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Risk-based planning of assessment actions for fatigue life prediction

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Abstract

It is vital to extend the service life of existing bridges as far as possible as a means for improved sustainability leading to reduced economic cost and resource consumption. This requirement is especially valid for bridges which are critical components of highly vulnerable infrastructure systems. Achieving this aim requires enhanced methods involving various actions and methods influencing different aspects of the assessment process. A framework is presented in this paper based on three common factors used to describe the assessment actions of existing bridges; (i) model sophistication, (ii) uncertainty consideration, and (iii) knowledge content. The framework elucidates the influence of different decisions on the assessment process and facilitates the planning of appropriate assessment actions. Furthermore, it provides a basic scheme for a risk-based decision analysis for determining suitable assessment actions or activities. A fatigue assessment of an existing bridge detail is used to demonstrate the application of the framework in practical cases.

1. Introduction

Bridges are crucial parts of every infrastructure system and their functionality must be maintained to secure important communication routes. This will become an increasing challenge for most countries with a developed

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infrastructure due to an increased number of bridges approaching their expected service life. For sustainability reasons the aim should be to extend the service life of the existing bridges as far as possible, before replacing them with newly built structures. This will require the use of sophisticated methods for assessment and service life prediction. Several large research projects have been aimed at these issues, e.g., BRIME (2001), Sustainable Bridges (2007), FADLESS (2014), and MAINLINE (2014). Advanced methods for assessment have been developed for various degradation phenomena and guidelines for monitoring and inspection have been produced. These methods are, however, rarely implemented in conventional assessments of existing bridges. Strict regulations may be one obstacle impeding the practical application of pioneering methods. Another is the lack of an established framework that supports decision makers to request and procure advanced assessment actions.

This paper is limited to fatigue assessment of existing steel bridges. Guidelines on how to evaluate the influence of fatigue propose flowcharts of stepwise procedures which starts with a preliminary evaluation, typically based on a deterministic comparison of stress levels, an intermediate step based on linear damage accumulation, and a final step based on fracture mechanics and a probabilistic verification format, e.g., Sustainable Bridges (2007) and Kühn et al. (2008). The current paper aims to represent the assessment process according three dimensions, as suggested by Honfi et al. (2017) and reproduced in Fig. 1. This representation builds on three factors, (i) model sophistication, (ii) uncertainty consideration, and (iii) knowledge content. Adopting this approach elucidates that improvements of the condition assessment can be reached by different measures, that do not necessarily involve more complex models in all aspects. This framework facilitates decisions on actions that can be focused on specific issues within the assessment procedure which will eventually lead to more accurate predictions.
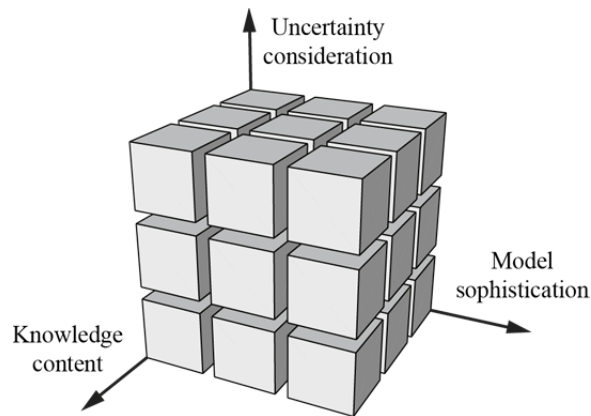

Fig. 1. A graphical presentation of the three factors describing a condition assessment. Reproduced after Honfi et al. (2017).

To support decision making, in beforehand on what assessment actions to pursue, an approach based on preposterior analysis is suggested in this paper. It is based on Bayesian decision theory, explained by Benjamin and Cornell (1970) as a posterior analysis where the outcome of experiments is considered, but before the experiments have been performed.

This paper presents an application of the assessment framework depicted in Fig. 1 combined with a preposterior decision support analysis. The application is demonstrated using a case study, the Söderström Bridge, a railway bridge in the city center of Stockholm, Sweden.

2. Condition assessment framework

Assessing the condition of a structure can involve a number of different decisions. A categorization of the different decisions to increase the level of assessment proposed in Honfi et al. (2017) and depicted in Fig. 1 is briefly described in the following sections.

2.1. Model sophistication

An assessment has to be based on some performance model of the structure and/or the deterioration process to inquire. The modeling sophistication is a measure of how complex the model is, typically based on how many variables it contains or how it represents the behavior of the structure. More sophisticated models may 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 in Fig. 1.

