Added value of regular in-service visual inspection to the fatigue reliability of structural details in steel bridges

Bahman HASHEMI [1], Johan MALJAARS [1], H.H. (Bert) SNIJDER [1]

[1] Eindhoven University of Technology, Eindhoven, Netherlands

Contact e-mail: s.b.hashemi@tue.nl

ABSTRACT: In order to design structural details of bridges for fatigue, the current version of the Eurocode for steel structures recommends partial factors for fatigue resistance based on the consequences of failure and on the maintenance method. The safe-life method is used for details where local formation of cracks could rapidly lead to failure or for details not accessible for inspection and has a relatively high partial factor. The damage tolerant method, on the other hand, is used for cases where fatigue crack initiation does not result in immediate failure so inspection and repair can be performed. In the current Eurocode, this comes with a relatively low partial factor. However, since the probability of crack detection of visual inspection by the naked eye is considerably different from more detailed inspection methods, the required partial factor to design a bridge for fatigue should be based on the way and level of inspection planned during the bridge service life. As a common practice, for most bridges, only visual inspections in short time intervals are carried out. In this paper, the added value of periodic visual inspection on the reliability status of a steel railway bridge is studied. The probability of failure after performing visual inspection is investigated by two approaches: 1) A statistical study on the main causes of bridge failure carried out by other researchers to find the relation between the safe-life design method and the design method considering visual inspection; 2) Conducting a survey to collect experts opinions on the matter and using a Bayesian algorithm to assign a probability distribution function to each opinion. A relation between reliability indices for the cases where a bridge is designed with and without considering the in-service visual inspection, is derived.

1 INTRODUCTION

Fatigue is a dominant failure mode for structures such as railway bridges subjected to time varying loading. Several empirical or semi-analytical fatigue resistance models have been developed since the 19th century. Among them, the most common ones to assess the fatigue life of welded steel details are the nominal stress-life model, also known as the S-N model, and the linear elastic fracture mechanics (LEFM) model. For details where local formation of cracks could rapidly lead to failure or for details not accessible for inspection, the final fatigue life can be calculated by using an S-N model. On the other hand, for the details where fatigue crack initiation does not result in immediate failure, general in-service inspection intervals can be determined during the design Phase and LEFM model can be used to update the reliability status based on the inspection and possible repair results (Lotsberg, Sigurdsson, Fjeldstad, & Moan, 2016). In the Eurocode standard for designing steel structures (EN1993-1-9, 2005), these design methods are referred to as the safe-life method and the damage tolerant method, respectively. According to the rules in EN 1993-1-10, between 0 and 3 inspections are required during the life of the structures (EN1993-1-10, 2005). However, in practice, most bridge owners perform visual in-service inspection every 5 to 10 years. Visual inspection is a highly subjective nondestructive evaluation technique and its

results can be highly variable and be dependent of many factors such as inspector's skills, weather condition, traffic condition, accessibility of the bridge and level of detail of the visual inspection. Nevertheless, due to its relatively low cost, it can be a strong tool to evaluate the general condition of the bridge as well as to plan detailed inspections. Although, the fatigue crack size, in case of detection, can be estimated with visual inspection, the LEFM model can only be used to evaluate the remaining fatigue life of the structures and update the safety status of the bridge with some uncertainty. However, using visual inspection still may provide a higher level of reliability than a design situation without any inspection planned during the service life (safe-life method). Therefore, it is expected that the reliability status of bridges with regular visual inspections planned for them, is in between that for bridges inspected with accurate crack detection techniques, and that of the safe-life method. In standards based on the limit state condition such as the Eurocode, partial factors are recommended to make sure the designed structure meets the minimum safety requirements. The general equation for the design of a structural component according to the Eurocode standard (EN1990, 2002) is;

$$\frac{R_c}{\gamma_M} - \gamma_F \times E_c \geq 0 \qquad \rightarrow \qquad R_d \geq E_d \tag{1}$$

where R_c and R_d are the characteristic and design values of the material resistance respectively, E_c and E_d are the characteristic and design values of the load effect, γ_M is the partial factor for the resistance and γ_F is the partial factor for the load effect. In the Eurocode system for fatigue design of bridges (EN1991-2, 2003), a partial factor larger than 1 is recommended only on the resistance side of the limit state (γ_{Mf}) and the partial factor on the load side (γ_{Ff}) is recommended as 1. The factor γ_{Mf} depends on the choice of fatigue assessment method as well as the consequences of failure. Table 1 shows the fatigue resistance partial factors according to EN 1993-1-9.

