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Reliability-based inspection planning in view of both crack initiation and propagation

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ABSTRACT: Fatigue cracks pose threats to the integrity of welded structures and thus need to be addressed in the whole service lives of structures. In-service inspections are important means to decrease the probability of failure due to uncertainties that cannot be accounted for in the design stage. To help schedule inspection actions, the decline curve of reliability index with time needs to be known. A predictive tool is normally developed based on crack propagation models neglecting the crack initiation stage, which leads to conservative predictions for fatigue life. Inspection plans built on those predictions are far from optimal, especially for welds with relatively long crack initiation life. This paper proposes to use a fracture mechanics based reliability analysis method that takes the crack initiation stage into account via the concept of Time-To-Crack-Initiation (TTCI). The optimum inspection plan for a fatigue prone ship structural component is derived by the new approach and compared to the commonly-used method that only considers crack propagation life. Two inspection planning approaches are tested to investigate the influence of incorporating crack initiation period: (i) target reliability approach and, (ii) equidistant inspection times approach. With each planning approach, two inspection methods are adopted: close visual and magnetic particle inspection. The paper concludes with recommendations on the inspection method and planning approach to adopt while considering and without considering the crack initiation stage.

1 INSTRUCTIONS

Structural integrity is a common issue of concern in many engineering fields and industries, e.g. ships, offshore platforms, nuclear pressure structures, wind turbines, bridge decks, etc. The Integrity of ship structures can be compromised by fatigue cracks, corrosion and other mechanical incentives. Among them, fatigue cracks can be more critical than others, as it can result in catastrophic rupture. Generally, fatigue cracks are caused by local stress concentrations in connections and holes. Welded joints are the concerns of this paper, as they are the most common connections in modern steel structures, and are prone to fatigue cracks due to material inhomogeneities, welding flaws, and complicated local geometries (Fricke, 2003).

Safety of welds against fatigue and fracture failure can be secured not only by design check, but also by quality control during construction and inspections during life cycle. Inspections and monitoring are regarded as important techniques to gather information that may be not available in the design stage, for example, damages during construction and assembly, changes to design, new environmental conditions, and most importantly, gross errors due to human factors. Based on inspection results and es-

tablished criterion, maintenance actions may be assigned to repair damages or revise errors. However, frequent inspections and maintenance are costly, especially for large engineering structures where there are thousands of welds. Therefore, it is important to schedule inspection and maintenance actions and direct them to those critical areas to optimize the effectiveness of inspections and maintenance.

A predicative model for fatigue degradation process is of decisive help for inspection planning (Lassen and Recho, 2009). Two distinctive models are S-N model and Fracture mechanics (FM) model. S-N model calculates fatigue damage based on Palmgren-Miner's rule together with S-N curves, while FM model predicts damage evolution in terms of crack propagation. Most of studies on inspection planning are based on FM model (Dong and Frangopol, 2016, Kim et al., 2013, Soliman et al., 2016, Lassen and Recho, 2013). The reason is that FM model predicts evolution history of crack size and shape, which is comparable with inspection results. S-N model is widely used as fatigue analysis tool during design.

FM model based inspection planning assumes that there are existing cracks in a structural component and the initial sizes of the cracks are known, and the crack initiation period is negligible com-

pared to crack propagation period. The assumptions are not always applicable. Some critical components can be well-manufactured and welded, so that they can withstand high number of fatigue loading. It can take long time to develop a detectable crack size in those components (Lassen and Recho, 2013). For them, the crack initiation life may account for a large part of their fatigue life and initial crack size is not available. How to schedule inspections for those components is a problem that has not been answered.

Some fatigue degradation models are developed that can include crack initiation period based on existing crack propagation models. Lassen and Recho (2009) propose a two phrase model to calculate fatigue life for filled steel welds where the crack initiation is treated by a local strain approach. Their model is physically sophisticated, but the transition point between crack initiation and propagation is not uniquely defined. Also, it is impractical to employ their model for probabilistic inspection planning, as it requires more computational efforts. Method based the concept of equivalent initial flaw size (EIFS) is introduced by some researchers (Xiang et al., 2010, Lu et al., 2010). It is assumed that crack propagates from the first cycle with a very small fictitious crack size, which is called EIFS. The EIFS is derived by back-extrapolation. The validity of this method is still an open question as the derived EIFS is normally in the range that linear elastic fracture mechanics is not applicable (Lassen and Sørensen, 2002b). Lassen and Sørensen (2002b) introduce a crack initiation model based on a serial of specimen tests. The crack initiation life is measured by special gauges from the first cycle to the cycle that a detectable crack is developed.

This paper proposes inspection planning methods for high-quality welds in view of both crack initiation and propagation. Probabilistic techniques are adopted to take into account best estimate of long-term stress range, crack initiation life, crack propagation life, inspection performance and associated uncertainties. The crack initiation life follows the model introduced by Lassen and Sørensen (2002b). The model is favoured in this paper because in the initiation stage crack sizes are generally below the size that can be reliably detected by an inspection method, and thus only the number of cycles to reach a detectable crack size matters for inspection planning. To investigate the influence of including crack initiation life, two inspection planning approaches are tested: target reliability approach and equidistant inspection times approach.

