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Investigation of updating methods for probability-informed inspection planning for offshore structures

G Ersdal[1,2,*] and N Oma[2]

[1] University of Stavanger, Norway
[2] Petroleum Safety Authority, Stavanger, Norway

[*] Corresponding author: gerhard.ersdal@uis.no

Abstract. The paper presents a novel process for probability-informed inspection planning based on the following principles. 1) A description of the strength of knowledge about a problem shall be included and be accounted for in the decision making, 2) Probabilistic methods should be used to predict quantities expressing the physical reality of nature (observable quantities) and their uncertainty, and 3) Any update of the probabilistic model should be limited to the actually observed quantities. The process for updating the probability of failure after inspection is programmed in accordance with these principles based on Monte-Carlo simulations and Bayesian parameter updating. The application of these principles and the proposed process is illustrated by an example calculation resulting in an example of inspection intervals for a jacket structure.

1. Introduction

Planning the extent and frequency of inspections is a key topic in in-service integrity management for offshore structures. In many cases this is being performed in accordance with prescriptive standards typically requiring first a base-line inspection during the first year of operation and then periodic inspections at fixed time intervals for specified structural details. In addition, an operator is typically required by such standards to do special inspections to monitor the development of known defects and anomalies and to perform un-scheduled inspection after special events such as major storms or collisions. This prescriptive time-based scheme for inspection planning has been in use for many years in the offshore industry. In addition, it has been the fundament for the in-service inspection program (IIP) provided by class societies for mobile offshore units (MOUs) and in the shipping industry.

A prescriptive time-based inspection programme is claimed to require a quite extensive inspection scope. Operators of offshore jacket structures seldom find signs of deterioration and damages corresponding with such an extensive inspection scope in the primary structure. As a result, a condition-based inspection programme (CBI) has been implemented by many operators to reduce the extent of the inspection scope if earlier inspections have found that the condition is good.

The inspection-intervals may be determined by previous experience, but probabilistic methods rapidly proved to be a more rational approach for determining the inspection intervals, especially for fatigue cracks. The general idea for determining the inspection intervals by probabilistic methods is that all uncertain parameters are modelled by a representative probability distribution. These parameters may include:

- The cyclic stress distribution
- The initial crack size in the welds
- The crack growth parameters in the Paris crack growth law
- Detection accuracy of the inspection method

Model uncertainties are normally included into the probabilistic model to account for the uncertainty in the various models used for calculating the fatigue crack growth, such as determining the long-term cyclic stress distribution and determining the uncertainty in the Paris crack growth model.

The probability distribution of the crack growth of various details can then be predicted by various probabilistic methods such as Monte Carlo simulation, first-order and second-order reliability methods (FORM and SORM). In a Monte Carlo simulation this can be performed by randomly selecting values for each uncertain variable from their probability distribution and calculate the crack growth based on each set of variables. The probabilistic methods can then produce a probability distribution of the expected crack size with time as indicated in Figure 1. The probability of failure can be defined as the probability of the crack exceeding a certain value (e.g. the thickness of the specimen as shown in Figure 1).

The next step is to implement an updating of the distribution of the crack size after an inspection has been performed. If the inspection has not revealed any indications of fatigue cracks, the expected crack size can be assumed to be lower than the crack size that can be determined by this inspection method. However, the crack size that is detectable by an inspection method is also an uncertain parameter and this is normally illustrated by a probability-of-detection (POD) distribution rather than a fixed number. In a Monte Carlo simulation, the updating of the crack-size distribution can be performed by filtering the possible expected crack size after the inspection.

As an example: Assume a case where one simulation is performed resulting in a crack of 3 mm in depth at the time of inspection. Further, let's assume that the POD curve gives a 90 percent probability of detecting a crack of this size, then there will be a 90 percent chance that this will be discovered. If we assume that the actual inspection did not find any crack, this simulation must be rejected. In the simulation this is included by a so-called Bayesian updating. The Bayesian updating in this context is performed by requiring a new crack size after inspection that is taken from the distribution of the cracks that was not detected in the inspection. The updated distribution of cracks can be illustrated as shown in Figure 2.