Table 1. Partial factors for material fatigue resistance of EN 1993-1-9

Assessment method	Consequences of failure	
	Low	High
damage tolerant	1.00	1.15
safe-life	1.15	1.35

A bridge structure is mostly categorized as a structure with high consequence of failure both in terms of cost and human safety.

There are some shortcomings in Eurocode's recommendation. For instance, the standard does not provide the method and interval of inspections for the damage tolerant approach and the accuracy and reliability of the visual inspection are not addressed. Thus, there should be another set of partial factors to design the bridges for fatigue when only regular in-service visual inspection is planned during their service life.

In this paper, the reliability status of bridges with regular visual inspection is studied by two approaches; 1) A statistical study on the main causes of bridge failure carried out by other researchers (Imam & Chryssanthopulos, 2010) to find the relation between the safe-life design method and the design method considering visual inspection; 2) Conducting a survey to collect experts opinions on the matter and using a Bayesian algorithm (Bolstad, 2010) to assign a probability distribution function to each opinion. These two approaches provide insight into the added value of performing in-service visual inspection with respect to safe-life design method.

2   METHODS

To find the relation between the reliability status of bridges designed by the safe-life method and designed including visual inspection, a common scenario is assumed in which, a bridge is

designed for a life of 100 years and at some point in service life, a fatigue crack occurs. With the assumption of visual inspection being performed with an interval of 5 to 10 years, the probability that the fatigue crack is detected before catastrophic failure occurs should be estimated. This probability is shown by $P_{\det|crack}$ in this paper. Following approaches are used to estimate this probability.

2.1   Statistical study

In 2010, Imam and Chryssanthopoulos published a review of bridge failure statistics, based on a literature survey and a web-based search. In their review, failure cases are distinguished between those resulting in bridge collapse and those that have not reached collapse but resulted in loss of serviceability. In addition, classification of the most common failure causes and modes of failure is undertaken in their study. Out of 164 detected failure cases, 87 cases are classified as collapsed and 73 cases are classified as non-collapsed. The share of fatigue as a main cause of failure for each class is shown in Figure 1.
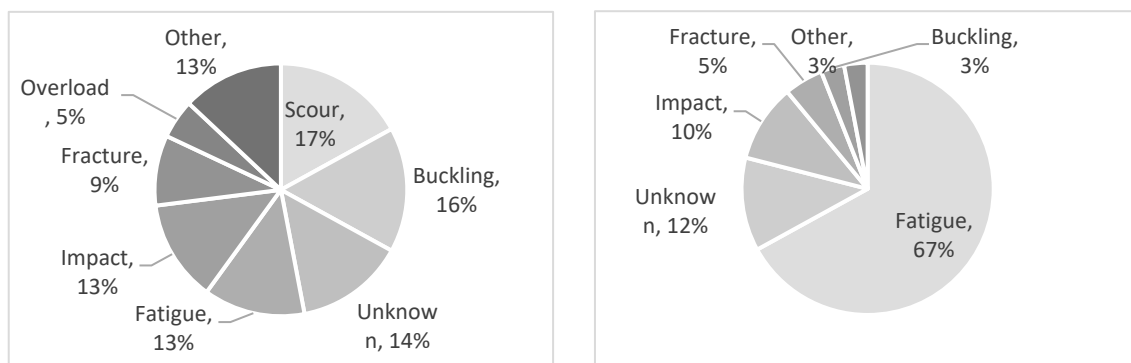

Figure 1. Main cause of failure for metallic bridges: collapsed structure (Left) and non-collapsed structure (Right)

It can be observed that out of 73 non-collapsed failure cases, 67% (49 cases) are related to fatigue. Also, out of 87 collapsed failure cases, 13% (11 cases) are related to fatigue. In can be conclude that in total, 60 bridges or bridge details suffered from fatigue failure but in 81% of the cases, fatigue damage was detected before catastrophic failure occurs i.e. $P_{\det|crack} = 0.81$. However, these results are biased i.e. the inspection method and interval may differ. Also, it is likely that almost no catastrophic collapses have been missed in the survey but more non-collapsed cases might not have been reported. Furthermore, the resistance of structural details for fatigue cracking as well as the redundancy of the bridges are different.

2.2   Experts opinions

24 members of the CEN/TC250/SC3 Working Group on EN 1993-1-9 have been asked about the added value of the periodic visual inspection. The members are all European experts in the field of fatigue. They were asked to estimate the probability that a fatigue crack is detected by regular visual inspection before catastrophic failure occurs for a bridge designed for a life of 100 years with the assumptions that a fatigue crack occurs in service and the general visual inspection is performed with an interval of 5 to 10 years. Their answers are presented in Table 2. The challenge is to obtain a single probability value based on these results. The Bayesian approach is selected for this purpose.