2.2. Uncertainty consideration

Uncertainty consideration can be distinguished between three main levels: deterministic, reliability-based, and risk-based assessments. Conventional assessments based on the regulations are typically performed using characteristic loads and material strengths, together with a verification based on partial safety factors. This format is characterized as deterministic within the current framework. Moving along the uncertainty consideration axis in Fig. 1 leads to a reliability-based assessment. This approach enables an explicit consideration of the uncertainties through stochastic variables and an assessment against an acceptable probability of failure. A risk-based assessment is a further advancement along the same axis. This allows a consideration of the costs, consequences and possibly even the benefits associated with identified damage and/or failure scenarios.

2.3. Knowledge content

Knowledge or information content describes 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 will 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 uncertainty considerations as well as the modeling sophistication.

2.4. Decisions concerning condition assessment

A conventional initial assessment can be viewed as the origin in Fig. 1. Advancement along any of the three axes involves an improved and more accurate condition assessment. Hence, moving away from the origin implies more informed decisions on further actions. However, advancement along any of the axes will also require additional resources leading to increased costs. By estimating probabilities of random events and assigning utility values to possible outcomes, an optimal route through the assessment cube can be determined with the aid of reposterior analysis. This approach is explained in relation to the case study in the following section.

3. Fatigue assessment of a bridge detail

The assessment of a fatigue critical detail from the Söderström Bridge in Sweden is used to demonstrate the practical application of the proposed assessment framework. This bridge has been subject to extensive assessment actions due to documented fatigue damages. A presentation of the bridge and the assessment actions can be found in Leander et al. (2010). The case study concerns the welded connections between the lateral bracing and the top flanges of the stringer beams. Despite indications of an exhausted fatigue life, no cracks have been found at any of these connections. A part of the bridge is shown in Fig. 2 together with an idealized visualization of the connection.

3.1. Initial assessment

An initial assessment should comply with the governing standards using information from drawings and load models from the regulations such as the Eurocode. Fatigue assessments are typically based on the safe life method

(a) A plan view of a part of the Söderström Bridge.   (b) The critical detail.
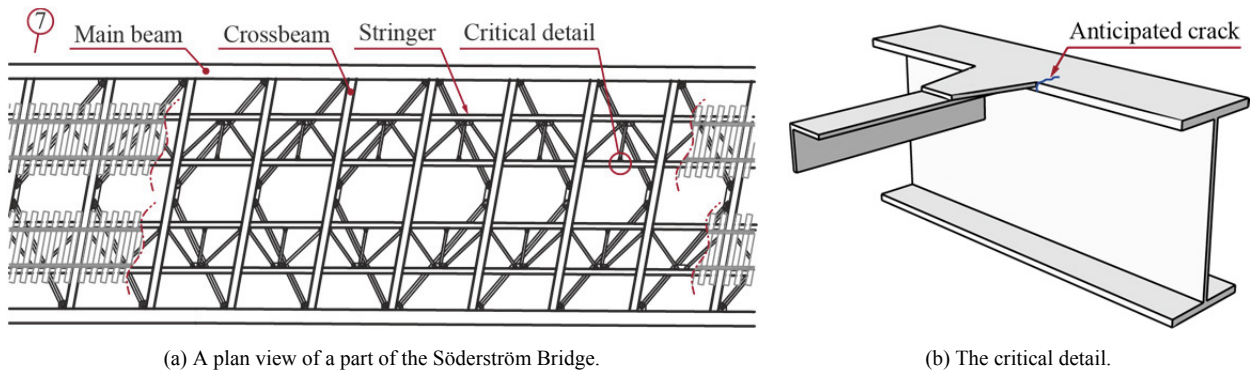
Fig. 2. The welded connections between the lateral bracing and the top flanges of the stringer beams is one of the critical details in the bridge..

considering fatigue endurances from tests and linear damage accumulation. This method is relatively simple and includes few variables. This step can be performed as a pure desktop assessment and is not treated further in this paper.

3.2. Model sophistication

The accuracy of the assessment could be improved by more detailed studies on both the load effect side and the resistance side. As an example, the stress range could be determined using a more sophisticated model for the structural analysis. Another improvement would be to adopt a verification format based on accumulated damage and an estimation of the load history. These improvements are supported by the regulations and can be performed using existing information. For this specific detail in the Söderström Bridge, more effort on structural analyses and prediction models has more or less confirmed the rather discouraging result attained with the simple assessment presented above, see e.g. Leander et al. (2010).

