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Value of inspection in steel structural integrity management

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Abstract. Fatigue cracking is a common problem that needs to be managed in the life cycles of steel structures. Operational inspections and repairs are important means of fatigue crack management. Driven by high relevance in safety control and budget saving, inspection and maintenance planning has been widely studied. However, the value of inspection and repairs has typically not been fully appreciated and quantified rationally before they are implemented. The basic idea of this paper is to address the planning problem with focus on repair other than on inspection. A maintenance strategy without inspection is studied and serves as comparison of a maintenance strategy with inspection. Then the value of repair and the value of inspection relative to repair can be evaluated respectively. An illustrative example is performed on a typical fatigue-prone detail in steel structures.

1. Introduction

Fatigue cracking is one of the most common failure mechanisms for steel structures subjected to cyclic loading. It cannot be avoided absolutely by design check due to inherent uncertainties associated with the fatigue process, and inspections and repairs are necessary. Inspection and maintenance planning has gained wide attention due to heavy costs involved and various uncertainties associated with material and loading characteristics, deterioration model, inspection quality and repair effect. Generic inspection planning is extensively studied based on Bayesian decision theory [1-3]. The problem is also formulated as a multi-objective optimisation problem based on event tree analysis and solved with optimisation techniques [4-7]. The primary focus of previous studies is on how inspection should be planned, and repair decision is dependent on a repair criterion and inspection result.

This paper addresses the problem from a different perspective with focus primarily on repair. The reason is that it is the repair activity that ultimately changes the reliability of structure. From this point, a maintenance strategy without any inspection is studied and serves as comparison of a maintenance strategy with inspection. On the basis of a case study on a typical fatigue-prone structural detail, the value of repair and the value of inspection relative to repair is discussed and evaluated.

2. Fatigue deterioration modelling

Based on fracture mechanics, fatigue process can be divided into three stages: crack initiation, crack propagation and final fracture. The crack size in the crack initiation stage is not critical as it is too small and is hardly detectable by typical non-destructive testing (NDT) methods. In practical, the crack initiation stage is often negligible comparable with the crack propagation stage because of the presence of initial flaws/cracks. Also, the final fracture usually occurs very quickly, and the crack propagation stage is thus the focus of crack control.

Paris' equation relates the crack propagation rate to the range of stress intensity factor, and is given by

$$\frac{da}{dN} = C\Delta K^m \tag{1}$$

where da is increment in crack propagation for dN stress cycles, C and m are material parameters, ΔK is stress intensity factor range, given by

$$\Delta K = \Delta\sigma Y(a)\sqrt{\pi a} \tag{2}$$

where $Y(a)$ is geometry function and $\Delta\sigma$ is stress range. The stress range is normally determined by design S-N curve, which is given by

$$\begin{cases} N_f \Delta\sigma^{m_1} = \overline{a_1} & N_f \leq 10^7 \\ N_f \Delta\sigma^{m_2} = \overline{a_2} & N_f \geq 10^7 \end{cases} \tag{3}$$

where m_1 and m_2 are the fatigue strength exponents, and $\overline{a_1}$ and $\overline{a_2}$ are the fatigue strength coefficients.

By integration of equation (1), the number of cycles for the crack to develop from the initial crack size a_0 to the critical size a_c can be expressed as

$$N = \frac{1}{\pi^{m/2} C\Delta\sigma^m} \int_{a_0}^{a_c} \frac{da}{a^{m/2} Y(a)^m} \tag{4}$$

If the geometry function $Y(a)$ is known, it is also possible to calculate the crack size $a(t)$ at time t when the structural detail has exposed to $N(t)$ cycles of fatigue loading.

3. Maintenance strategy

Three maintenance strategies are tested. The first one is that no human intervention is planned, and the structure has a failure probability which is determined by the design and construction quality. The second one is that one repair is planned during the life cycle. The timing for the repair t_r is optimized and shown in the following section. If the structure is survived at the time of the planned repair, one repair will be implemented. The third one is that one inspection is planned during the life cycle. The timing for the inspection t_i is optimised in the following section. If the structure is survived at the time of the planned inspection, one inspection will be implemented. If a crack is detected, it will be repaired. The maintenance strategies are summarized in Table 1.

Table 1. Three strategies for operational maintenance.

Case	Maintenance activity
Case1	No inspection & no repair
Case2	Repair is planned without inspection
Case3	Repair would be done following plan inspection

4. Failure probability and probability of repair

4.1. Failure probability without repair

Failure probability is calculated based on formulation of a limit state, in which the structural capacity is defined by a failure criterion. The limit state formulation in this paper is based on serviceability analysis. The basic idea is that a structural detail is not serviceable if a through thickness crack exists, so a critical crack size equals to plate thickness is used as a failure criterion. Limit-state function can be formulated as

$$M(t) = a_c - a(t) \tag{5}$$

where a_c is the critical crack size, $a(t)$ is the crack size at time t under fatigue loading.

The probability of failure is given by

$$P_f(t) = P(M(t) < 0) \tag{6}$$

4.2. Probability of repair

The probability of inspection is actually implemented at time t is the probability that the structure is survived at that time, and is given by

$$P_i(t) = 1 - P_f(t) \tag{7}$$

In Case 2, the probability of repair is equal to the probability of inspection. In Case 3, the repair strategy that all detected cracks are repaired is used. This means that the probability of repair is equal to the probability of detection. If the smallest detectable crack size of an NDT method is a_d, then the limit state function for detection or no detection is defined as

$$D(t) = a_d - a(t) \tag{8}$$

The function is negative when a crack is detected and it is positive when no crack is detected. The probability of repair is given by

$$P_r(t) = \left(1 - P_f(t)\right) \cdot P(D(t) < 0) \tag{9}$$

4.3. Failure probability with planned repair

The failure probability before planned repair time t_r is equal to the initial failure probability without repair. The failure probability after planned repair time t_r should take into account the influence of planned repair.