2 RELIABILITY WITHOUT INSPECTION

From the point of fracture mechanics, fatigue crack growth process consists of three stages: crack initia-

tion, crack propagation and fracture. As the final fracture happens typically very quickly, the total number of cycles (fatigue life) N_F consists of the number of cycles spent in the initiation stage (crack initiation life) N_I and the number of cycles in the propagation stage (crack propagation life) N_p , and is expressed as

$$N_F = N_I + N_p \quad (1)$$

2.1 Crack propagation models

2.1.1 Paris's model

Paris's Model relates the rate of crack propagation with material parameters, stress range and local geometry. The one-dimensional Paris law is given by

$$\frac{da}{dN} = C \Delta K^m \quad (2)$$

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

$$\Delta K = \Delta \sigma Y(a) \sqrt{\pi a} \quad (3)$$

where $\Delta \sigma$ is stress range and $Y(a)$ is geometry function.

2.1.2 Elber's model

In order to take into account crack closure effect, Elber proposes Equation 4 to model the crack propagation.

$$\frac{da}{dN} = C \Delta K_{eff}^m \quad (4)$$

where ΔK_{eff} is the effective stress intensity factor range, given by

$$\Delta K_{eff} = \begin{cases} 0 & K_{op} \geq \frac{\Delta K}{1-R_S} \\ \frac{\Delta K}{1-R_S} - K_{op} & \text{else} \\ \Delta K & K_{op} \leq \frac{\Delta K}{1-R_S} \cdot R_S \end{cases} \quad (5)$$

where R_S is stress ratio and K_{op} is the stress intensity factor at which the crack is opened.

2.1.3 Bi-linear model

It is found that the crack propagation rate does not stay the same during crack propagation and bi-linear model as Equation 6 are proposed by standards, e.g. British Standard(2005)

$$\frac{da}{dN} = \begin{cases} C_1 (\Delta K)^{m_1} & \Delta K_{th} < \Delta K \leq \Delta K_{tr} \\ C_2 (\Delta K)^{m_2} & \Delta K_{tr} < \Delta K \end{cases} \quad (6)$$

where ΔK_{th} is threshold of the stress intensity factor range; ΔK_{tr} is transition of the stress intensity factor range; C_1 , C_2 , m_1 and m_2 are material parameters.

2.1.4 Two-directional model

The model is an extension of the Paris law for the crack propagation in the depth and length direction and is expressed as

$$\begin{cases} \frac{da}{dN} = C_a(\Delta K_a)^m & \Delta K_a > \Delta K_{th} \\ \frac{dc}{dN} = C_c(\Delta K_c)^m & \Delta K_c > \Delta K_{th} \end{cases} \quad (7)$$

where C_a and C_c are crack propagation rate in the depth and length respectively.

2.2 Crack initiation life

Fatigue cracking is a complicated phenomenon. The mechanism for crack initiation relates largely to material behaviour in grain size level and surface treatment of structures. In detail, crack initiation period can be further divided into crack nucleation period and small crack propagation period, both of which normally happen in the dimension that is much smaller than the smallest crack size that can be reliably detected by non-destructive inspection methods. This paper concerns about the time to crack initiation.

The crack initiation in steel welds can be treated with a local weld notch approach (Lassen and Recho, 2009). The number of cycles for crack initiation N_I is determined by the Coffin-Manson Equation with Morrow's mean stress correction

$$\frac{\Delta \varepsilon}{2} = \frac{(\sigma_f' - \sigma_m)}{E} (2N_i)^b + \varepsilon_f' (2N_i)^c \quad (8)$$

where b and c are fatigue strength and ductility exponents; σ_f' and ε_f' are fatigue strength and ductility coefficients.

The local stress and strain is governed by the Ramberg-Osgood stabilized cyclic strain curve expressed by

$$\Delta \varepsilon = \frac{\Delta \sigma}{E} + 2 \left(\frac{\Delta \sigma}{2K'} \right)^{\frac{1}{n'}} \quad (9)$$

where K' is cyclic strength coefficient and n' is strain hardening exponent

The approach is based on the mechanics of crack initiation, but the transition point between crack initiation and propagation is at present not uniquely defined. Some roughly guidance on the transition crack size is proposed. Lawrence et al. (1996) suggest that the transition depth a_{tr} should be between 0.05 and 0.1mm. Often practitioners just set the transition depth to 0.25 mm arbitrarily (Lassen and Recho, 2013). Radaj and Vormwald (2007) propose a transition crack size about 0.5mm in depth and 1 mm in length for semi-elliptical surface cracks in medium strength steel. The transition depth of 0.5 mm is adopted by ABS (2003).

