use the obtained information for practical decision making. Existing studies try to quantify and assess the benefits of information collected through monitoring systems in a life-cycle perspective prior to their implementation [19].

The main objective of the BIG BRO project is to support decisions about maintenance and upgrading. Therefore a fifth pillar, namely *decision theory*, is required, which links the previous ones and ensures a consistent consideration of the different aspects detailed in the previous subsections.

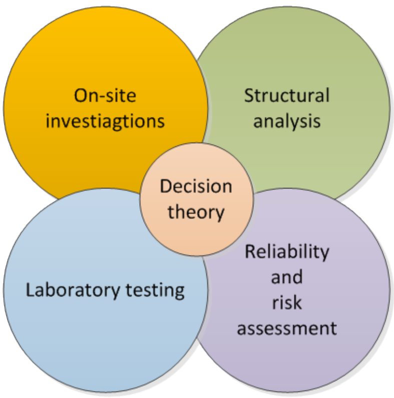

Figure 3. Linking the pillars

In the development of the framework for the project the concept of Value of Information [20] from the pre-posterior Bayesian decision analysis [21] seems promising. These concepts are not widely accepted in structural engineering practice, except by a relatively small group of experts, and therefore their potential has not yet been fully realized in practical applications. Another obstacle for utilizing these concepts is that the required modelling and computational capacities are often large [22].

However, this scientific basis allows evaluating if maintenance or upgrading strategy is beneficial even before a decision is made concerning its implementation. The main idea is that the expected benefit from the future information (to be obtained e.g. through inspection and monitoring) is assessed for values predicted using probabilistic models.

Updating information through inspection and monitoring are often treated separately from decision making frameworks, although combining the two in a unified network is proposed e.g. in [23]; see Figure 4. However, practical implementation of such frameworks is not straightforward for bridge operators.

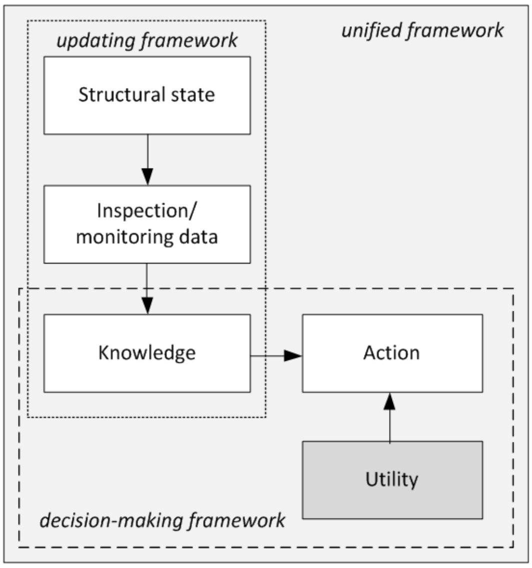

Figure 4. Unified framework for inspection and decision making (adapted from [23])

The basic idea of practically useful risk-based maintenance planning is to minimize the overall service life costs (including direct and indirect costs of failures, repairs and inspections). With such a framework it is possible to assess the utility of different inspection strategies, and thus enable selecting the most beneficial one among several decision alternatives.

3 Reassessment of bridges

An important aspect in the decision making process about maintenance and upgrading actions for bridges is to decide how detailed the condition assessment should be; as these assessments are often the basis for deciding on various subsequent actions. In the BIG BRO project this has been identified as a central issue; one which the proposed framework should be able to answer.

Several previous research projects have focused on the assessment of existing bridges with the aim of extending their service life and thus optimising the resources spent on their maintenance; see, e.g., [24],[25]. A generally accepted assessment procedure follows and builds upon the framework presented by Schneider [26] as shown in Figure 5 (adapted from [27]).

The usual framework of reassessment starts with an initial assessment based on available information (e.g. documentation from design, construction and/or visual inspection) using relatively simple approaches (if any) for the analysis. The main purpose is to show, with as little effort as possible, that the structure fulfils the regulatory requirements for a specified period of time (e.g. relating to inspection intervals). If, however, the requirements are not fulfilled, it may be beneficial to carry out an enhanced assessment as an intermediary step before extensive resources are spent towards repair, strengthening, monitoring etc.

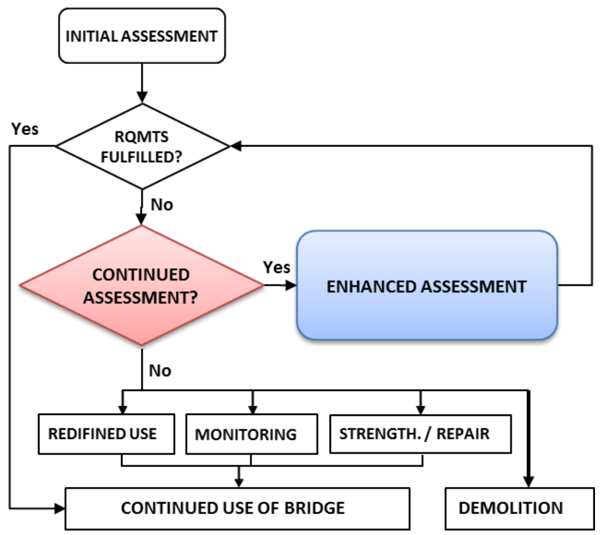

Figure 5. General bridge (re)assessment procedure adapted from [27]

