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Probabilistic fatigue life updating accounting for inspections of multiple critical locations

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ABSTRACT

Many steel structures contain multiple fatigue sensitive details that have similar geometries and are subjected to similar load fluctuations. Examples are orthotropic (bridge) decks and stiffened (ship) hulls where tens to thousands of similar details are present in one structure. Generally only visual inspections on fatigue cracks are considered for these structures because more accurate techniques are considered to be too expensive and time consuming when so many details need to be inspected. Visual inspections are known to have a low probability of detection. Consequently Bayesian update techniques usually show a marginal effect of the result of visual inspections on the reliability of structures with respect to fatigue failure. On the other hand the inspection result of one location also provides information on similar details at other locations and thus the significance of the inspection result may be larger if multiple potential crack locations occur and cracks are not detected at any of these locations. This paper provides a probabilistic fatigue crack growth (fracture mechanics) model of a system containing a fatigue sensitive detail at multiple locations that accounts for the results of inspections. Spatial correlations of loading, resistance, and uncertainty variables between the different locations are evaluated and estimated through a literature review and are accounted for in the model. The model is demonstrated on a practical example of an orthotropic bridge deck containing a detail at 100 locations. The paper shows that visual inspections may be effective provided that a certain minimum inspection reliability can be guaranteed, that the structure is relatively tolerant to large cracks, and that the geometry and loading conditions are similar for a large number of locations.

1. Introduction

Worldwide there is a main challenge in maintaining existing infrastructures and offshore structures. One of the main failure mechanisms of steel structures is fatigue [1]. Replacement or even upgrading of structures for which initial calculations indicate that the design life has expired is in many cases not necessary. Instead it is possible to evaluate the current state of the structure on the basis of fatigue inspections. If cracks are not found or if detected cracks are repaired, the structure may be fit for use.

Probabilistic models are put forward in literature dedicated to the evaluation and updating of the reliability of inspected structures, e.g. [2–7]. The general approach followed in these studies is using inspection results to update the initial belief of the governing variables of a crack growth (fracture mechanics) model using the Bayesian theorem, [8]. The models are used to determine the time interval to the subsequent inspections e.g. for offshore structures [9,10] and aircraft structures [11].

The general principle of the methods in the above mentioned studies is explained in Fig. 1. This figure provides the crack size, a, on the vertical axis as a function of the time, t, on the horizontal axis. The crack grows in time due to the fluctuating loads from an initial defect with size a_0 to a final crack size, a_f. Due to the wide distributions of the variables that determine the crack growth, [12,13], the scatter in the crack growth is relatively large (light grey area) and consequently the scatter in fatigue life is large (light grey distribution). If an inspection is carried out using an inspection technique with a detection limit, a_d, it is possible to update the probability density functions of the variables based on the inspection result. This reduces the scatter in crack growth, especially at the lower bound of the determined life (dark grey area and distribution). Based on the updated crack growth prediction it is possible to determine the required interval to the next inspections.

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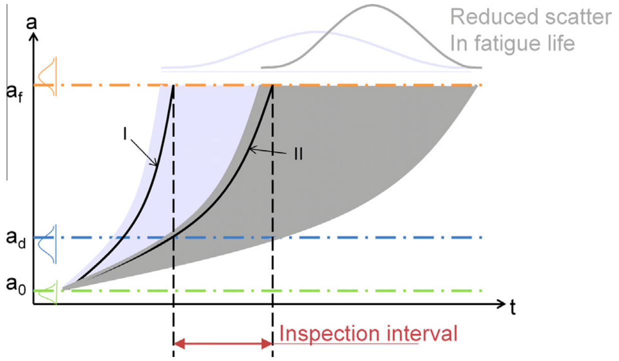

Fig. 1. Principle of fatigue life updating through considering inspection result with crack size, *a*, as a function of time, *t*. Curve I: *x*% probability of exceeding without inspection (prior). Curve II: *x*% probability of exceeding accounting for the inspection result (posterior).

Most structures contain multiple fatigue sensitive details. A number of authors have considered multiple details in probabilistic crack growth models accounting for inspection results. Kim and Frangopol [14] and Soliman et al. [15] have developed probabilistic methods for cost-optimised inspections of structures containing more than one critical details. Rabiei and Modarres [16] have developed a method that considers information from multiple sources such as physical models, monitoring data, and inspections, to update the fatigue life prediction. Variations on the classical fracture mechanics crack growth model [17] have been developed, such as models accounting for stress ratios and load sequence effects in variable amplitude loading, [18,19]. Guan et al. [20] have provided a framework for fatigue failure in which the most appropriate of these models and their variables are selected and updated using the Bayesian theorem.

Studies considering visual inspections in updating the reliability are rare due to the poor probability of detection of this method, [21], which generally results in short inspection periods. However, in practice visual inspections are often applied because of the relatively low costs involved. Especially for structures with fatigue sensitive details that occur multiple times in that structure – hundreds or thousands – more advanced inspection methods are often considered too expensive and too time consuming. Examples of such structures are welded orthotropic bridge, ship, or platform decks with deck plate, stringer and crossbeam connections or stiffened ship hulls.