The crack initiation life can also be accounted for based on the EIFS concept. The approach extrapolates the crack propagation period to a very small equivalent initial flaw size. The total fatigue life is calculated by

$$N_F = \int_{a_{eqi}}^{a_c} \frac{da}{C(\Delta \sigma \sqrt{\pi a} Y(a))^m} \quad (10)$$

The equivalent initial flaw size a_{eqi} is calibrated to S-N curves or specimen test data with the criterion of total fatigue life or probability of failure. The calibration typically requires much computational efforts and the derived a_{eqi} is very sensitive to crack propagation parameters (Palmberg, 2001).

Lassen and Sørensen (2002b) propose an explicit model for crack initiation based on specimen tests on the time to crack initiation (TTCI). The specimens are tested under constant amplitude axial loading $\Delta S = 150\text{MPa}$. Crack growth curves are measured from the smallest detectable crack size ($a_0=0.1\text{mm}$) to the final critical crack size ($a_c=0.5t$, t was the plate thickness) and the corresponding cycles spent is defined as N_p . The number of cycles from the first cycles to the cycle when a crack depth of 0.1mm is developed is recorded and defined as N_I . Test data shows that approximately 31% of the fatigue life is spent before a crack depth of 0.1 mm is reached. The crack initiation period N_I is determined by

$$N_I = N_{I_0} \frac{(150\text{Nmm}^{-2})^m}{E[\Delta S]^m} \quad (11)$$

where m is crack propagation exponent and normally assumed to be 3.0. N_{I_0} is the number of cycles spent in the crack initiation stage when the stress range is 150MPa, and follows Weibull distribution with a mean value of 145,000 cycles with a COV of 0.34.

The model is adopted by Ayala-Uraga and Moan (2007) to calibrate a bi-linear FM model for welds, and is also employed in the present paper for reliability-based inspection planning.

2.3 Failure criterion and Limit-state function

If criterion for fracture is defined, capacity of a structure component against fracture can be calculated. A limit-state function can be formulated as.

$$M(t) = R(t) - S(t) \quad (12)$$

where R is a function modelling fatigue capacity and S is a function modelling fatigue load effect or fatigue demand.

Failure criterion should be defined based on analysis of the consequence of failure and the redundancy of the structure. In fatigue and fracture analysis, two failure criteria are generally applicable. The first criterion is based on serviceability analysis. It is thought that a structural component is not serviceable if a through thickness crack exists, so a critical crack size equals to plate thickness T can be used as a failure criterion. Using this criterion, a limit-state function can be formulated.

$$M(t) = a_c - a(t) \quad (13)$$

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

As the crack propagation curve near the final fracture is typically highly non-linear, the calculated fatigue life and the reliability is not very sensitive to the value of a_c . In engineering practice, more strict failure criterion can also be used, e.g. $a_c = 0.5T$, based on engineering experiences.

The capacity and load can also be expressed by number of cycles, and limit-state function such as Equation 14 can be used.

$$M(t) = N_F - N(t) \quad (14)$$

where N_F is the capacity of a structural component against fracture and $N(t)$ is the fatigue loading experienced by the component till time t .

Previous studied on inspection planning generally calculate N_F by integration of a crack propagation model, while in the present paper the crack initiation life is included in N_F and Equation 1 is used.

The other failure criterion is based on the concept of material fracture toughness K_{mat} . It is thought that brittle fracture occurs if the stress intensity factor K caused by fatigue loading is larger than the material fracture toughness K_{mat} . Using this criterion, a limit-state function can be formulated as.

$$M(t) = K_{mat} - K \quad (15)$$

The above equation is not frequent used for inspection planning for welds, as the steels in structural engineering are mostly ductile materials. In addition, considering brittle fracture normally increases computational requirements (Souza and Ayyub, 2000).

3 CHARACTERIZATION OF INSPECTION METHODS

Commonly-used inspection methods for engineering structures are non-destructive testing (NDT) methods and visual inspection. NDT methods have high reliabilities of detection, but the costs are also high. On the contrary, the accuracy of visual inspection is lower than NDT methods, but the cost is also much lower. Because of this, visual inspection is still used in large engineering structures where the inspection work is very large and there is redundancy with the structures, such as ship structures. For those structures, visual inspection is efficient and NDT only be required where the consequences of failure are very serious (Lotsberg et al., 2016). In summary, inspection methods are dependent on failure consequences and requirements in accuracy, cost and accessibility. In this paper, close visual inspection (CVI) and magnetic particle inspection (MPI) are adopted.

The performance of an inspection method is characterized by the smallest crack size that can be reli-

ably detected by an inspection method. As there are uncertainties associated with inspections, the smallest crack size that can be detected is treated as a variable a_d in this paper and it has a distribution. Its distribution is equal to the so-called probability of detection (PoD). PoD reflects the reliability of an inspection method to detect an existing crack and it is a function of crack size. The PoD curve for an inspection method is obtained from blind-tests or in-service inspection data. In this paper, the PoDs for CVI and MPI are modelled with the commonly-used exponential distribution (Chen et al., 2011, Moan and Song, 2000). The PoD (also the cumulative probability function for variable a_d) is given by $PoD = F(a_d) = 1 - \exp(-a_d/v_d)$ (16) where v_d is the mean detectable crack size. The v_d values associated with CVI and MPI are 2mm and 0.89mm respectively (Dong and Frangopol, 2016). The PoDs for CVI and MPI is given by Figure 1.