A prediction model based on linear elastic fracture mechanics (LEFM) is an increase of the model sophistication level. It enables a consideration of fatigue crack propagation as a nonlinear process. A safety margin based on number of cycles to failure can be expressed as

$$M_{\mathrm{FM}} = \int_{a_0}^{a_c} \left(\frac{da}{dN} \right)^{-1} da - N \tag{1}$$

where a_0 is the initial crack depth, a_c is the critical crack depth representing the final failure of the detail, da/dN is the crack growth rate, and N is the total number of accumulated cycles. Guidelines on how to perform a deterministic analysis can be found in BSI (2013). A stress intensity factor range (SIFR), on which the crack growth rate is dependent, is suggested by Leander et al. (2013) for the specific detail studied. A superficial verification using this model has also shown an exhausted fatigue life. Thus, for the current case, a higher level of model sophistication still does not provide any appreciable improvement in service life.

3.3. Uncertainty consideration

The governing regulations suggest a deterministic safety format based on characteristic values and partial safety factors. An advancement along the uncertainty consideration axis is to adopt a reliability-based assessment as suggested in, e.g., JCSS (2013). A further enhancement is a risk-based assessment treated in, e.g., Sørensen (2009) and Goyet et al. (2013). A general limit state equation for fatigue assessment can be formulated as

$$g(\mathbf{x}, N) = N_c(\mathbf{x}) - N \tag{2}$$

where $N_c(\mathbf{x})$ represent the resistance as the number of cycles to failure and N is the total number of accumulated cycles. A state of failure is then defined by $g \leq 0$ and the probability of failure as

$$P_f = P[g \leq 0] \tag{3}$$

The reliability index β is related to the probability of failure as $\beta = -\Phi^{-1}(P_f)$. The reliability, or equivalently the associated probability of failure, can be estimated using conventional reliability methods such as FORM, SORM or a simulation based method. However, it should be noted that the limit state equations can be strongly nonlinear, especially if LEFM is considered, and as such, the use of FORM may not be appropriate.

For a performance model based on linear damage accumulation, a limit state based on accumulated damage is often preferred. Reformulating and expanding (2) gives

$$g(\mathbf{x}, N) = \delta - \frac{1}{K_1} \sum_i n_i \left(C_S S_{r,i} \right)^{m_1} - \frac{1}{K_2} \sum_j n_j \left(C_S S_{r,j} \right)^{m_2} \tag{4}$$

A description of the limit state equation (4) can be found in Leander el al. (2015). For a performance model based on LEFM, the limit state equation (2) is applicable with $N_c(\mathbf{x})$ determined by integration of the expected crack growth $E[da/dN]$ from the initial crack depth a_0 to a critical crack depth a_c. The expected crack growth rate can then be expressed as (JCSS, 2011)

$$E\left[\frac{da}{dN}\right] = A_a E\left[S_r^{m_a} \right]_{S_{th}}^{S_{ab}} \left(C_S C_{SIF} \sqrt{\pi a}\, Y(a) M_k(a) \right)^{m_a} + A_b E\left[S_r^{m_b} \right]_{S_{ab}}^{S_\infty} \left(C_S C_{SIF} \sqrt{\pi a}\, Y(a) M_k(a) \right)^{m_b} \tag{5}$$

A complete description of the limit state equation for LEFM can be found in Leander el al. (2016). Stochastic variables used for the current case are listed in Table 1 together with their distributions, mean values and coefficients of variation (CoV). These properties are essentially as suggested by JCSS (2013).

Table 1. Stochastic variables. N~Normal, LN~Lognormal , DET~Deterministic.

Linear damage accumulation				Linear elastic fracture mechanics (LEFM) (Crack growth in mm/cycle and stress intensity in MPa(m)$^{1/2}$)			
Variable	Distribution	Mean	CoV	Variable	Distribution	Mean	CoV
δ	LN	1	0.3	C_S	LN	1	0.04
C_S	LN	1	0.04	C_{SIF}	LN	1	0.07
$\ln K_1$	N	26.5	0.49	A_a	LN	4.80×10^{-18}	1.70
K_2	Fully correlated to K_1			A_a	LN	4.80×10^{-18}	1.70
m_1	DET	3	-	m_a	DET	5.10	-
m_2	DET	5	-	m_b	DET	2.88	-
				K_{th}	LN	140	0.40
				a_0	LN	0.15	0.66
				a_c	DET	113	-

3.4. Knowledge content

Additional knowledge or information regarding the actual physical state of the bridge can be directly integrated with the reliability-based models described in Sec. 3.3. In this case study, a stress range spectrum determined by

monitoring was considered in both performance models. Strains measured close to the critical detail have been recalculated to stresses and a cycle counting has given the stress range spectrum shown in Fig. 3(a). The stress ranges and the number of cycles were considered as deterministic values. The uncertainty of the measured response was considered by the model uncertainty C_S listed in Table 1. The results of the reliability analyses are presented in Fig. 3(b). For a target reliability of $\beta = 3.1$ the fatigue life was estimated to 8.6 million and 20 million cycles based on linear damage accumulation and LEFM, respectively. In service life it corresponds to about 3 and 7 years, respectively.