Table 2. Experts opinion

	Option	Number of votes
A	Less than 20 %	1
B	20 % to 50 %	9
C	50 % to 80 %	9
D	More than 80 %	5

The Bayes Theorem describing the probability of an event, based on prior knowledge of conditions which are related to the event and for a general case of independent events A and B, is presented by following equation;

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \tag{2}$$

where P is the notion for probability, $P(A|B)$ is the posterior probability i.e. the probability of event A occurring given that B is true, $P(B|A)$ is the likelihood and $P(A)$ and $P(B)$ are the marginal probabilities of events A and B, respectively. The idea is to update a primary knowledge based on the observation of the new data. In this study a uniform distribution is assumed for the primary knowledge which is the probability of detecting cracks before collapse. a binomial equation is used for the likelihood function in a way to include the expert's opinion. The likelihood distribution investigates the probability of detecting the crack having the value of any option in Table 2. The general binomial equation is as follow:

$$P(x = k) = \binom{n}{k} P^k (1-p)^{n-k} \tag{3}$$

Which means if a test is repeated n times, what is the probability that the desired outcome happens k times if p is the probability of the desired outcome happening once. With these assumptions, the posterior is expected to have a normal distribution described by the following equation;

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}(\frac{x-\mu}{\sigma})^2} \tag{4}$$

where μ and σ are the mean and standard deviation of the normal distribution, respectively.
In this study the desired outcome is detecting the crack before collapse and it is desirable to know the probability that the crack is detected in i % of the cases. The likelihood distribution can be calculated as following:

$$p = 0.01: P(x = i|p = 0.01) = \binom{100}{i} 0.01^i 0.99^{100-i}$$

$$p = 0.02: P(x = i|p = 0.02) = \binom{100}{i} 0.02^i 0.98^{100-i} \tag{5}$$

$$\dots$$

$$p = 0.5: P(x = i|p = 0.5) = \binom{100}{i} 0.5^i 0.5^{100-i}$$

$$\dots$$

$$p = 0.99: P(x = i|p = 0.99) = \binom{100}{i} 0.99^i 0.02^{100-i}$$

$$p = 1: P(x = i|p = 1) = \binom{100}{i} 1^i 0^{100-i}$$

As an example the calculations for option B of Table 2 are presented here;

$$P(x \geq 20\% \cap x \leq 50\%) = P(x = 20\% \cup x = 21\% \dots \cup x = 50\%) = \sum_{i=20}^{50} P(x = i) \tag{6}$$

where $P(x = i)$ is calculated as in (5).

The likelihood function should have the normal distribution. Therefore, its parameters are selected in such a way that the integral of the equation (4) be equal to 1. In other words, $P(B)$ in equation (2) is selected to normalize the likelihood function.

Figure 2 shows the probability distribution functions of the posterior for each option with their parameters.

Option A: $\mu = 20.59 , \sigma = 3.98$

Option B: $\mu = 50 , \sigma = 4.93$

Option C: $\mu = 79.41 , \sigma = 3.98$
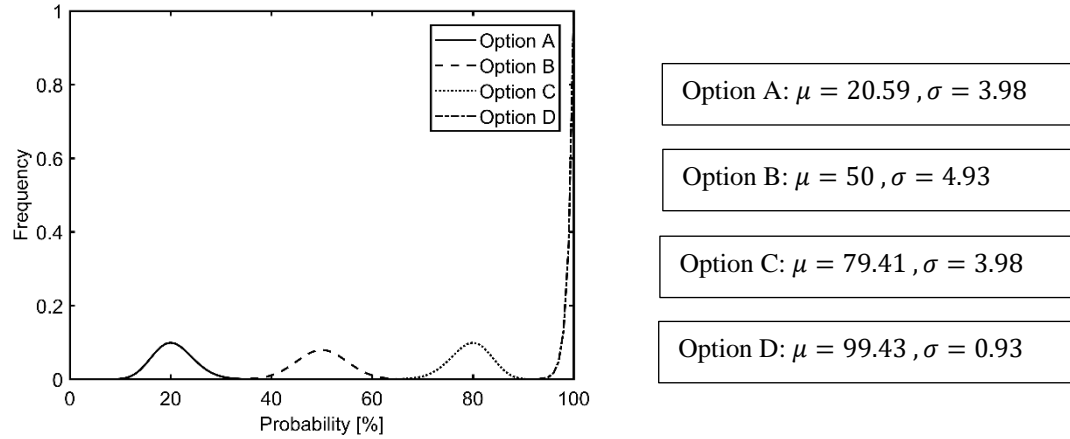
Option D: $\mu = 99.43 , \sigma = 0.93$