Most of the previous studies considered one detail at a time. In case of details at multiple locations in a structure – with similar geometry and similar loading – one can make use of spatial correlations between the underlying variables of the crack growth mechanism. In comparison with an inspection of a single detail without a detected crack, the significance of the inspection result may be larger if multiple potential crack locations occur and cracks are not detected at any of these locations. Visual inspection may be feasible in such cases. An alternative is to inspect a certain fraction of all locations using more advanced inspection methods.

Spatial correlations have been considered in a number of studies. Feng et al. [22] studied the influence of spatial correlations between the power law approximations of the stress intensity factors of two types of crack in a stiffened panel. Their results show the importance of spatial correlations on the failure probability of a parallel system. Sørensen and Ersdal [23] have shown that a high degree of correlation between the uncertain parameters in different components is needed in order to obtain substantial information which can be used in inspection planning. Moan and Song [24] have studied the influence of inspection updating on the fatigue failure probability of a series system. Uraga and Moan [25] have considered the fatigue reliability of a parallel system consisting of 2 joints. They have mentioned the qualitative influence of spatial correlations but have not implemented these in their analyses. All these studies considered a small number of details or locations.

This paper provides a method to determine the reliability of a structure considering fatigue failure of a detail repeated multiple times in that structure, where spatial correlations are accounted for. The method is demonstrated for the case of an orthotropic bridge deck. The influence of various inspection strategies on the reliability of the bridge deck structure – including visual inspections – are provided.

2. Fatigue crack growth (fracture mechanics) model

2.1. General fracture mechanics procedure

The crack growth model used is based on classical fracture mechanics (FM). The principles of the method are described in many articles and books – such as [26,27] – and are briefly summarised hereafter.

The stress intensity factor, *K*, is a basic parameter in FM and represents the stress state in the vicinity of the crack tip caused by a remote load. In case of a semi-elliptical surface crack at the toe of a weld, Fig. 2, the stress state is usually represented by the stress intensity factor at the deepest point, K_a, and the stress intensity factor at the surface, K_c. For a given geometry and loading, the stress intensity factors are derived either analytically or by the finite element method and are often expressed by equations. In this paper, the following expressions are used:

$$\begin{aligned} K_a &= (s_m Y_{ma} M_{ma} + s_b Y_{ba} M_{ba})\sqrt{\pi a} \\ K_c &= (s_m Y_{mc} M_{mc} + s_b Y_{bc} M_{bc})\sqrt{\pi a} \end{aligned} \tag{1}$$

where *s* is the remote stress, *a* is the crack depth, *Y* is the geometry correction factor for a semi-elliptical surface crack or a through thickness crack, *M* is the geometry correction factor for a weld toe (both correction factors are addressed hereafter), subscripts *m* and *b* indicate membrane loading and bending loading, respectively, and subscripts *a* and *c* indicate the surface and deepest points, respectively.

The FM model for fatigue crack growth makes use of the empirical relationship between the ranges of the stress intensity factors, ΔK_a or ΔK_c, and the crack size increment per cycle, $\mathrm{d}a/\mathrm{d}N$ or $\mathrm{d}c/\mathrm{d}N$, where *a* is the crack depth and *c* is the semi crack width, Fig. 2, and *N* is the number of stress cycles. The empirical relationship used in this paper is the 2 stage curve provided in BS 7910:2013 [28]. In depth direction, the relationship is expressed as (Fig. 3):

$$\frac{\mathrm{d}a}{\mathrm{d}N}(\Delta K_a) = \begin{cases} 0 & \text{if} \quad \Delta K_a \leqslant \Delta K_0 \\ A_1(\Delta K_a)^{m_1} & \text{if} \quad \Delta K_0 < \Delta K_a \leqslant \left(\frac{A_2}{A_1}\right)^{\frac{1}{m_2-m_1}} \\ A_2(\Delta K_a)^{m_2} & \text{if} \quad \Delta K_a > \left(\frac{A_2}{A_1}\right)^{\frac{1}{m_2-m_1}} \end{cases} \tag{2}$$

where A_1, A_2, m_1, m_2, and ΔK_0 are empirical, material related variables. A similar expression is used for the width direction, $\mathrm{d}c/\mathrm{d}N$ versus ΔK_c. Eq. (1) is substituted into Eq. (2) and an incremental numerical integration procedure is carried out in which the relationships between the number of stress cycles, *N*, and the crack size parameters, *a* and *c*, are determined. The procedure starts at an initial, representative defect of a welded structure prior to loading, expressed with a_0 and c_0, and ends at the attainment of a final or critical crack size, expressed with a_f and/or c_f.

The expressions for *Y* and *M* in Eq. (1) are a function of the crack size, expressed by *a* and *c*, the plate thickness, *T*, and the node