Title	Probabilistic maintenance optimization with respect to inspection quality
Authors(s)	Zou, Guang; Banisoleiman, Kian; González, Arturo
Publication date	2018-09-12
Publication information	Proceedings of the 16th International Probabilistic Workshop (IPW 2018)
Conference details	The 16th International Probabilistic Workshop (IPW2018), Vienna, Austria, 12-14 September 2018
Link to online version	http://probabilistic.boku.ac.at/
Item record/more information	http://hdl.handle.net/10197/9571

BETON-UND STAHLBETONBAU International Probabilistic Workshop 2018

Guang Zou
Kian Banisoleiman
Arturo González

Probabilistic maintenance optimization with respect to inspection quality

Abstract: Maintenance scheduling and optimization against fatigue failures are of significant interest to marine and offshore sectors for safety assurance, integrity management and cost control. The main challenge is to integrate uncertainties associated with material properties, fatigue loads, deterioration modelling, inspection and maintenance methods within risk-informed and optimal maintenance decision-making process. While optimization of inspection times has been the objective of many studies, the influence of inspection quality (mean detectable crack size) on lifetime fatigue reliability has not been addressed sufficiently. This paper applies probabilistic fracture mechanics and reliability/risk methods to optimization of both inspection quality and inspection time simultaneously and assess the effect of inspection quality on lifetime fatigue reliability. Results revealed that there is a reliability-based optimum inspection quality for maintenance scheduling, which is different from the cost-based optimum inspection quality. A higher inspection quality than the optimum one can lead to excessive maintenance, which occurs when a maintenance strategy leads to a higher failure probability conditional on repair than the failure probability conditional on no detection. Excessive maintenance can lead to increases in both expected failure costs and maintenance costs, and thus should be avoided.

1 Introduction

With the current requirements on sustainable economic growth, it is becoming increasingly important to make full use of existing infrastructures and assets. It is therefore necessary to address the problem that structural performance may degrade over time and no longer meet the requirements due to operational and environmental loads and hazards. For marine and offshore structures, a very common factor causing structural degradation is growth of fatigue cracks, which typically develop under cyclic wave loading. Maintenance actions are assigned to increase integrity and fatigue reliability of such structures. However, maintenance actions, e.g. inspection, repair, replacement etc., can be very expensive and cumbersome, for example usually comprising of a substantial number of locations and areas susceptible to damage. Hence, how to best utilize the benefits of maintenance with minimal costs is of great interest and has gained wide attention in these industry sectors.

Probabilistic methods have been recognized as powerful tools in dealing with the variabilities and uncertainties associated with loading, material properties, fatigue resistance, deterioration modeling and inspection quality etc., in a rational and consistent way. Inspection times can be planned with probabilistic and risk approaches based on a reliability or risk threshold[1-3]. Life cycle methods and optimization techniques are employed to address the probabilistic optimization problem consisting of achieving optimum maintenance decision-making considering both fatigue reliability and maintenance costs[4-6]. In these studies, inspection times are the design parameters, and inspection methods (or qualities, or detectable crack sizes) are pre-defined. Several studies also compare the influence of inspection qualities from the perspective of life cycle costs[7, 8]. However, only a small amount of attention has been paid to the effect of inspection quality on fatigue reliability.

This paper analyses inspection optimization with a focus primarily on inspection quality. The effects of inspection quality on the reliability and on the optimum inspection times/intervals are investigated. It is found that there is an optimum inspection quality solely from the perspective of fatigue reliability. A better inspection quality than the optimum may actually decrease fatigue reliability in certain circumstances.

2 Probabilistic fatigue modelling

Welded details in marine and offshore structures are especially prone to fatigue failures due to the severe notch effect, presence of initial flaws and tensile residual stresses, introduced in the welding process. These factors can be taken into account in fatigue analysis using a fracture mechanics (FM) approach. Based on FM, fatigue process comprises of three stages: crack initiation, crack growth and fracture. For welded details, the crack initiation stage is usually very short compared to crack growth stage. The crack initiation stage is thus neglected in fatigue analysis. As the final fracture usually occurs very quickly, the crack growth stage thus accounts for a major part of fatigue life.

