Decision support for bridge condition assessment

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ABSTRACT: The paper presents the first steps of the development of a theoretical framework for a rational yet practical decision making process concerning the condition assessment of existing bridges in Sweden. The main focus is on how to choose the appropriate level of enhanced conditions assessment considering aspects of model sophistication, uncertainty consideration and knowledge content utilisation. A conceptual case study is presented exemplifying how the framework can be used to structure the assessment actions of a steel bridge subjected to fatigue deterioration.

1 INRODUCTION

A substantial part of the bridge stock in European countries, including Sweden, is rather old and requires regular maintenance to ensure sufficient structural safety and serviceability. To support maintenance decisions various inspection and monitoring options are available for evaluating the actual condition of transport infrastructure assets. However, even the most advanced technology is ineffective if it is unclear how the obtained data should be used.

The performance of an existing infrastructure asset may be characterized by the probability of failure and the associated risks. These 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 mean for making more rational decisions concerning maintenance strategies. Several research papers have been published about reliability- and risk-based approaches to support inspection and maintenance of bridges and other type of structures. However, the potential advantages of these methods are less often utilized in practice. This is mainly due to the lack of a description of a formalized methodological framework fitted to the needs and current practices of the bridge operators.

The present paper describes the first steps of the development a decision support framework to be suggested in Sweden. The main focus here is to formalise the procedure of condition assessment i.e. the decision on moving to a higher level of assessment before deciding in which circumstances further, potentially costly, actions are required; e.g. repair or rehabilitaion.

2 CONDITION ASSESSMENT OF BRIDGES

2.1 *Existing frameworks*

If there is a doubt about the performance of an existing bridge there are several available actions to make sure that the bridge fulfils relevant requirements of structural safety. The current study focuses on condition assessment options where no interventions are carried out to ensure that the load bearing capacity of a structural system is sufficient to carry the required loads. A decision should then be made for how detailed the condition assessment should be; as these assessments might provide the basis for determining various subsequent actions. Several frameworks for the assessment procedure of existing bridge structures have been developed in various research projects (e.g. BRIME 2001, Sustainable Bridges 2007). These are usually based on the procedure proposed by Schneider (1997) which has been adopted by the JCSS, RILEM (JCSS, 2001), and more recently by ISO 13822 (ISO 2010); see Figure 1.

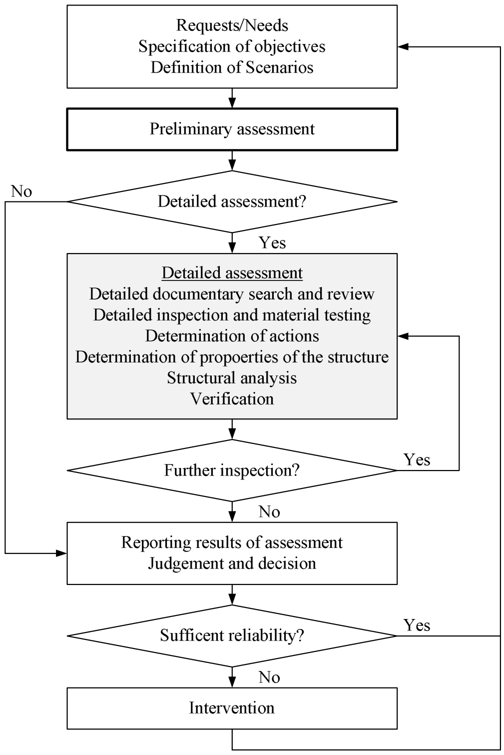

Figure 1. Condition assessment procedure from ISO 13822 (ISO, 2010).

Although the general framework is generally accepted, little guidance (and agreement) exists on how the detailed assessment should be carried out systematically. In Table 1 a brief summary of various levels of the detailed assessment available in the literature are given.

2.2 *Swedish practice*

The Swedish Transport Administration (STA), called Trafikverket in Swedish, uses an advanced bridge management system called BaTMan for the operation and maintenance of their bridge (and tunnel) portfolio. BaTMan contains administrative data, photos, technical information, load capacity, all inspection records and construction drawings (if available); a specification of the required data is provided by the STA (Trafikverket 2014). Requirements and advice on the performance and documentation of inspections is also available as an online manual (Trafikverket, 2015). These documents ensure that the activities (e.g. inspection) related to the management of bridges are carried out consistently and properly. The inspection manual also provides information on typical damages and their causes for the common bridge types and their structural members.