(a) Stress range spectrum based on 39 days of strain measurements.　　　(b) Estimated reliability.
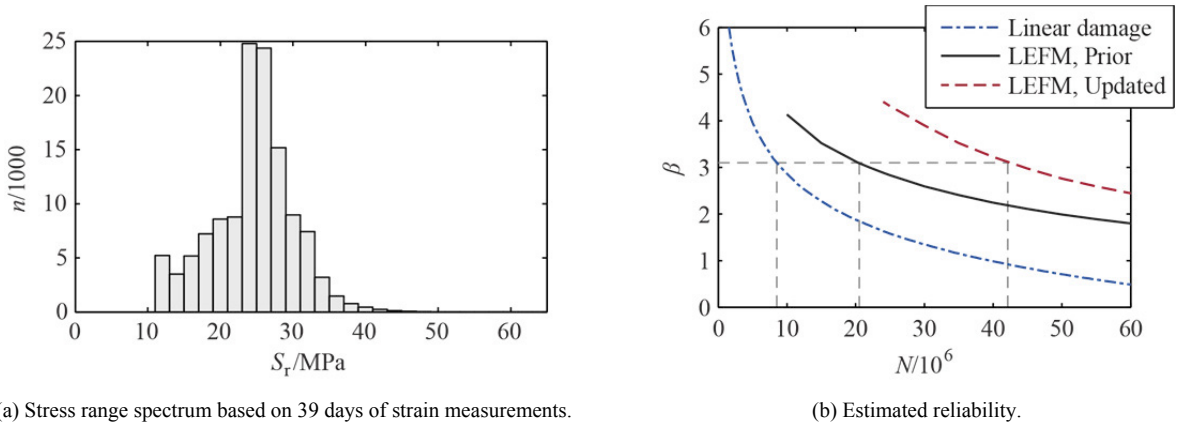
Fig. 3. A welded connections between the lateral bracing and the top flange of a stringer beam.

The model based on fracture mechanics allows an updating of the reliability considering results from inspections. The preferred and most common outcome of an inspection is that no crack is detected. The inspection itself is, however, contains uncertainties which must be considered in the evaluation of the result. The updating of the probability of failure can be expressed as a conditional probability using Bayes' theorem (Madsen et al., 2006)

$$P_f^U = P\left[g\left(\mathbf{x}\right) \leq 0 \mid H_D\left(\mathbf{x}\right) \leq 0\right] = \frac{P\left[g\left(\mathbf{x}\right) \leq 0 \cap H_D\left(\mathbf{x}\right) \leq 0\right]}{P\left[H_D\left(\mathbf{x}\right) \leq 0\right]} \tag{6}$$

where P_f^U is the updated probability of failure and $H_D(\mathbf{x})$ is a detection event that can be expressed as

$$H_D\left(\mathbf{x}\right) = a\left(\mathbf{x}, N_i\right) - a_d \tag{7}$$

where $a(\mathbf{x}, N_i)$ is the estimated crack depth at N_i cycles and a_d is the lower level detectability which is typically called the probability of detection (PoD). In the case study, the PoD curve suggested in DNV GL (2015) for magnetic particle testing was used, considering good conditions above water during inspection. Assuming an inspection at 20 million cycles with no detected crack, the updated reliability is shown in Fig. 3(b). For a target reliability of $\beta = 3.1$ the fatigue life increases from 20 to 42 million cycles.

4. Risk-based planning of assessment actions

The initial assessment indicated an exhausted fatigue life. The subsequent assessment actions are more or less academic exercises in an endeavor to determine the remaining fatigue life as accurately as possible. The question is whether these actions can be motivated from the perspective of a decision maker. A risk-based evaluation using preposterior analysis is suggested in this paper. The theoretical method was proposed already by Benjamin and

Cornell (1970), as a support tool for decisions related to the civil engineering industry. It has, however, gained little attention outside the research community.

Two decision alternatives are considered here; however, the procedure can easily be extended with more alternatives. The first decision alternative is limited to a reliability-based fatigue assessment based on linear damage accumulation, without any consideration of inspections. The second alternative is an assessment based on LEFM and a consideration of results from an inspection. The aim of the assessment is to prove a sufficient reliability for a service life of 60 million cycles.