Paris law gives a formulation for the relationship between crack growth rate and the driving force for crack growth, stress intensity factor, as per Equation (1) and (2).

$$\frac{da}{dN} = C\Delta K^m, \quad \Delta K_{th} \le \Delta K \le K_{mat} \tag{1}$$

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

where a is crack size; N is number of cycles; da/dN is crack propagation rate; C and m are material parameters; ΔK is stress intensity factor range; K_{mat} is material fracture toughness; ΔK_{th} is threshold value for the stress intensity factor range; $Y(a)$ is geometry function; $\Delta\sigma$ is stress range.

If failure was defined as the crack depth reaching a critical size a_c, then the crack growth period can be obtained by integration of Equation (1) from an initial crack size a_0 to a_c, as shown by Equation (3).

$$N = \frac{1}{\pi^{m/2} C \Delta\sigma^m} \int_{a_0}^{a_c} \frac{da}{a^{m/2} Y(a)^m} \tag{3}$$

A typical stiffened plate in ship structure, as shown in Figure 1, is studied herein. It is well known that the stiffeners improve the stability of the plate, but the welded details may be prone to fatigue due to poor welding techniques. In this case, the required service life of the joints are 20 years. The frequency of wave loading is about 0.16Hz, which corresponds to approximately 5×10^6 cycles per year.

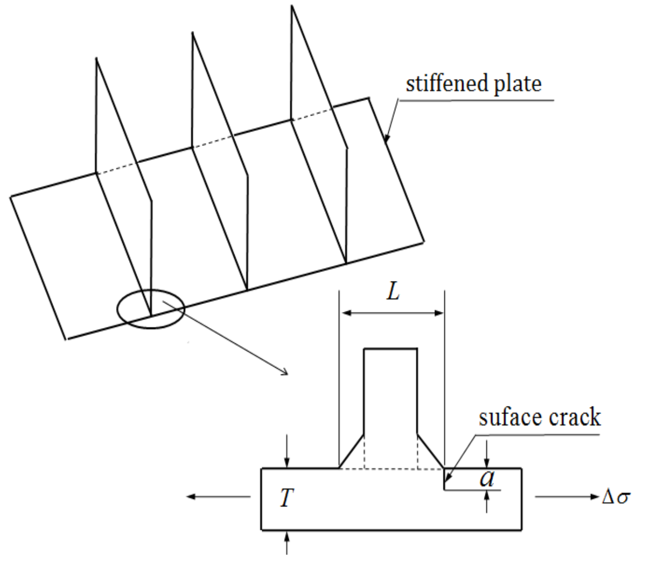

Fig 1 Typical welded details in ship structure

Equation (4) describes the fatigue resistance of the welded detail given by a two-segment S-N curve.

$$\begin{aligned} N_F \Delta\sigma^{m_1} &= \overline{a_1} \qquad N_F \le 10^7 \\ N_F \Delta\sigma^{m_2} &= \overline{a_2} \qquad N_F \ge 10^7 \end{aligned} \tag{4}$$

Where N_F is fatigue life; m_1 and m_2 are the fatigue strength exponents; and $\overline{a_1}$ and $\overline{a_2}$ are the fatigue strength coefficients. The parameters for the S-N curve can be found in rules of ship classification societies. The fatigue design factor (FDF) of the detail is 3, which requires the allowed maximal equivalent stress range to be $\Delta\sigma_e = 21.03\text{MPa}$. The design plate thickness is $T = 25\text{mm}$. The parameters are summarized in Table 1.

The initial crack size a_0 and the crack growth rate C are treated as variables, as it is widely acknowledged that uncertainties associated with these two parameters are largely influential on the modelling results via Equation (1) and (2). Uncertainties associated with calculation of stress range $\Delta\sigma$ are modelled as an additional variable B. The mean value and standard deviation (SD) for all variables are listed in Table 2.

Table 1 design parameters of the structural detail

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

Table 2 Variable in reliability analysis

Variable	Distribution	Unit	Mean	SD
a_0	Exponential	mm	0.04	0.04
$\log_{10} C$	Normal	$\text{N}^{-4} \cdot \text{mm}^{5.5}$	-12.74	0.11
B	Normal	-	1	0.15

3 Reliability analysis

3.1 Initial reliability

Reliability is defined in terms of exceedance of a safety margin. Herein Equation (5) is used to define safety margin based on crack size.

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

where $M(t) < 0$ signifies fracture failure. Failure is defined as occurrence of through-thickness crack, i.e., the critical crack size a_c is set to be equal to the plate thickness T. Failure probability P_f and reliability index β are given by Equation (6) and (7) respectively.

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

$$\beta(t) = -\Phi^{-1}\left(P_f(t)\right) \tag{7}$$

where Φ is cumulative distribution function of standard normal distribution.