For Case 2, the failure probability after planned repair is given by

$$P_f^1(t) = P_f(t_r) + P(M(t_r) > 0 \cap M(t - t_r) < 0) \tag{10}$$

For Case 3, the failure probability after planned repair is given by

$$\begin{aligned} P_f^1(t) = P_f(t_r) &+ P(M(t_r) > 0 \cap D(t_r) > 0 \cap M(t) < 0) \\ &+ P(M(t_r) > 0 \cap D(t_r) < 0 \cap M(t - t_r) < 0) \end{aligned} \tag{11}$$

5. Illustrative example

An illustrative example is performed on fatigue-prone T joints subjected to cyclic fatigue loading, which are common connections in steel structures. Typical structure is a plate with stiffeners. The stability of the plate is improved by stiffeners, but cracks are highly likely to initiate and propagate along the weld toes of the joints. Fatigue reliability of such joints is a problem that needs to be addressed during the life cycle of the structure detail. The geometry and critical location of a T joint is shown in Figure 1.

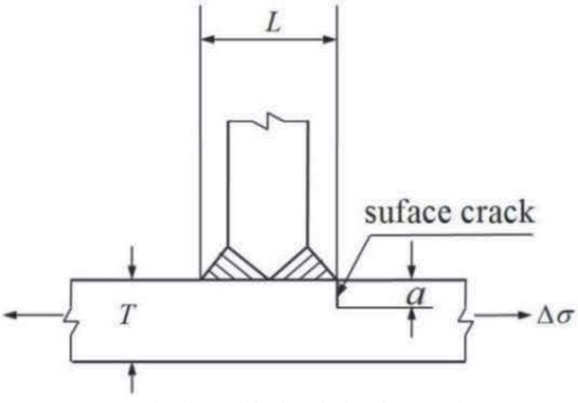

Figure 1. Typical welded T joint in steel structures.

5.1. Probabilistic model

Fatigue performance of such structural detail is given by a bi-linear S-N curve [8]. The frequency of fatigue loading is approximately 0.16Hz, which corresponds to $N_0 = 5 \times 10^6$ cycles per year. The uncertainties associated with loads and stress calculations are modelled with a normally distributed variable B. The plate thickness is $T = 25$mm. The required service life is $T_{SL} = 20$ years. The parameters and variables used in the model are summarised in tables 2 and 3.

Table 2. Parameters used in the model.

Parameter	Unit	Value
T_{SL}	year	20
N_0	cycle	5×10^6
$\log_{10} \overline{a_1}$	$\mathrm{N}^4 \cdot \mathrm{mm}^{-6}$	11.855
$\log_{10} \overline{a_2}$	$\mathrm{N}^4 \cdot \mathrm{mm}^{-6}$	15.091
T	mm	25
a_d	mm	0.89
m_1	-	3
m_2	-	5

Table 3. Variables used in the model.

Parameter	Distribution	Unit	Mean	Standard Deviation
a_0	Exponential	mm	0.043	0.043
$\log_{10} C$	Normal	$\mathrm{N}^{-4} \cdot \mathrm{mm}^{5.5}$	-12.74	0.11
B	Normal	-	1	0.15

5.2. Results and discussions

In this study, Case 1 represents initial structural reliability, which is determined by design check and manufacture quality control, without any operational maintenance. Case 2 reflects the influence of repair on the life cycle reliability (the reliability at the end of service life), while Case 3 reflects the influence of both inspection and repair. The timing for the inspection t_i and for the repair t_r in Case 2 and 3 are optimised with the objective to maximise the life cycle reliability. The optimum maintenance plans in Case 2 and 3 are analysed with respect to life cycle reliability.

Table 4 summarizes calculation results for Case 1, 2 and 3, which include the reliability index β, optimum time for inspection and repair t_i and t_r, the probability for inspection and repair and P_i and P_r. Based on the results, the following discussions are made:

Table 4. Optimised maintenance plan.

	Case1	Case2	Case3
β	1.12	2.40	2.62
t_i (year)	n/a	n/a	9
t_r (year)	n/a	10	9
P_i	n/a	n/a	0.998
P_r	n/a	0.996	0.311

1) In Case 2, the structure is intervened by repair in the middle of its service life when the repair is optimum from the point of increasing life cycle reliability. Compared with Case 1, the life cycle reliability increases from 1.12 to 2.40 owe to repair, by which the structure is physically changed.
2) Comparing Case3 with Case1, it can be seen that with the adoption of inspection and possible repair (if detected by inspection), life cycle reliability increases significantly from 1.12 to 2.62. The increase in reliability is benefited from both repair and inspection.

3) An interesting finding is found by comparing Case 3 with Case2 that repairs do not always increase structural reliability. The probability of repair in Case 2 is much higher than that in Case 3, but the structural reliability in Case 2 is lower than Case 3.
4) The value of inspection in Case 3 lies in two aspects. On one hand, the cracks that grow fast are detected and their failure probability is lowered by physically changing the structure. On the other hand, the cracks that grow slow are identified and their failure probability is lowered according to the new information gained by inspection (no detection).

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