Table 1. Condition assessment levels from various research projects

	Assessment level				
Ref.	1	2	3	4	5
BRIME, 2001	Partial factors method, loads and resistances from records and standards, simple structural model	Partial factors method, , loads and resistances from records and standards, refined structural model	Partial factor method, material properties and loads based on in-situ observations	Modification of partial factors, material properties and loads based on in-situ observations	Full probabilistic assessment
SAMCO, 2006	Direct assessment of serviceability values from measurements (no structural analysis)	Assessment of safety and serviceability using simple model based methods (data from documents)	Assessment using refined model based methods (data from tests, monitoring, etc.)	Adaptation of target reliability measures and assessment with modified structure-specific values.	Full probabilistic assessment (data from tests, monitoring, etc.).
Wenzel, 2009	Condition assessment (simple instrumentation and simple decision support)	Performance assessment (more detailed then the previous level, more indicators)	Detail assessment and rating (includes analytical model representing the structure)	Lifetime prediction (data from at least 3 years and simulations, special software for decision support)	
Skokandic et al., 2016	a) Linear analysis b) + updated loads from measurements	a) Non-linear analysis with global safety factor b) + updated loads from measeurements	a) Probabilistic approach b) + Bayesian updating		
Plos et. al, 2017	Simplified analysis methods	3D linear shell (FE) analysis	3D non-linear shell FE analysis elements and fully bonded reinforcement	3D non-linear FE analysis with continuum elements and fully bonded reinforcement	3D non-linear FE analysis with continuum elements including reinforcement slip

Bridges (and other assets e.g. tunnels) are inspected regularly and systematically to ensure that requirements on safety (and accessibility) are met; a minimum inspection interval of 6 years is common. However, there might be reasons to inspect more frequently, e.g. based on the result of a previous inspection. The initial inspection intends to clarify the physical and functional condition of the bridge and provides a basis for the planning of required actions. Based on the results of the inspection, a condition class (CC) is assigned to each structural element. The CC spans from 0 to 3 (see Table 2) and describes to what extent structural members fulfil their functional requirements at the time of inspection. A condition assessment is the basis for evaluating sufficient capacity and includes the inspection, the damage assessment and the calculation of load-bearing capacity. These calculations are updated in the event a new CC is assigned.

Table 2. Condition classes (CC) system used in BaTMan (Trafikverket, 2015; Safi, 2012).

CC	Assessment	Description
3	Defective function	Immediate action is needed
2	Defective function within 3 yrs	Action is needed within 3 yrs
1	Defective function within 10 yrs	Action is needed within 10 yrs
0	Defective function beyond 10 yrs	No action is needed in 10 yrs

Damage assessment might include more detailed inspections, simple calculations or more detailed analysis to decide if the bridge in its current state has sufficient load-carrying capacity. Damage assessment is made with the help of external consultants and, together with the bridge manager, a decision is made on e.g. which method and what level of modelling to use. If the structural condition requires frequent inspections instrumentation might be used, although it is relatively uncommon. At this level there is no systematic procedure on how decisions should be made on selecting certain actions in the successive condition assessment process. However, in practice there is a discussion to gradually increase the level of assessment. This process, according to the authors of this paper, should be formalised.

3 PROPOSED CLASSIFICATION OF METHODS FOR DETAILED ASSESSMENT

3.1 Levels of condition assessment

As discussed earlier, bridge management decisions are based on the result of some type of condition assessment; whether qualitative or quantitative. Assessing the condition of a structure as a basis for decision making can be done in a number of different ways and determining an appropriate assessment 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 (see Figure 2):

1. Modelling sophistication;
2. Considerations of uncertainty and/or risk;
3. Knowledge/information content.

The 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/factors. The performance model is a model for which quantitative results pertaining to the condition (often structural) of the bridge can be determined. More sophisticated models can better capture reality and predict structural performance of the bridge. However, increasing the level of complexity can be time-consuming, require additional data, introduce errors, etc. Therefore the expected costs and benefits of moving to a higher level of sophistication should be evaluated and compared with options of moving along the other two axes.

There are generally speaking three different levels for the second factor, consideration of uncertainties/risks in an enhanced assessment: deterministic, reliability-based and risk-based assessments. Deterministic calculations utilize representative values for the variables involved and the results are compared with prescribed criteria; i.e. in the form of code specified safety targets. Going from a deterministic calculation to a reliability based one will require a stochastic modelling approach in which case explicit considerations of uncertainties is required. Usually those parameters which are considered most significant are modelled as random variables, with associated distribution parameters, while the remaining variables are modelled as being deterministic. A move to the third level, in which a risk-based approach is adopted, will require some consideration of the costs, consequences and possibly even the benefits associated with identified damage and/or failure scenarios.