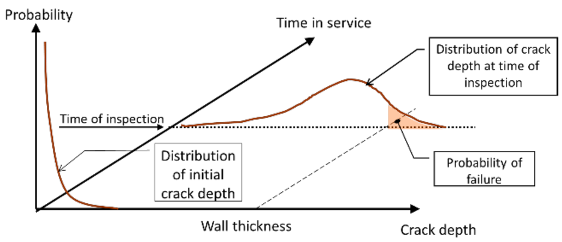

Figure 1. Illustration of development of crack depth distribution over time in service from an assumed initial crack depth distribution to the expected distribution of crack depths at time of inspection.

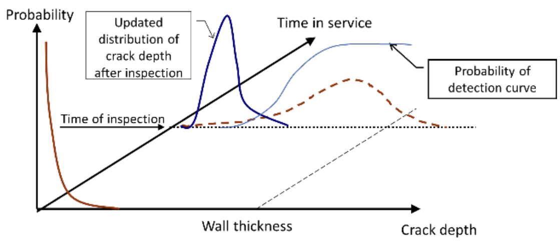

Figure 2. Updated distribution of crack depth after inspection taking into account the new information gained by the inspection result.

An example of the results of an analysis using such updating is shown in Figure 3. In this example inspection has been determined to be needed after approximately 18 years. After the inspection, assuming no cracks found, the probability is updated, and the next inspection is then needed after an additional 12 years. The inspection intervals indicated in this example, assuming no cracks found in any of these inspections, can then be found to be 18, 12, 20 and 25 years respectively (see Figure 3).

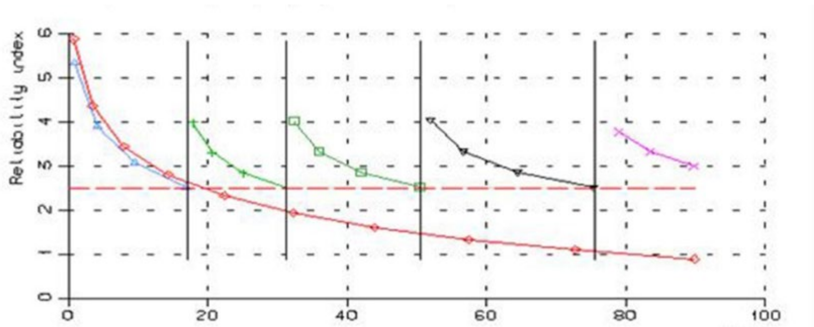

Figure 3. Updated probability of fatigue crack in structure (www.dnvgl.com).

The industry approach to structural design may introduce a bias on the load response. This is important in the design of new structures in order to provide sufficiently safe structures. However, a bias larger than unity may contribute to unrealistic strong effects in a general updating process.

Although the example in Figure 3 is purely an illustration it indicates the trend that is often the result of probability-based inspection planning, namely that the inspection intervals for ageing structures seems to increase with age rather than to decrease as one would intuitively expect. Hence, an alternative method of updating the failure probability is presented in this paper to investigate a different method for establishing inspection intervals. This method updates the probability distribution functions for the parameters where new information is available [1, 2] rather than performing a general updating [3].

In addition, the probability-informed inspection planning presented herein is a suggestion for a method that is believed to be in line with PSA's Risk and Risk management Memorandums [4, 5].

2. Proposed principles and method for probability and risk-informed analysis

Risk and probabilistic methods for decision making is a way to account for the inherent uncertainties in a problem. Such uncertainties can be in the physical parameters like the loads from waves and the material parameters that describes the fatigue crack growth. These uncertainties will also be in the model we use to determine the crack growth based on the Paris' equation. In addition, the presence of gross errors (design errors and fabrication defects) are uncertain. Some of these uncertainties can be included in the probabilistic analysis based on available knowledge. This knowledge is however often taken from other structures and from laboratory experiments not necessarily representing the structure being analysed.

The uncertainty can be illustrated as shown in Figure 4 where the inner green circle is the uncertainties that is included in the analysis based on good and relevant data (wave data for the specific field may fall into this category if measured properly for a significant long period). The next circle (in orange) illustrates other uncertainties that is included in the analysis but based on more uncertain data (the assumed uncertainty in the wave loading and crack growth model may fall into this category). The next circle (in blue) illustrates known uncertainties that are not included in the analysis (e.g. uncertainties related to gross errors). The area outside this circle illustrates the unknown uncertainties which for obvious reasons are not included in the analysis, but it may be relevant for the safety of the structure.