Figure 2. Probability distribution functions of posteriors based on experts opinions of Table 2

The number of votes for each option can be used as the weight (w) of that option. Having the probability distribution function (*f(x)*) and weight of each opinion, the probability that the crack is detected before the catastrophic failure occurs is calculated as follow:

$$\begin{cases} \text{option A: } P_1 = \int_0^{20} f(x)dx = 0.44, & w1 = 1/24 \\ \text{option B: } P_2 = \int_{20}^{50} f(x)dx = 0.5, & w2 = 9/24 \\ \text{option C: } P_3 = \int_{50}^{80} f(x)dx = 0.56, & w3 = 9/24 \\ \text{option D: } P_4 = \int_{80}^{100} f(x)dx = 1, & w4 = 5/24 \end{cases} \tag{7}$$

$$P_{\text{det}|crack} = w_1 P_1 + w_2 P_2 + w_3 P_3 + w_4 P_4 = 0.624 \tag{8}$$

This means, based on expert opinions, by performing regular in-service visual inspection, in 62.4% of the cases, fatigue damage is detected before catastrophic failure occurs.

2.3   Target reliability index

The target reliability index (β_t) is the answer to the question "What level of safety is sufficient?". Several factors play a role in this answer, including the consequence of failure in terms of both loss of human life and economical aspects, the required cost for improving safety, the structure's planned service life and the type of considered limit state. The maximum allowed probability of failure (P_{fm}) is directly related to the β_t as follows:

$$P_{fm} = \Phi(-\beta_t) \tag{9}$$

where $\Phi(.)$ is the cumulative normal distribution function.

In the Eurocodes, β_t for the fatigue limit state is ranging between the target values of the reliability indices for the ultimate and serviceability limit states. For structures such as bridges which can

be categorized into consequence class 3, with details having large consequences of failure and that are designed according to the safe life concept, the target reliability index for fatigue is set equal to the ultimate limit state value of 4.3 ($P_{fm} = 8.54 \times 10^{-6}$) with a reference period of 50 years (EN1990, 2002). The International Organization for Standardization (ISO2394:2015, 2015) also recommends a set of target reliability indices for different design scenarios. For bridges where the relative costs of safety measures are moderate and the consequences of failure are great, $\beta_t = 3.8$ ($P_{fm} = 7.23 \times 10^{-5}$) is recommended for the entire life of a detail designed without considering inspection.

To study the added value of in-service visual inspection, the required target reliability index for this design scenario is obtained based on the findings of the sections 2.1 and 2.2.

3   RESULTS AND DISCUSSIONS

To design a structural detail according to the Eurocodes, partial factors are used to take into account the stochastic parameters in a deterministic limit state approach. These partial factors for the safe-life design method and for the different consequences of failure are presented in Table 1. In calibration of these partial factors, a minimum safety requirement is determined and presented mathematically by a maximum allowed probability of failure (target reliability index). Therefore, a designed structural detail is assumed to be safe as long as the safety requirement is reached. By considering regular in-service visual inspection in the design phase, it is expected that the probability of failure is reduced (higher reliability) and as a result, smaller values of partial factors are required. In other words, reduction in failure probability because of visual inspection makes it possible to use higher values of maximum allowed probability of failure (P_{fss}) and smaller values of target reliability index (β_{ss}). The amount of increase in maximum allowed probability of failure is estimated by the knowledge extracted from a statistical study as well as a survey to collect experts opinion on the matter.

The enhanced maximum allowed probability of failure by performing regular in-service visual inspection is calculated as:

$$P_{fss} = \frac{P_{fm}}{1 - P_{\det|crack}} \qquad (10)$$

The corresponding reliability index to P_{fss} is calculated as:

$$\beta_{ss} = -\Phi^{-1}(P_{fss}) \qquad (11)$$

In section 2.3, two different recommended values for the target reliability indices (β_t) by two standards to design a structural detail for fatigue in a steel bridge are presented. The maximum allowed probability of failure and its corresponding target reliability index as well as the reduction in target reliability index with respect to the standard values, are presented based on the findings of both investigated approaches in Table 3. To demonstrate the added value of regular visual inspection to the fatigue reliability of steel bridges, a case study has been performed. A cover plate detail at midspan of a 20 meter simply supported girder has been designed for fatigue based on the safe life approach of (EN1993-1-9, 2005) with a design life of 100 years. The partial factor of 1.35 has been used for the material fatigue resistance in design. The procedure followed to design a girder for fatigue can be found in the study of Helmerich et al. (Helmerich, Kuhn, & Nussbaumer, 2007). The reliability of this designed girder is subsequently calculated under actual traffic crossing. The reliability index has a decreasing trend during the bridge's service life and at the end of life it should not be smaller than the target reliability index. Therefore, by setting the value of the target reliability index as presented in the left column of Table 3, the fatigue life of the safe-life design approach ($\beta_t = 4.3$) is compared with the fatigue life obtained by including