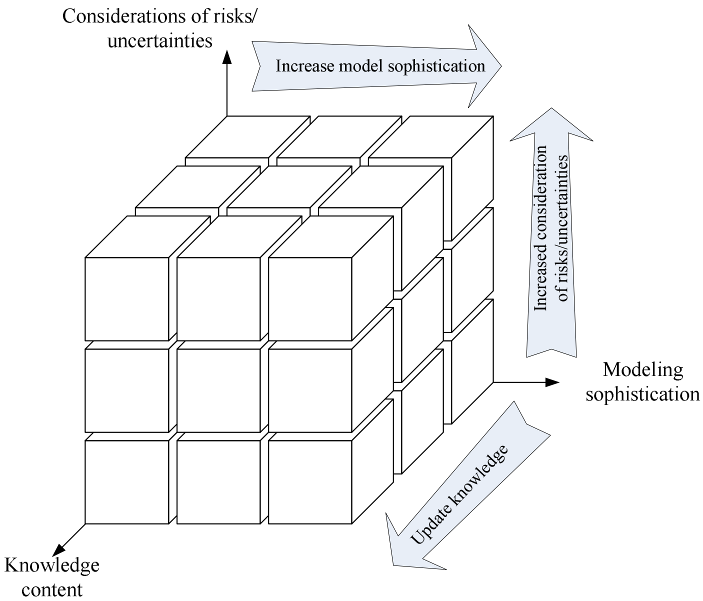

Figure 2. Three factors governing levels of enhanced condition assessment.

The third factor, knowledge/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/or the loads acting upon it, and thus do away with potentially unneeded conservative modelling 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 modelling sophistication. For example, in a deterministic assessment it may alter the value of some of the modelling parameters while for reliability based assessments the information may be directly integrated using Bayesian updating.

3.2 Decisions concerning condition assessment

The initial assessment which determined a bridge whose condition is in doubt can be viewed as the origin in Figure 2. Increasing the level of any one of these factors, either individually or in combination, is a strategy for improved and more informed decision making. In other words, an enhanced assessment essentially involves moving further away from the origin. Utilizing the cube in a decision making context then requires specific attentions to one or more of the following questions:

1. How can we determine which method is most suitable for the case being studied (i.e. can we determine a quadrant of the cube which is more suited than others)?
2. Are there methods which, for one reason or another, are less appropriate; e.g. due to higher degrees of uncertainty, high costs of implementation, or given certain preconditions are not fulfilled?
3. Is there an optimal way of navigating the cube?

Generally speaking, moving further away from the origin will require resources. Optimum decision making concerns determining a decision which achieves the greatest benefit (in terms of improved performance) in relation to the resources required (considering that these are limited).

4 CASE STUDY

In this section a conceptual case study is used to better explain the concept of the 'assessment cube' and successive navigation along its axes. The case builds upon a fatigue assessment of a specific bridge detail. The general approach presented in Section 3 is, however, applicable to various other deterioration phenomena and bridge types.

4.1 Step 1: Initial assessment

A natural first step is an initial assessment which can be viewed as the origin in Figure 2. In Sweden, this is typically performed in accordance with the regulation for assessment of existing bridges issued by the Swedish Transport Administration (Trafikverket, 2016). It prescribes a deterministic verification format based on characteristic strength and load effect. The verification is depicted by a safety margin M calculated as

$$M = \frac{\Delta\sigma_{\mathrm{C}}}{\gamma_{\mathrm{Mf}}} - \gamma_{\mathrm{Ff}}\, \Phi\, \Delta\sigma_{\mathrm{E}} \qquad (1)$$

where $\Delta\sigma_{\mathrm{C}}$ is the characteristic fatigue strength, Φ is a dynamic amplification factor, $\Delta\sigma_{\mathrm{E}}$ is a damage equivalent stress range representing the load effect, and the γ factors are partial safety factors. The safety margin is equivalent to the verification format in the Eurocode EN 1993-2. The calculation of the safety margin and, hence, an estimation of the load carrying capacity of the detail is readily performed using information from drawings and load models from the regulations. This step can be performed as a pure desktop assessment.

4.2 Step 2: Update knowledge

The next step to enhance the assessment is, in this case, selected as advancement along the knowledge axis in Figure 2. Considering fatigue, the load effect is a source of large uncertainties which has a decisive influence on the service life predictions. By monitoring strains at critical locations, the influence of dynamics and the response of the bridge due to real traffic can be recorded (or updated based on published studies). The result is that Φ and $\Delta\sigma_{\mathrm{E}}$ from (1) can be replaced with a measured estimation of the stress range. Leander et al. (2015) showed that the partial safety factors suggested for deterministic fatigue assessment are appropriate also when measured response is considered.