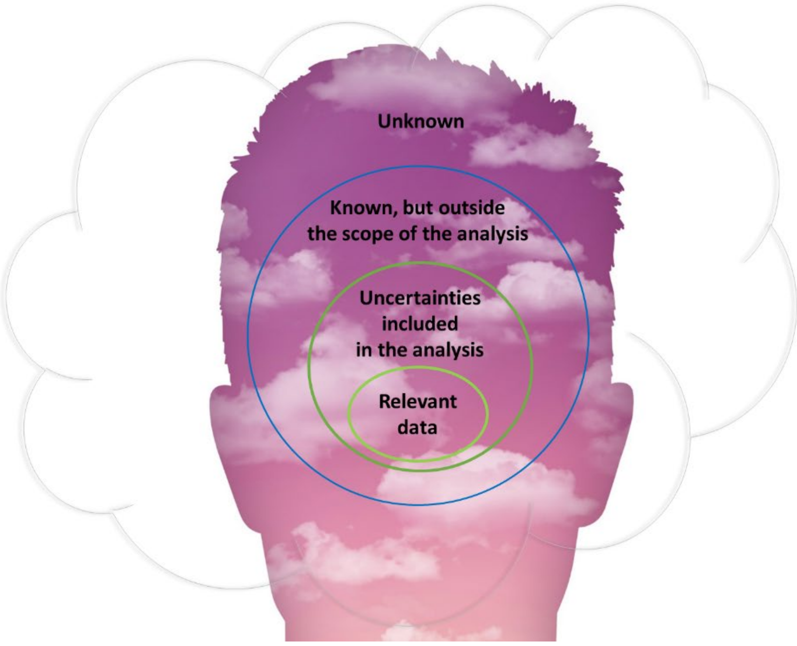

Figure 4. Uncertainty related to a decision-making problem [5].

If one accepts the illustration in Figure 4 and the fact that there are uncertainties that are not included in the probability- and risk-informed analysis it is rational to conclude that the probabilities and consequences that we describe will have limitations. Because of these limitations, the principles presented in this paper is suggested to be used for probability- and risk-informed analysis for inspection planning of structures.

The strength of knowledge behind a calculated probability and the consequences of an event are limited by the modelling of uncertainties mentioned above. Hence, assigned probabilities and consequences are not sufficient to make decisions alone, e.g. by comparing the calculated probability with an acceptance criterion and making the decision solely by this comparison without evaluations of sensitivity and strength of knowledge behind the calculated results. Uncertainties by means of the strength of knowledge behind the physical problem need to be investigated and accounted for. This leads to:

Principle 1: *A description of the strength of knowledge about a problem shall be included and be accounted for in the decision making*.

Taking principle 1 into account it is rational to argue that the probabilistic analysis should focus on determining observable quantities[1] (such as crack sizes and wave heights) rather than probabilistic values ($P_{failure}$). This is because the decision maker is better fit to evaluate such observable quantities, but also that data about future events can be used to validate these observable quantities (while experience indicate that a $P_{failure}$ seldom can be validated). This leads to:

Principle 2: *Probabilistic methods should be used to predict quantities expressing the physical reality of nature (observable quantities) and their uncertainty.*

This principle's focus on observable quantities rather than abstract probabilistic values for a crack growth and inspection planning analysis is an attempt to highlight uncertainty about e.g. the crack size, the inspection intervals and the load model rather than a discussion about the calculated probabilities. Modelling can then be used to get insight into factors influencing the safety of the structure, identify

[1] Observable quantities are values that are unknown at the time of the analysis but may become known at a later stage (Aven 2012). These observable quantities can be predicted by the probabilistic analysis and uncertainties related to these observable quantities can be described.

major contributors to the safety of the structure and see the effect of changes by use of sensitivity analysis.

The 3rd principle is an extension of principle 2 and is requiring that also Bayesian updating based on e.g. performed inspections is focusing on the parameter that is being observed (e.g. the crack size), while traditional updating methods (general updating) in probability analysis may be used to update several parameters (including parameter that is not actually observed). This leads to:

Principle 3: *Any update of the probabilistic model should be limited to the actually observed quantities*.