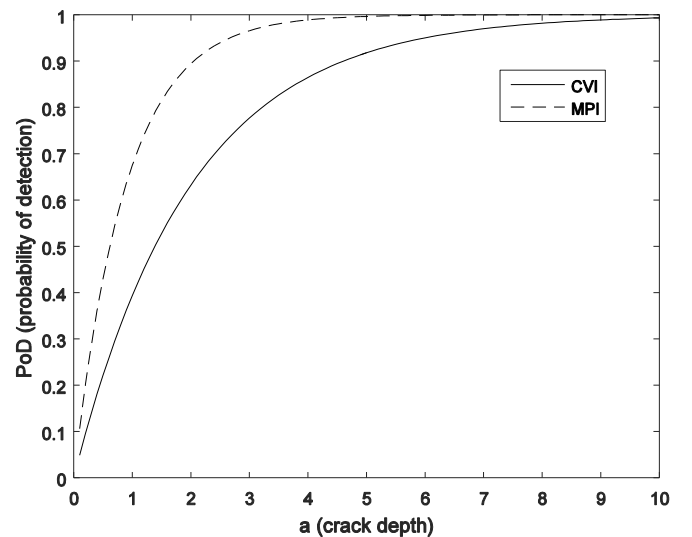


Figure 1. PoD curves for CVI and MPI

4 INSPECTION STRATEGIES

Establishment of suitable inspection strategies is one of the most important tasks of structural integrity management. Generally inspection strategy means where to inspection, when to inspection and how to inspect. The locations for inspections are determined by risk analysis with considerations in the importance of a component and previous inspection results. This paper concerns about inspection times and inspection methods.

Inspection planning can be based on time, reliability, cost or multi-objective optimization. In this paper the economic aspects of inspections are not considered, and reliability-based and time-based inspection planning methods for high-quality welds are investigated. Reliability-based inspection planning means that inspections are scheduled every time

when the calculated reliability is not higher than the target reliability level and can be expressed as

$$\beta_i \leq \beta_t \quad i = 1, 2, \dots, n \quad (17)$$

where β_t is the target reliability index, n is the number of inspections, β_i is the calculated reliability index when the i th inspection is supposed to be done. Time-based inspection is a relatively simple approach, in which inspections are schedule periodically, e.g. every 5 years.

5 RELIABILITY UPDATING WITH INSPECTIONS

Inspection techniques are in essence, means to gather new information on structures or load effects. The new information provided by inspections, regardless of the inspection outcome, can be used to update the reliability level. In this way, one has more confidence in reliability of the structure and uncertainties are reduced.

Reliability updating is based on the definition of conditional probability and Bayesian Theorem

$$P(F|I) = \frac{P(F \cap I)}{P(I)} \quad (18)$$

where $P(F|I)$ is the probability the event F occurs given that event I occurs.

In this paper, F is fracture failure occurs, and I are the inspection outcomes. F is given by

$$F(t) = N_F - N(t) \leq 0 \quad (19)$$

The event of no detection is considered, as it is the most common outcome. The even can be expressed by

$$I(t) = a_t - a_d \leq 0 \quad (20)$$

If n inspections are implemented with no detection, then the event can be expressed as

$$I(t_1, t_2, \dots, t_n) = a_{t_1} - a_d \leq 0 \cap a_{t_2} - a_d \leq 0 \cap \dots \cap a_{t_n} - a_d \leq 0 \quad (21)$$

where $a_{t_1}, a_{t_2}, \dots, a_{t_n}$ are the predicted crack size at time t_1, t_2, \dots, t_n . In this paper, it is assumed that each inspection is independent.

Substituting Equation (19) and (21) into Equation (18), one can obtain the probability of fracture failure given that n inspections have been implemented with no detection,

$$P(F|I) = \frac{P(N_F - N(t) \leq 0 \cap a_{t_1} - a_d \leq 0 \cap a_{t_2} - a_d \leq 0 \cap \dots \cap a_{t_n} - a_d \leq 0)}{P(a_{t_1} - a_d \leq 0 \cap a_{t_2} - a_d \leq 0 \cap \dots \cap a_{t_n} - a_d \leq 0)} \quad (22)$$

6 AN ILLUSTRATIVE EXAMPLE

The proposed inspection planning methods are illustrated on stiffened plates, which are typical fatigue-prone components in ship structures. Fatigue cracking in the root of a stiffener is shown in Figure 2. If the ship is a cruiser, the target reliability for such stiffeners are 2.5, 3.0 and 3.5 respectively for the failure consequence for not serious, serious and very serious (Mansour, 1996). The relationship between

the reliability index and probability of failure is shown in Table 1. There are thousands of such stiffeners in a ship structure and fatigue failure caused by cracks is common in its service life. For example, if the number of stiffeners in a ship is 5000, and the calculated reliability index in 20 years is 2.5, there would be $5000 \times 6.2097 \times 10^{-3} = 31$ stiffeners fail within 20 years.