Monte Carlo simulation has been employed to calculate the reliability index. It is checked that the samples are large enough so that the statistical results are stable. Figure 2 shows the decline of reliability index with service year. As the lifetime reliability index (the reliability index at the end of required service life) is lower than the target reliability index, i.e. β_t=2, maintenance interventions are needed.

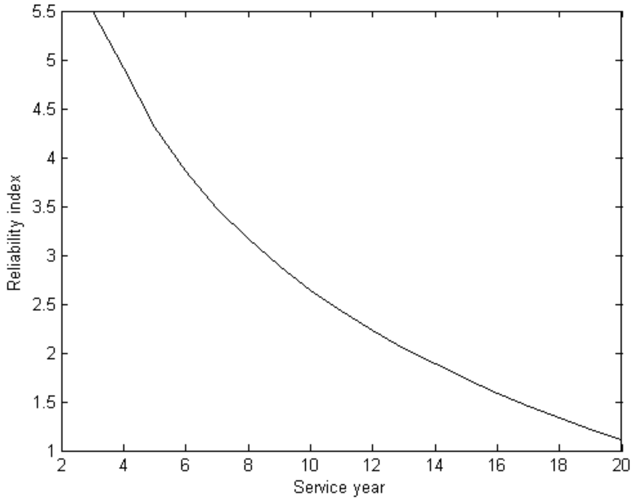

Fig 2 Decline of reliability index with service year

3.2 Reliability with planned maintenance

A maintenance strategy is adopted such that detected cracks are repaired immediately. After repair, the structural detail is assumed to return to its initial damage state, which means that the distribution of the crack size after repair is identical to the distribution of initial crack size a_0. This maintenance strategy reduces failure probability and failure risk of the structural detail, as excessive cracks, if identified by inspections, will be repaired before the end of required service life.

At the maintenance planning stage, inspection times and qualities need to be decided. However, at the planning stage, the damage conditions and inspection results are unknown due to the stochastic nature of crack growth. So, event tree analysis must be carried out in order to calculate the lifetime failure probability. At a planned inspection time, there are three possible cases or branches:

- The structural detail has already failed (B1)
- The structural detail has survived, and inspection result is detection (B2)
- The structural detail has survived, and inspection result is no detection (B3)

Based on the above analysis, the failure probability conditional on each case can be calculated, and Equation (7) provides the failure probability with one planned maintenance intervention.

$$P'_f(t) = \sum_{b=1}^{3} P_b \cdot P_{f|b} \tag{7}$$

where P_b is the probability of branch b occurring, and $P_{f|b}$ is the failure probalbity conditional on branch b occurring.

Inspection quality is characterized by the mean detectable crack size a_d of an inspection method. In order to make the effect of inspection quality clear, herein one maintenance intervention is planned during the life cycle. Figure 3 shows the lifetime reliability index against inspection time for the three inspection methods under investigation: magnetic particle inspection (MPI), close visual inspection (CVI) and visual inspection (VI). The a_d associated with these inspection methods follows [3, 8].

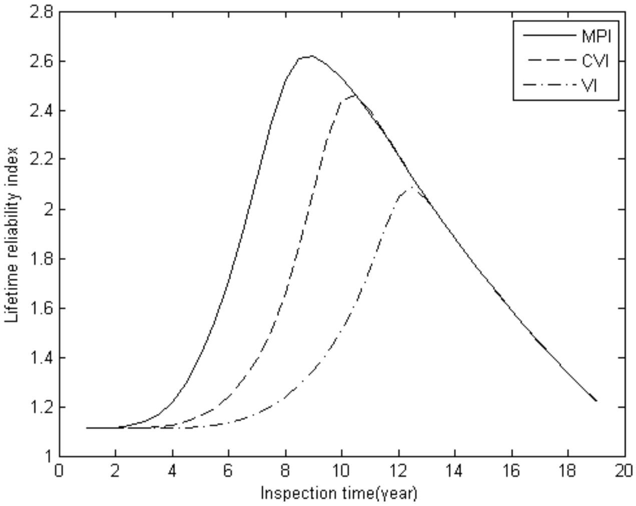

Fig 3 Effect of inspection method on lifetime reliability index

Table 3 summarizes the optimum inspection times and maximum reliability indexes adopting the three inspection methods.