For structures, example of such possible observable parameters includes e.g. wave heights, measured strains, measured number of load cycles and crack sizes. In this paper the primary observable quantity used is the crack size found during inspections. Also, the suggested inspection intervals can be observed to detect if insufficient or excessive inspections is proposed.

Based on these three principles it is proposed to perform the probability-informed inspection planning analysis as follows:

- Inspection intervals should not be determined directly from the acceptance criteria. The uncertainty in the estimated inspection intervals should be evaluated and experience from integrity management of real structures should be taken into account in the evaluation.
- The strength of knowledge about the problem should be described and accounted for in determining the inspection intervals.
- The analysis should be performed to illustrate the uncertainty in the observable quantities (crack size and necessary inspection intervals).
- The updating procedure should exclusively update the observed quantities (e.g. crack size).

3. Proposed method for inspection planning

A process for probability-informed inspection planning following the principles presented in section 2 for inspection planning of an offshore jacket structure is illustrated in ***Figure 5***.

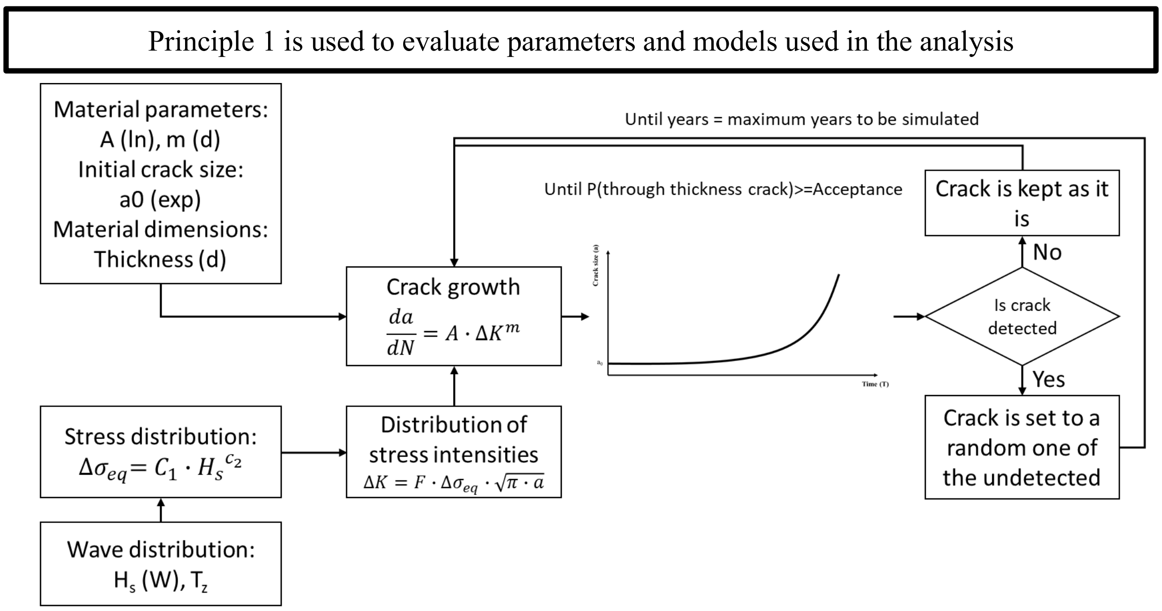

Figure 5. A proposed process for probability-based inspection planning based on the three principles proposed. Principle 2 and 3 are accounted for by the focus on the observable parameter crack size.

In this process the crack growth is simulated until inspection. The inspection is simulated by calculating the probability of detecting (P_D) the simulated crack size based on the PoD-curve. Then, by drawing a random number $\hat{r}$ between 0 and 1 we can simulate the event. If $\hat{r} > P_D$ the simulated

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inspection is classified as a NO-FIND event and, if $\hat{r} \leq P_D$ the simulated inspection is classified as a FIND event.

If the simulations indicate that a crack is detected the crack size is updated by setting the crack size to the largest of 1) the crack size of a random one of the undetected and 2) a random value of the initial distribution of cracks. The undetected cracks are retained as they are. Both detected and undetected cracks are then simulated further until the maximum simulation time is achieved.

The proposed method for updating will differ from the general updating approach [3]. In a general updating also the stress distribution, stress concentration factors etc. will be updated as part of the process. This will in the traditional approach in the case of no-finding lead to increased inspection intervals and in the case of findings lead to decreased inspection intervals. In the proposed method in this paper this increase and decrease of inspection intervals will not occur as the stress distribution, stress concentration factors and all other not-observed parameters are left as is in the updating.