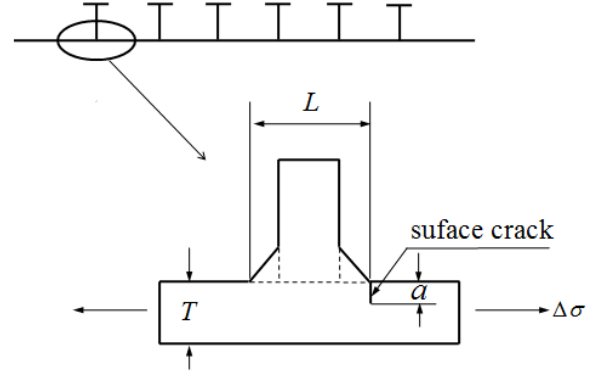


Figure 2. A fillet welded joint in a stiffened plate

Table 1. Relationship between β and P_f

β	4.0	3.5	3.0	2.5	2.0
P_f	3.1671×10^{-5}	2.3263×10^{-4}	1.3499×10^{-3}	6.2097×10^{-3}	2.2750×10^{-2}

6.1 Stochastic modeling

The crack propagation parameters C and m follow DNVGL (2015), which treats m as deterministic and C is lognormal distributed. The statistics recommended by Lassen and Sørensen (2002b) are adopted for mean value and COV of for N_I and $\Delta\sigma$. The smallest crack sizes a_{d1} and a_{d2} that can be detected by CVI and MPI are treated as variables and follow exponential distributions. The mean values for a_{d1} and a_{d2} are 2mm and 0.89mm respectively (Dong and Frangopol, 2016). The statistics and distributions for all the variables are listed in Table 2.

Table 2 Variables used in reliability calculation

Variable	Distribution	Mean	COV
m	Deterministic	3	NA
C	Lognormal	1.83×10^{-13}	0.22
$\Delta\sigma$	Lognormal	18.5MPa	0.20
N_I	Weibull	7.729×10^7	0.34
a_{d1} (CVI)	Exponential	2mm	1
a_{d2} (MPI)	Exponential	0.89mm	1
T	Deterministic	25mm	NA

6.2 Results and discussions

In this paper, three inspections are considered at the most. If more inspections are needed, reliability can be updated with the same procedure. Figure 3-10

show the initial reliability index and the updated reliability indexes by inspection results. Three inspection strategies are studied: reliability-based inspection with $\beta_t = 2.5$ (Figure 3, 4) reliability-based inspection with $\beta_t = 3.5$ (Figure 5, 6) and time-based inspection (Figure 7-10). Two inspection methods (CVI and MPI) are adopted with each inspection strategy. The results are analysed with respect to number of inspections, inspection times, inspection intervals and reliabilities before inspections in Table 3-6 respectively. The meanings of the symbols in the figures are as follows.

- β_0 : Initial reliability without inspection;
- β_1 : Reliability after the first inspection and the result is no detection;
- β_2 : Reliability after two inspections and the results are no detection;
- β_3 : Reliability after three inspections and the results are no detection;
- ICI: Crack initiation life is included;
- NCI: Crack initiation life is neglected.

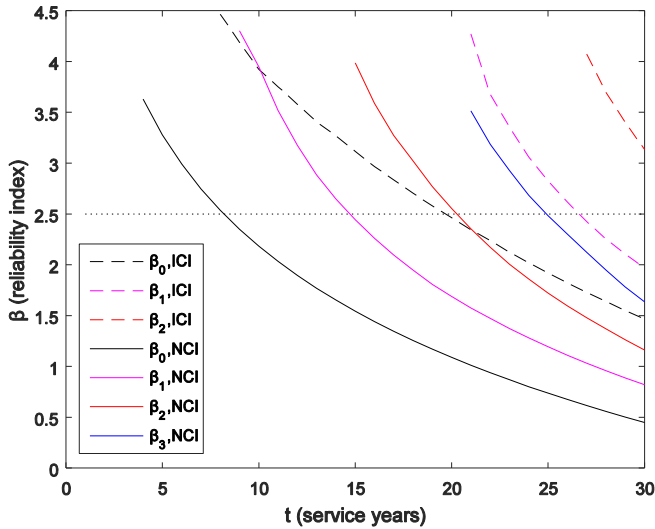


Figure 3. Reliability-based inspection updating ($\beta_t = 2.5$, CVI)