The decision alternatives are depicted as a decision tree in Fig. 4 where the assessment actions are denoted A_0 to A_n, the random outcome of the inspection is denoted z_0 if no crack is found and z_1 if a crack larger than a_d is found, the maintenance depending on the outcome z is denoted M_0 if no maintenance is required and M_1 if a repair action is required. The true state of the detail is denoted θ_0 representing no failure and θ_1 representing failure. To the right, utilities are listed including costs due to the assessment actions, maintenance actions and the true state of the detail.

The utilities in Fig. 4 were assigned the tentative values of -1000 for failure of the detail, -100 for maintenance action M_1, and -1 for the assessment action A_1. The probabilities of the true states θ_1 were assigned values estimated in the previous sections. A prior estimation of $P[\theta_1|A_0] = 0.3$ based on linear damage accumulation was considered. A posterior probability of $P[\theta_1|z_0, A_1] = 0.01$ was assumed for the event of no detected crack, and $P[\theta_1|z_1, A_1] = 0.12$ for the event of a detected crack. The latter was estimated by using the complement to the detection event (7) in the updating of the probability of failure with (6). The probability $P[z_0|A_1]$ was determined as (Benjamin and Cornell, 1970)

$$P\left[z_0 \mid A_1\right] = P\left[z_0 \mid A_1, \theta_0\right]P'\left[\theta_0\right] + P\left[z_0 \mid A_1, \theta_1\right]P'\left[\theta_1\right] \qquad (8)$$

where $P[z_0|A_1,\theta_0]$ is the likelihood of z_0 on the condition that A_1 and θ_0 occurs, and $P'[\theta_0]$ is the prior probability of θ_0. In the case study, a low expectation on the accuracy of the assessment method was assigned reflected by a likelihood of 0.5. This gave a probability of $P[z_0|A_1] = 0.5 \times 0.7 + 0.5 \times 0.3 = 0.5$ which is assigned to the z_0 branch in Fig. 4. The other probabilities are assigned in a consecutive maner.
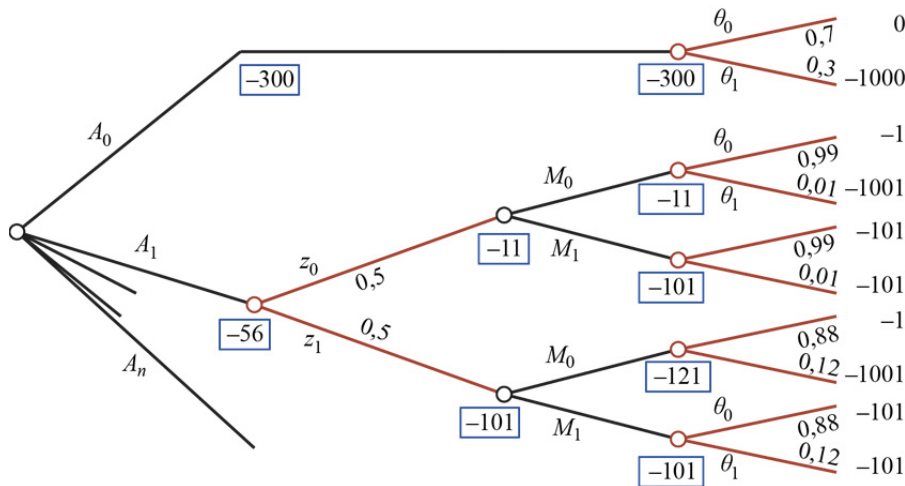

Fig. 4. A decision tree covering two assessment actions A_0 and A_1.

When all probabilities and utilities are assigned, the expected utility can be calculated for each assessment decisions. The result shows that the expected utility is -300 and -56 for assessment action A_0 and A_1, respectively. This means that the assessment based on LEFM together with inspections gives a lower expected cost, despite the extra cost of the assessment action. From the perspective of a decision maker it would be beneficial to procure the

more detailed assessment based on LEFM. It should, however, be noted that the result is valid for this specific case study and the tentative utility values.

In the assessment of bridges, an acceptable probability of failure should be included as a conditional value in the risk-based analysis. In the case study, the tentative values can in this respect be questionable.

5. Conclusions

The contribution of this paper is a framework that enables a distinction between the influences of different assessment decisions. It builds on three factors, (i) model sophistication, (ii) uncertainty consideration, and (iii) knowledge content. The framework is aimed to facilitate the procurement of enhanced assessments of existing structures.

The fatigue assessment of a bridge detail is used to demonstrate the practical application of the framework. Examples of different levels within the three assessment factors are provided.

A risk-based analysis is also suggested as a complement to the assessment framework to support decisions on appropriate assessment actions.

Acknowledgements

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