4. Proposed method for evaluating strength of knowledge

Several models for the description of strength of knowledge exists. In general, the following reasoning may be implemented [6]:

- If risk is found negligible according to probability, and the strength of knowledge is strong, the risk is judged as negligible.
- If risk is found in negligible region according to probability with large margins, the risk is judged as negligible unless the strength of knowledge is weak.
- If risk is found negligible according to probability with moderate or small margins, and the strength of knowledge is not strong, the risk is judged as not being in the negligible region.
- If risk is *not* found to be negligible according to probability, the risk is judged as not being in the negligible region.

In the context of this paper this may be understood as:

- If strength of knowledge behind the parameters and models are strong the results of the probabilistic analysis can be regarded as trustworthy and the calculated failure probability can be used to compare with reasonable target failure probabilities.
- If strength of knowledge behind the parameters and models are fair the results of the probabilistic analysis should be used with care and the calculated failure probability should be compared with reasonable target failure probabilities with large margins.
- If strength of knowledge behind the parameters and models are poor probabilistic analysis should be avoided.

In addition to the strength of knowledge, also the influence of the parameter and model on result of the probabilistic analysis and the final decision is of importance, as also indicated in Selvik et al [7]. Hence, in this paper it is proposed to include an evaluation of the influence of the parameter and models and classify these as Minor, Medium or Large. Further, a simplified approach is used to describe the strength of knowledge regarding parameters (e.g. initial crack size, material parameters etc.) and models (e.g. wave to stress model, crack growth model etc.).

The strength of knowledge is classified as Good, Fair and Poor. Good strength of knowledge indicates that a large database is available and that frequentist-probability can be established. Parameters based on good knowledge may be used directly into the analysis without additional evaluations. Poor strength of knowledge indicates mostly guestimates by the analyst or by the engineering community. Parameters based on poor knowledge should not be used in probabilistic analysis and decisions on inspection intervals should rather be based on trustworthy experience and deterministic models. Fair knowledge is used to illustrate situations in between poor and good. Parameters based on fair knowledge may require additional parameter sensitivity evaluations.

To combine the strength of knowledge and the influence of the parameter and models, action categories as indicated in Table 1 may be used.

In category 1 (green) the strength of knowledge is good in combination with minor or medium influence or, the strength of knowledge is fair in combination with minor influence. Parameters or models in this category could in most cases be used as they are, but the evaluation of the strength of knowledge and the assumptions herein should be clearly stated.

For categories 2-3 a further evaluation is needed. If possible, more data should be collected to improve the strength of knowledge. Limitations in the strength of knowledge should be clearly stated. The results of the probabilistic analysis should be used with care and the calculated failure probability should be compared with reasonable target failure probabilities with reasonable margins.

For category 4, probabilistic analysis should not be used unless significantly more data is available for probability- and risk-informed evaluations.

Table 1. Categories based on strength of knowledge and influence on result of evaluations.

	Influence on result of decision making		
Strength of knowledge	Minor	Medium	Large
Good	1	1	2
Fair	1	2	3
Poor	3	4	4

Model uncertainty are often used in probability-informed methods to account for formulation inexactness (e.g. in the Paris crack growth formula), measurement errors and insufficient data. Model uncertainty is typically included by a parameter with a mean value of 1.0 (or a bias value if relevant) and a coefficient of variation (CoV). Sensitivity evaluations of parameters are often similarly used to evaluate the effect of changes in a parameter on the result of the probabilistic analysis. The use of such model uncertainty and sensitivity analysis is a common method to include uncertainties.

After inspections it may be argued that the strength of knowledge has improved as more information about the actual crack size has been gathered. This increased knowledge is however included in further analysis by the updating process.

5. Illustration of the proposed model by an example

An example of probability-informed inspection planning for a node on an offshore jacket structure is used to illustrate the proposed method. The example is based on the master thesis by Neeraas [8]. A short overview is given in section 5.1.

5.1. Example of probabilistic crack growth analysis

Monte Carlo simulations of crack growth and results of inspections are programmed in MathLab and used to evaluate the need for inspections. The input parameters to the analysis is given in Table 2.