Table 3 Reliability-based optimal inspection time for given inspection methods

Inspection method	**Inspection quality(mm)**	**Maximum reliability**	**Optimum inspection time(year)**
MPI	0.89	2.615	9.0
CVI	2.00	2.465	10.5
VI	4.35	2.088	12.5

Base on Figure 3 and Table 3, it can be seen that:

1) Inspection quality can affect the lifetime reliability index. Among the three methods, MPI can help to achieve the highest lifetime reliability index.

2) Inspection quality can affect the optimum inspection time. Generally, the better quality of inspection method is adopted, the earlier inspection should be implemented in order to maximize reliability index.

3) The effect of inspection quality on lifetime reliability index is marginal if an inspection is planned at the late stage of service life.

4 Reliability-based optimum inspection quality

As shown in the above section, inspection methods with different quality can help to achieve different levels of lifetime reliability index. An interesting question remains: is it true that adopting an inspection method with higher quality will achieve a higher reliability index? To answer this question, the optimum inspection quality and time were derived with the objective to maximize the lifetime fatigue reliability index. The optimum results are shown by Table 4. The optimum inspection quality is $a_{d,opt} = 1.05$ with the maximum lifetime reliability index $\beta = 2.625$. Compared with the optimum inspection quality, the quality of MPI is higher, but the lifetime reliability index achieved is lower. It is concluded that there is an optimum inspection quality with the objective of maximizing lifetime fatigue reliability index, and a higher inspection quality than the optimum one may lead to a lower reliability index.

Table 4 Derived optimal inspection quality and time based on reliability maximization

Inspection quality(mm)	Max lifetime fatigue reliability	Inspection time(year)
1.05	2.625	9.0

5 Discussions

The reasons for the above findings are investigated by analyzing the contributions to lifetime failure probability from the inspection results of detection and no detection while adopting. A planned inspection contributes to increments in lifetime reliability in two distinctive ways, B2 and B3 (Section 3.2), as follows:

- B2: If inspection result is detection, detected cracks will be repaired and damage extent mitigated before failure occurs. Lifetime reliability thus increases.

- B3: If inspection result is no detection, no further action will be implemented. However, based on the information of no detection, updated failure probability (or belief on failure) is lower than the initial predicted failure probability. Lifetime reliability thus also increases.

Table 5 compares the three inspection methods with different qualities (MPI, the optimum $a_{d,opt}$, CVI) in terms of the probability of occurrence of B2 and B3 (P_2, P_3), and failure probability conditional on B2 and B3 ($P_{f|2}$, $P_{f|3}$). The planned inspection time is $t_i = 9$ years. It should be noted that the failure probabilities conditional on repair are the same for the three inspection methods. Based on Table 3-5, the following points are noted.

1) Adopting MPI may lead to excessive maintenance, which describes the case when a lower lifetime fatigue reliability is achieved while adopting a higher inspection quality than the optimum quality $a_{d,opt}$. The failure probabilities conditional on detection and repair (B2) for both MPI and $a_{d,opt}$ are higher than the failure probabilities conditional on no detection (B3). Adopting MPI leads to a higher probability of occurrence of B2 (detection and repair) than $a_{d,opt}$, and thus leads to a higher overall lifetime failure probability and a lower reliability index.

2) Compared with optimum maintenance, excessive maintenance is unbeneficial for lifetime fatigue reliability. For example, Table 4 shows a maximum lifetime fatigue reliability index of 2.625 for optimum inspection quality of 1.05 mm, compared to a lower lifetime fatigue reliability index of 2.615 for a higher inspection quality of 0.89 mm for MPI in Table 3. Although the difference in the reliability index is not significant, the lower lifetime fatigue reliability index means a higher expected failure cost compared with the optimum inspection quality. More importantly, excessive maintenance leads to more maintenance costs, and hence a higher life cycle total costs. In this regard, a higher inspection quality than the optimum value is not recommended.

3) Excessive maintenance occurs when a maintenance strategy leads to a higher failure probability conditional on repair than the failure probability conditional on no detection.

4) Compared with adopting the optimum quality $a_{d,opt}$, adopting CVI may lead to inadequate maintenance, which describes the case when a lower lifetime fatigue reliability is achieved while adopting a lower inspection quality than the optimum quality $a_{d,opt}$. The failure probability conditional on detection and repair (B2) for CVI is lower than the failure probability conditional on no detection (B3). In such circumstances, adopting an inspection method with quality better than CVI can result in a higher probability of occurrence of B2 (detection and repair) and a lower overall failure probability.