The enhanced assessment, which is a central focus in the BIG BRO project, can include two major options, which can be used independently or in tandem:

1. Collect more information;
2. Improve analysis method.

Gathering more information can be done through e.g. inspections, monitoring or testing. There exist a vast number of methods to collect information on performance (through various indicators) with varying accuracy and associated costs.

The analysis method can be improved in a number of different ways and determining an appropriate approach is in itself an important decision. It is thus convenient to differentiate between these approaches by considering specific aspects associated with them and their application in practice. The following three factors are considered here:

1. Sophistication of the performance model;
2. Considerations of uncertainties and consequences;
3. Information content.

The levels of these factors could span from simple (or even non-existent) to largely complex and their specific combinations can be represented in the three-dimensional space (defined by the aforementioned factors as axes), see Figure 6.

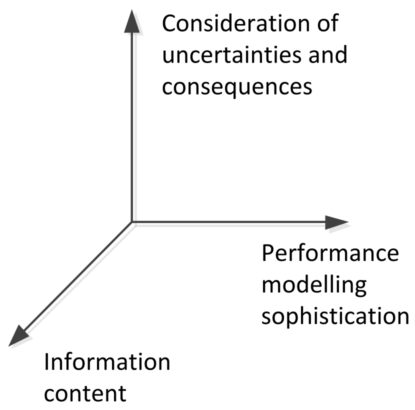

Figure 6. Main factors of enhanced assessment

The performance modelling sophistication is a measure of how encompassing the performance model is and could generally be related to the model complexity; i.e. more sophisticated models usually contain more variables and are computationally more expensive (which usually makes them more expensive monetarily as well). The performance model is a model for which quantitative results pertaining to the condition (often structural) of the bridge can be determined. A typical example of a high level of performance modelling is the use of non-linear finite element analysis with a large number of degrees of freedom.

The second factor is the consideration of uncertainties and consequences that are included in the condition assessment from deterministic to risk-based probabilistic assessment. Here again the more advanced consideration increases the required computational capacity.

The third factor, i.e. the information content prescribes the degree to which additional (updated) knowledge is included in the assessment. This type of information will generally provide a more accurate depiction of the actual state of the structure and thus doing away with potentially unneeded conservative modeling assumptions. The exact manner with which this additional information can affect the assessment may depend on the level of risk/uncertainty considerations as well as the modeling sophistication. For example, in a deterministic assessment it may alter the value of some of the modeling parameters while for reliability/probability based assessments the information may be directly integrated using Bayesian updating.

It should be noted that these factors are not completely independent from each other. For example the sophistication level of the performance model will to some extent determine which sources of uncertainty can be considered. Similarly the consideration of uncertainties will affect the possibilities of directly including new information.

An advisable approach could be to increase the level of sophistication successively in all three dimensions if possible and maintain a consistent level of crudeness [28]. It is believed that the potential gain in assessment accuracy is highest when moving from the lowest levels to moderately complex ones. However, this hypothesis requires further study.

4 Discussion

The previous sections highlighted some important aspects that need to be considered when decisions about maintenance and upgrading of bridge structures are made; aspects which form the foundation for a consistent and rational decision making framework.

It is important, however, that such a framework should be pragmatic and address the relevant issues in a way that the decision maker can best utilize the results.

In the first stage of the BIG BRO project a theoretical framework is described for a decision support methodology for the assessment, maintenance and upgrading of existing transportation infrastructure. The development follows 4 main steps:

1. Understand what could be done (state-of-the-art), what is being done (state-of-the-practice) and what is needed;
2. Create an 'inventory' of methods for testing and monitoring, structural response modelling, reliability analysis and current practice of maintenance strategies;
3. Critically evaluate available methods with regard the usability in a decision support system and suggest developments;
4. Suggest a theoretical framework, by integrating methods and tools from the inventory and define requirements for implementation of the methodology.

Further steps after the formal description of the framework will focus on:

- Development of methods and tools; and
- Implementation and demonstration of the methodology.

5 Conclusions

The present paper provided a brief overview about the ongoing research project BIG BRO aiming to develop practically useful decision support framework related to maintenance and upgrading of bridges concerning enhanced assessment and associated choices and actions.

6 Acknowledgements

The authors acknowledge the financial support provided by the Swedish Transport Administration (Trafikverket) and the strategic innovation programme InfraSweden2030, a joint effort of Sweden's Innovation Agency (Vinnova), the Swedish Research Council (Formas) and the Swedish Energy Agency (Energimyndigheten).

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