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 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.

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, \(\Delta K\) is stress intensity factor range, given by
\[
\Delta K = \Delta \sigma (a) \sqrt{\pi a} \tag{2}
\]
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
\[
\begin{align*}
N_f \Delta \sigma^{m_1} &= \bar{a}_1 & N_f \leq 10^7 \\
N_f \Delta \sigma^{m_2} &= \bar{a}_2 & N_f \geq 10^7
\end{align*} \tag{3}
\]
where \(m_1\) and \(m_2\) are the fatigue strength exponents, and \(\bar{a}_1\) and \(\bar{a}_2\) 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
\[
N = \frac{1}{\pi^{m/2}C^2 \bar{a}^{m}} \int_{a_0}^{a_c} \frac{da}{a^{m/2}Y(a)^m} \tag{4}
\]
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 \(t_l\) 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.

| Case   | Maintenance activity                  |
|--------|---------------------------------------|
| Case 1 | No inspection & no repair             |
| Case 2 | Repair is planned without inspection  |
| Case 3 | 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

$$ P_i(t) = 1 - P_f(t) $$

(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

$$ D(t) = a_d - a(t) $$

(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

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

(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

$$ P_f^2(t) = P_f(t_r) + P(M(t_r) > 0 \cap M(t - t_r) < 0) $$

(10)

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

$$ P_f^3(t) = P_f(t_r) + \left[ P(M(t_r) > 0 \cap D(t_r) > 0 \cap M(t) < 0) + P(M(t_r) > 0 \cap D(t_r) < 0 \cap M(t - t_r) < 0) \right] $$

(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.](image)

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 $T = 25mm$. 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| $5 \times 10^6$ |
| $\log_{10} \bar{a}_1$ | $N^4 \cdot mm^{-6}$ | 11.855 |
| $\log_{10} \bar{a}_2$ | $N^4 \cdot mm^{-6}$ | 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 | $N^{-4} \cdot mm^{5.5}$ | -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 $\beta$, 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 |
|---------|-------|-------|-------|
| $\beta$ | 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 Case 2 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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References
[1] Faber MH. Risk-based inspection: The framework. Structural engineering international. 2002;12(3):186-195.
[2] Straub D, Faber MH. Risk based inspection planning for structural systems. Structural safety. 2005;27(4):335-355.
[3] Kim S, Soliman M, Frangopol DM. Generalized Probabilistic Framework for Optimum Inspection and Maintenance Planning. Journal of Structural Engineering. 2013;139(3):435-447.
[4] Soliman M, Frangopol DM, Mondoro A. A probabilistic approach for optimizing inspection, monitoring, and maintenance actions against fatigue of critical ship details. Structural Safety. 2016;60:91-101.
[5] Kim S, Frangopol DM. Efficient multi-objective optimisation of probabilistic service life management. Structure and Infrastructure Engineering. 2017;13(1):147-159.
[6] Dong Y, Frangopol DM. Incorporation of risk and updating in inspection of fatigue-sensitive details of ship structures. International Journal of Fatigue. 2016;82:676-688.
[7] Lotsberg I, Sigurdsson G, Fjeldstad A, Moan T. Probabilistic methods for planning of inspection for fatigue cracks in offshore structures. Marine Structures. 2016;46:167-192.
[8] DNV G. DNVGL-RP-0005: Fatigue design of offshore steel structures. Det Norske Veritas AS, Oslo, Norway; 2014.