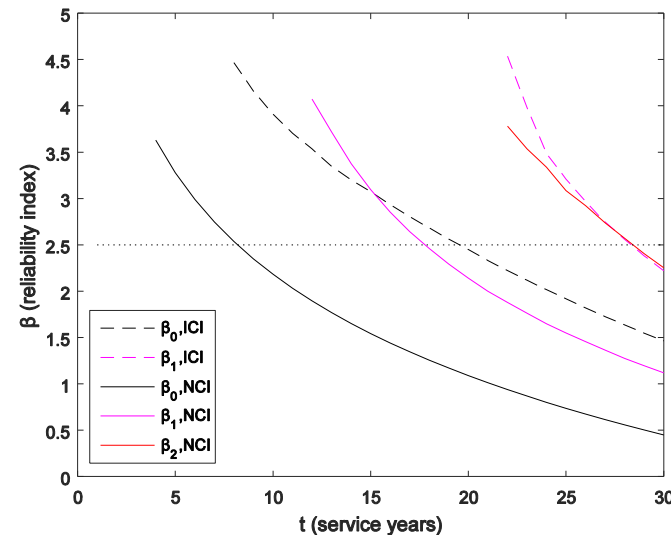


Figure 4. Reliability-based inspection updating ($\beta_t = 2.5$, MPI)

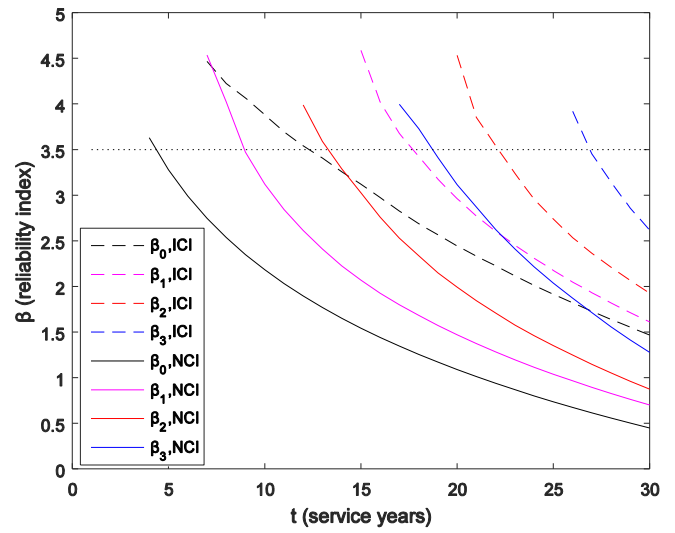


Figure 5. Reliability-based inspection updating ($\beta_t = 3.5$, CVI)

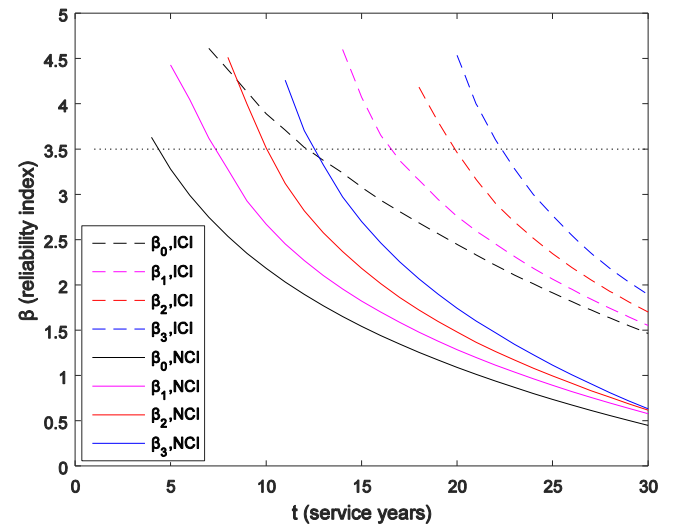


Figure 6. Reliability-based inspection updating ($\beta_t = 3.5$, MPI)

6.2.1 Number of inspections

Table 3 show that if the target reliability is chosen as 2.5, the number of inspections derived from probabilistic analysis considering both crack initiation and propagation is less than that only accounting for crack propagation. However, if the target reliability is chosen as 3.5, the conclusion cannot be drawn. This means that derived the number of inspection based on reliability is sensitive to the target reliability level. If the target reliability is high, regular inspections are necessary, even though crack initiation life is considered and the component has higher reliability level.

Table 3. Number of inspections

Inspection strategy	Number of inspections n		
	NCI	ICI	
$\beta_t = 2.5$	CVI	>3	2
	MPI	3	2
$\beta_t = 3.5$	CVI	>3	>3
	MPI	>3	>3
$\Delta t_1 = 15, \Delta t_2 = \Delta t_3 = 6$	CVI	NA	3
	MPI	NA	3
$\Delta t_1 = \Delta t_2 = \Delta t_3 = 6$	CVI	3	NA
	MPI	3	NA

6.2.2 Inspection intervals

Table 4 shows that the time for the first inspection can be delayed by 11 years and 8 years respectively for $\beta_t = 2.5$ and $\beta_t = 3.5$ if crack initiation life is considered. As the reliability of the component is high in the crack initiation stage, so the times for inspections can be delayed. Inspection plans built on analysis neglecting crack initiation life can be too conservative and the first inspection may be a waste of money. This is important when planning inspections for welds.