It should be noted that the measured response has to be converted to a stress range spectrum by some cycle counting method. It might also be appropriate to reformulate the verification format conforming to the Palmgren–Miner rule. However, this is a straightforward operation described in many regulations and guidelines.

4.3 Step 3: Consideration of uncertainties

The preceding steps are based on deterministic verifications using characteristic values and partial safety factors. A consideration of the uncertainties of the variables and a probabilistic safety format enables an alternative assessment based on acceptable failure probabilities or target reliabilities. This represents advancement along the axis denoted 'consideration of uncertainties' in Figure 2. The assessment can be depicted by a limit state equation formulated as

$$g(\mathbf{x}, N) = N_\mathrm{c}(\mathbf{x}) - N \tag{2}$$

where $N_\mathrm{c}(\mathbf{x})$ represent the resistance and can be estimated by, e.g., the Palmgren–Miner rule for the stochastic variables in $\mathbf{x}$, and N is the number of accumulated cycles. A state of failure is defined as $g(\mathbf{x}, N) \leq 0$ and the probability of failure can be estimated as $P_f = P[g(\mathbf{x}, N) \leq 0]$. This approach enhances the possibility to utilize the potential in measured response by considering uncertainties related to the monitoring explicitly.

4.4 Step 4: Increasing model sophistication

The Palmgren–Miner rule incorporated in the governing regulations is based on a linear accumulation of fatigue damage. It is, however, well known that the initiation and propagation of fatigue cracks is a nonlinear process. A model based on linear elastic fracture mechanics (LEFM) enables a possibility to replicate this process. However, since it is not supported in the governing standards for assessment of bridges there is no established safety format at hand. Therefore, it is recommendable to combine this step with a probabilistic safety format as suggested in the preceding step. The limit state equation (2) will be the same but the resistance $N_\mathrm{c}(\mathbf{x})$ must be determined based on LEFM together with adequate stochastic variables in $\mathbf{x}$.

4.5 Step 5: A further update of knowledge

The model based on LEFM described in Step 4 considers the physical size of a crack which can be compared with result from inspections. With a stochastic description of a detection event $H_\mathrm{D}(\mathbf{x})$, a prior estimation of the failure probability can be updated as

$$P_\mathrm{f}^\mathrm{U} = P[g(\mathbf{x}) \leq 0 | H_\mathrm{D}(\mathbf{x})] = \frac{P[g(\mathbf{x}) \leq 0 \cap H_\mathrm{D}(\mathbf{x})]}{P[H_\mathrm{D}(\mathbf{x})]} \tag{3}$$

where $H_\mathrm{D}(\mathbf{x})$ can be formulated to describe detection, no detection, or a sizing event (Madsen et al. 2006).

4.6 Step 6: Risk based decision support

Decisions on what steps to take in the assessment can be made intuitively but should be based on objective grounds. Here, a risk-based approach is suggested following the principle of pre-posterior decision analysis. It corresponds to a further advancement along the uncertainties/risk axis in Figure 2. Pre-posterior analysis provides a consistent and systematic framework for evaluating the cost/risk of different possible decisions before they have been made. It also facilitates an identification of optimal decisions regarding assessment activities. The expected outcome is a path in the decision tree suggesting the options giving the highest benefit or lowest expected cost. In the presented case study the decision is restricted to following options, i.e.: 1) increase model sophistication, 2) update knowledge by inspection, 3) enhance uncertainty consideration and 4) stop enhanced assessment and intervene or do nothing. Based on the random outcome of these options another decision follows. Applications to related problems can be found in, e.g., Sørensen (2009) and Goyet et al. (2013).

5 CONCLUSIONS

A framework for classification of actions for condition assessment of bridges has been proposed. The three factors: 1) model sophistication, 2) uncertainty/risk consideration, and 3) knowledge content have been identified as key parameters. The purpose of this distinction is to elucidate how different actions can be incorporated in an enhanced assessment and how these influence the overall estimation of the condition.

The framework can be visualised as a cube depicted in Figure 2. A conceptual case study have been presented describing how the framework can be used to structure the assessment actions of a steel bridge subjected to fatigue deterioration.

The ultimate goal of the presented framework is to support decision on maintenance and upgrading actions on bridges, thus it could be extended to include the possibilities of actual interventions. A proposal considering pre-posterior decision analysis has been mentioned. This possibility will be further explored in the project.

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