the regular visual inspection, both based on the outcomes of the statistical study ($\beta_{ss} = 3.92$) and on the experts opinions ($\beta_{ss} = 4.08$). For this purpose, the actual railway traffic crossing a bridge in the Netherlands, measured for a year by a weigh in motion (WIM) system has been used. A reliability analysis has been performed using the Crude Monte Carlo Simulation (CMCS) method (Kroese, Taimre, & Botev, 2011). Distributions of the random variables involved in the fatigue life calculation have been selected as presented by Hashemi et al. (Hashemi, Maljaars, & Snijder, 2019).

Table 3. Added value of visual inspection in terms of the reduced target reliability index

	EN 1990 ($\boldsymbol{\beta_t = 4.3}$)			ISO 2394 ($\boldsymbol{\beta_t = 3.8}$)		
	P_{fss}	β_{ss}	Reduction in β_t (%)	P_{fss}	β_{ss}	Reduction in β_t (%)
Statistical study	4.49×10^{-5}	3.92	8.8	3.80×10^{-4}	3.36	11.6
Experts opinion	2.27×10^{-5}	4.08	5.1	1.92×10^{-4}	3.55	6.6

Figure 3 shows the trend of the reliability index over the service-life for the considered girder in this case study. Table 4 presents the calculated fatigue life for each design approach.
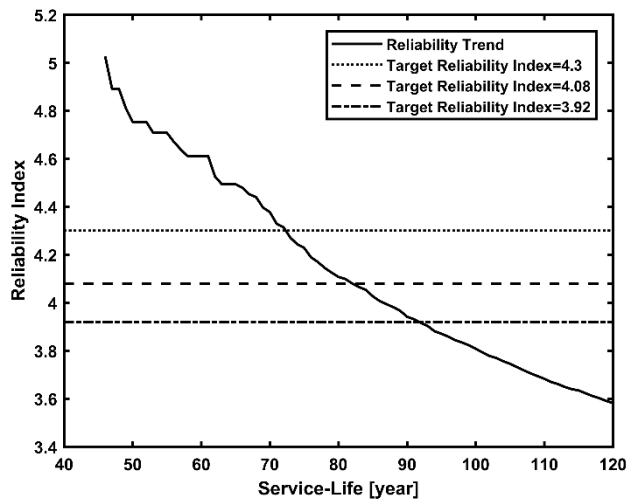

Figure 3. Reliability Index trend and fatigue life

Table 4. Fatigue Life

	Fatigue Life (year)
$\beta_t = 4.3$	72
$\beta_{ss} = 4.08$	82
$\beta_{ss} = 3.92$	91

The case study demonstrates that the bridge can be used 15 % to 25 % longer in time if regular visual inspections are performed as compared to no inspections.

4   CONCLUSIONS

The main conclusions of this study are pointed out here:

- The partial factors recommended by the Eurocode to design a steel structural detail for fatigue are categorized based on the design method and the consequences of failure. The safe-life method where no inspection is considered during service life and the damage tolerant method where detailed inspection is considered in design are the two main design methods. However, in practice, regular visual inspection is performed during the service life. The added value of performing visual inspection to the reliability of the structure has been investigated.

- Two approaches have been followed to study the added value of regular visual inspection to the fatigue reliability of a structural detail. 1) A statistical study on the main causes of bridge failure carried out by other researchers to find the relation between the safe-life design method and the design method considering visual inspection; 2) Conducting a survey to collect expert opinions on the matter and using a Bayesian algorithm to assign a probability distribution function to each opinion.

- If bridges are designed for a service life of 100 years, and at some point in their life, a fatigue crack occurs, by performing visual inspections every 5 to 10 years, based on the statistical study, in 81 % of the cases fatigue damage will be detected before catastrophic failure happens while based on the experts opinions, in 62.4 % of the cases fatigue damage will be detected.

- By performing regular visual inspection, the probability of failure is decreased (higher reliability). Therefore, lower values of the target reliability indices can be used in the calibration of partial factors.

- The safe-life target reliability index is reduced by an average of 10% and 6% based on the statistical study and experts opinions, respectively.

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