Table 5 shows that even though the interval for the first inspection can be extended if crack initiation life is included, the intervals for the following inspections show no noticeable difference between plans based on ICI and NCI. The reason may be that the reliability decrease of the component in the former stage of service years is caused by crack initiation while the decrease in the latter stage caused by crack propagation.

Table 4. Inspection times

Inspection strategy		Inspection times (year) t_i	
		NCI	ICI
$\beta_t = 2.5$	CVI	9/15/21	20/27/NA
	MPI	9/18/29	20/29/NA
$\beta_t = 3.5$	CVI	5/8/11	13/17/20
	MPI	5/9/14	13/18/23
$\Delta t_1 = 15, \Delta t_2 = \Delta t_3 = 6$	CVI	NA	15/21/27
	MPI	NA	15/21/27
$\Delta t_1 = \Delta t_2 = \Delta t_3 = 6$	CVI	6/12/18	NA
	MPI	6/12/18	NA

Table 5. Inspection intervals

Inspection strategy		Inspection intervals (years) Δt_i	
		NCI	ICI
$\beta_t = 2.5$	CVI	9/6/6	20/7/NA
	MPI	9/9/11	20/9/NA
$\beta_t = 3.5$	CVI	5/3/3	13/4/3
	MPI	5/4/5	13/5/5
$\Delta t_1 = 15, \Delta t_2 = \Delta t_3 = 6$	CVI	NA	16/6/6
	MPI	NA	15/6/6
$\Delta t_1 = \Delta t_2 = \Delta t_3 = 6$	CVI	6/6/6	NA
	MPI	6/6/6	NA

6.2.3 Inspection methods

Table 4-6 show that the updated reliabilities increase more with the results from MPI than from CVI if both results are no detection, and accordingly the inspection intervals can be longer if MPI is used than CVI. This indicates that inspection methods with higher performance is able to increase inspection interval and possibly decreases the number of inspections if the results are no detection.

6.2.4 Time-based inspection plans

In view of convenience in logistics, sometimes time-based inspection plans are preferred in engineering practices. So time-based inspection planning is also

studied in this paper. The time interval is determined based on the results of previous probabilistic analysis. The interval is 6 years if crack initiation life is neglected. If crack initiation life is considered, the interval for the first inspection is 15 years and the intervals for the following inspections are 6 years. The reliabilities of the component before inspections are listed in Table 6. The table shows that the intervals of inspections are able to keep the reliability of the component above 2.5 if CVI is used, and above 3.2 if MPI is employed. The table also demonstrates that reliability-based inspection plans is able to keep the safety margin above a certain level more evenly than time-based inspection plans. In this regards, reliability methods are more rational.

Table 6. Reliability before inspections

Inspection strategy		Reliability before inspections	
		β_i	
		NCI	ICI
$\beta_t = 2.5$	CVI	2.54/2.64/2.55	2.58/2.62/NA
	MPI	2.54/2.67/2.53	2.58/2.55/NA
$\beta_t = 3.5$	CVI	3.63/3.62/3.51	3.58/3.65/3.80
	MPI	3.63/4.02/3.59	3.58/3.68/3.54
$\Delta t_1 = 15, \Delta t_2 = \Delta t_3 = 6$	CVI	NA	3.27/3.04/2.74
	MPI	NA	3.27/3.34/3.21
$\Delta t_1 = \Delta t_2 = \Delta t_3 = 6$	CVI	3.28/2.66/2.56	NA
	MPI	3.28/3.20/3.41	NA

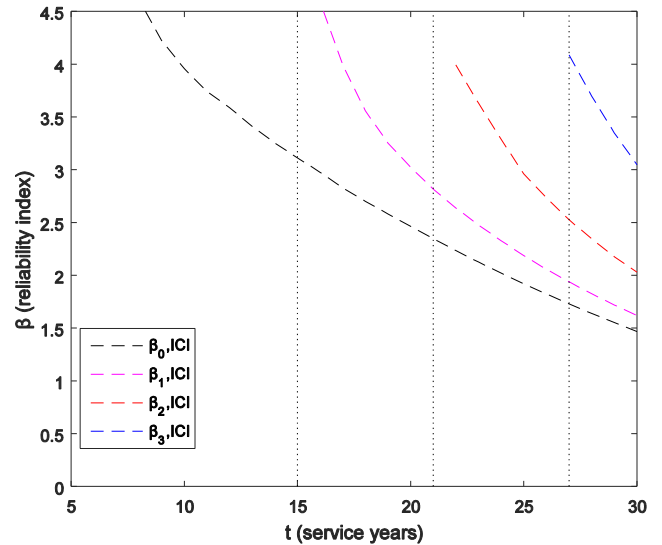


Figure 7. Time-based inspection updating based on the model ICI (CVI)

7 CONCLUSIONS

The safety of welded structures against fatigue and fracture cannot be absolutely guaranteed due to the uncertainties in the fatigue process. It is well-known that the initial flaw size a_0 in a structural component is associated with high degree of uncertainties, and thus is one of the most influential variables for prediction of the crack propagation life. The initial flaw size a_0 here signifies the initial state of the component. This paper accounts for the initial state of welds via the concept of TICI or crack initiation life, and formulates fatigue life with both crack initiation life and crack propagation life. The benefits of such fatigue degradation model are that crack initiation life is included in the predictions and one does not need to know the statistical information on initial flaw size.