5) Compared with optimum maintenance, inadequate

maintenance is unbeneficial for lifetime fatigue reliability, as discussed in 4) above. However, it may be economical in terms of life cycle total costs, depending on the ratio of the cost of repair to the cost of failure.

Table 5 Contributions to lifetime failure probability by B2 and B3

Case	Probability of occurrence			Conditional failure probability		
	MPI	$a_{d,opt}$	CVI	MPI	$a_{d,opt}$	CVI
B2	0.311	0.266	0.131	7.72e-3	7.72e-3	7.72e-3
B3	0.687	0.732	0.867	1.06e-4	4.58e-4	1.90e-2

6 Conclusions

Maintenance optimization and decision-making, in face of uncertainties in material property, fatigue loading, deterioration modelling and quality of inspection method, has been a complex task, yet very important for marine and offshore structures in terms of life cycle safety, reliability and cost management. This paper has employed probabilistic fracture mechanics and reliability/risk analysis methods for optimizing inspection quality as well as inspection time. The effect of inspection quality on lifetime fatigue reliability index are presented. Based on the investigations, the main following main findings and conclusions can be drawn.

1) There is a reliability-based optimum inspection quality (mean detectable crack size) for maintenance scheduling, which is different from the cost-based optimum solution. The level of the reliability-based optimum inspection quality depends on the stochastic nature of crack growth. It is therefore not appropriate to state that the higher inspection quality, the higher lifetime fatigue reliability, which is intuitive thinking.

2) A higher inspection quality than the optimum one can lead to excessive maintenance, which occurs when a maintenance strategy leads to a higher failure probability conditional on repair than the failure probability conditional on no detection.

3) Excessive maintenance can lead to increases in both expected failure costs and maintenance costs, and thus should be avoided.

Acknowledgement

The authors would like to express their gratitude to the European Union's Horizon 2020 research and innovation programme for their funding toward this project under the Marie Sklodowska-Curie grant agreement No. 642453 (http://trussitn.eu).

Bibliography

[1] Lotsberg, I.; Sigurdsson, G.; Fjeldstad, A.; Moan, T.: *Probabilistic methods for planning of inspection for fatigue cracks in offshore structures*. Marine Structures, 2016. **46**: p. 167-192.

[2] Chen, N.Z.; Wang, G.; Guedes Soares, C.: *Palmgren-Miner's rule and fracture mechanics-based inspection planning*. Engineering Fracture Mechanics, 2011. **78**(18): p. 3166-3182.

[3] Dong, Y.; Frangopol, D.M.: *Incorporation of risk and updating in inspection of fatigue-sensitive details of ship structures*. INTERNATIONAL JOURNAL OF FATIGUE, 2016. **82**: p. 676-688.

[4] Faber, M.H.; Straub, D.; Goyet, J.: *Unified approach to risk-based inspection planning for offshore production facilities*. Journal of Offshore Mechanics and Arctic Engineering, 2003. **125**(2): p. 126-131.

[5] Kim, S.; Soliman, M.; Frangopol, D.M.: *Generalized Probabilistic Framework for Optimum Inspection and Maintenance Planning*. Journal of Structural Engineering, 2013. **139**(3): p. 435-447.

[6] Eltaief, M.; Chateauneuf, A.; Bouraoui, C; Hassine, T.: *Dynamic approach for optimal inspection planning of fatigue cracked components*. Journal of Constructional Steel Research, 2015. **115**: p. 263-275.

[7] Soliman, M.; Frangopol, D.M.; Mondoro, A.: *A probabilistic approach for optimizing inspection, monitoring, and maintenance actions against fatigue of critical ship details*. Structural Safety, 2016. **60**: p. 91-101.

[8] Madsen, H.; Torhaug, R.; Cramer, E.: *Probability-based cost benefit analysis of fatigue design, inspection and maintenance*. in Marine structural inspection, maintenance and monitoring symposium. 1991 Society of Naval Architects and Marine Engineers, New York.

Authors

Mr. Guang Zou
Lloyd's Register EMEA
Lloyd's Register Global Technology Centre
Southampton
UK
guang.zou@lr.org

Dr. Kian Banisoleiman
Lloyd’s Register EMEA
Lloyd’s Register Global Technology Centre
Southampton,
UK
kian.banisoleiman@lr.org

Assoc. Prof. Arturo González
University College Dublin
School of Civil Engineering
Dublin
Ireland
arturo.gonzalez@ucd.ie