Reliability-based and time-based inspection planning methods are proposed based on the fatigue degradation model, PoD curves and inspection results. Probabilistic methods are employed to tackle with uncertainties associated with crack initiation life, crack propagation rate, stress range calculation and inspection performance. The proposed methods are applied to a fatigue-prone weld in ship structure. Based on probabilistic analysis, the following conclusions are obtained.

- 1) The interval for the first inspection can be extended if crack initiation life is considered. However, the intervals for the following inspections show no noticeable difference with or without crack initiation life. If crack initiation life is considered, it is proposed to adopt a relatively long interval for the first inspection and allocate more inspections on the latter part of service life.
- 2) The number of inspections may decrease if crack initiation life is considered, depending on the target reliability level.
- 3) If time-based inspections are preferred in engineering practice, the inspection intervals can also be determined based on probabilistic analysis.
- 4) In all circumstance, inspection methods with high performance can provide more reliable information, and thus are preferred from the point of structural safety. So the choice of inspection methods cannot be determined solely by safety factor.

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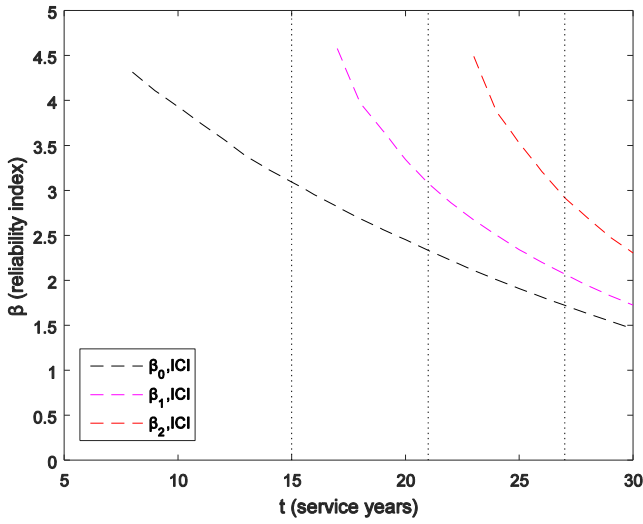


Figure 8. Time-based inspection updating based on the model ICI (MPI)

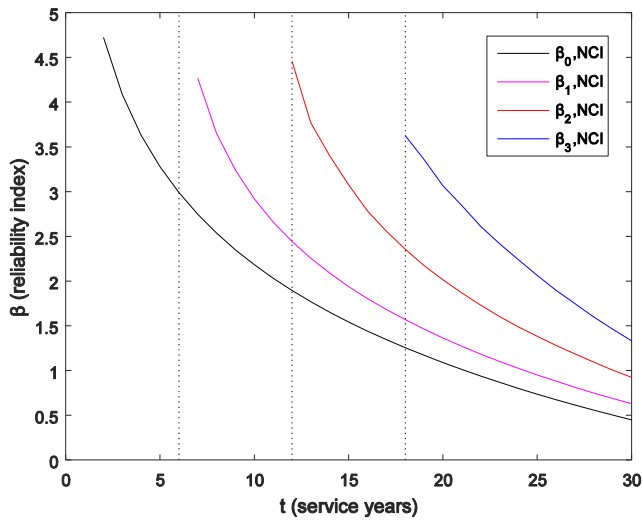


Figure 9. Time-based inspection updating based on the model NCI (CVI)

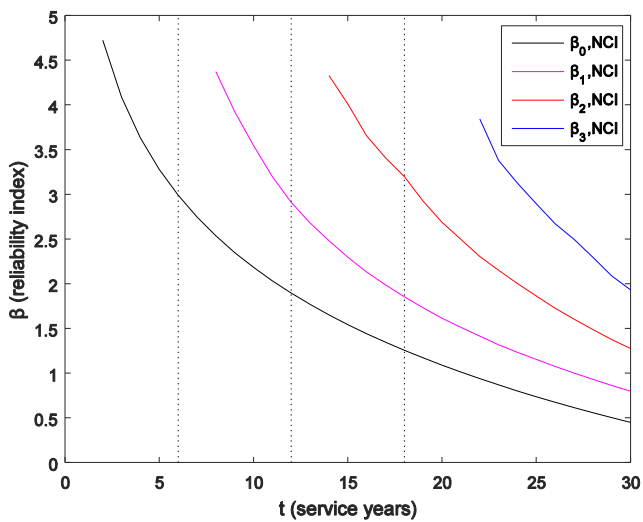


Figure 10. Time-based inspection updating based on the model NCI (MPI)

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