Based on the wave height and period the width of the stress intensity, ΔK, can be defined by the equivalent stress range $\Delta\sigma_{eq}$, e.g. as described in Ersdal [9] for a tubular node in a jacket structure.

$$\Delta\sigma_{eq} = \frac{C_1}{1.702 - 0.138 \cdot m_a} \cdot (H_s)^{C_2 - 0.03} \tag{1}$$

where C_1 and C_2 are coefficients, H_s is the significant wave height and m_a is the slope of the crack-growth curve in the Paris equation.

Crack-growth is modelled by the Paris equation:

$$\frac{da}{dN} = A \cdot \Delta K^{m_a} \tag{2}$$

where A and m_a is material parameters and:

$$\Delta K = \Delta\sigma \cdot F(a,t) \cdot \sqrt{\pi \cdot a} \tag{3}$$

where ΔK is the stress intensity range, $\Delta\sigma$ is the stress range of each cycle, $F(a,t)$ is the geometric stress function for the detail and a is the present crack depth. As an example, for a tubular member node the geometric stress function may be set to [10]:

$$F(a,t) = \left(1.08 - 0.7 \cdot \frac{a}{t}\right) \cdot \left(1.0 + 1.24 \cdot e^{-22.1\frac{a}{t}} + 3.17 \cdot e^{-357\frac{a}{t}}\right) \tag{4}$$

where a is the present crack depth and t is the thickness of the material. For each sea-state the crack growth can be calculated as [10]:

$$da_i = A \cdot \left[\Delta\sigma_{eq} \cdot F(a_{i-1}, t) \cdot \sqrt{\pi \cdot a_{i-1}}\,\right]^m \cdot N_w \tag{5}$$

where N_w is the number of cycles in the sea-state.

Table 2. Input parameters for the Monte Carlo simulation.

Input parameters	Comment	Distribution
Initial crack size	Exponential distribution with an average initial crack size of $\mu_{a0} = 0.11mm$ (DNV 1992)	$f(x) = \lambda \cdot e^{-\lambda \cdot x}$ $F(x) = 1 - e^{-\lambda \cdot x}$ where $\lambda = \frac{1}{\mu_{a0}}$
Material parameters in Paris equation	Normally determined by calibration to SN-curve	m is fixed to of 3.0, i.e. one-slope curve is used. Mean ln(A) = 29.1 with a standard deviation of 0.64.
Long-term distribution of significant wave heights	Given by the Weibull distribution where H_C, H_0 and γ are statistical values in the Weibull distribution and should be taken from proper metocean specifications.	$F_{H_s}(h) = 1 - exp\left[-\left(\frac{h-H_0}{H_C-H_0}\right)^\gamma\right]$
Mean zero up-crossing period of the sea-state	Given as a function of the significant wave height.	$T_Z = 3.3 \cdot \sqrt{H_s}$ with a minimum value of $T_Z = 5.72\ s$

As sea-states are simulated the crack growth is calculated and the crack increases. At the end of each year the number of cracks larger than the thickness (i.e. through-thickness cracks) is counted and if the number of through thickness cracks divided by the total number of simulations exceeds the acceptance requirements (0.01 and 0.001) an inspection is performed.

An inspection will always have a certain probability of detecting a crack, and the probability of detection (PoD) is normally expressed by curves e.g. given by DNVGL-RP-C210 [11].

$$PoD(a) = 1 - \frac{1}{1+\left(\frac{a}{X_0}\right)^b} \tag{6}$$

where a is the depth of the crack and X_0 and b is parameters depending on the individual inspection methods. For close visual inspection the PoD curve is given by the crack length. The ratio between crack depth and crack length $\frac{a}{c}$ may be assumed to be 0.15 [10].

Figure 6 shows the crack growth of 20 random simulations of a detail in an analysis. The updates after inspection can normally be seen as a sudden drop in the crack size. However, some examples of the opposite can be seen, as the updated crack size (selected as a random value of the undetected cracks) may be larger than the detected crack.

Figure 7 shows an example of the distribution of crack sizes before and after updating due to inspection at the second inspection [8]. The distribution of cracks prior to updating is shown in red, and the distribution of cracks after updating is shown in blue (note that blue over red becomes purple in these figures). It can easily be seen that the number of large cracks is reduced, and it is also possible to see that the number of small cracks is increased after the updating.

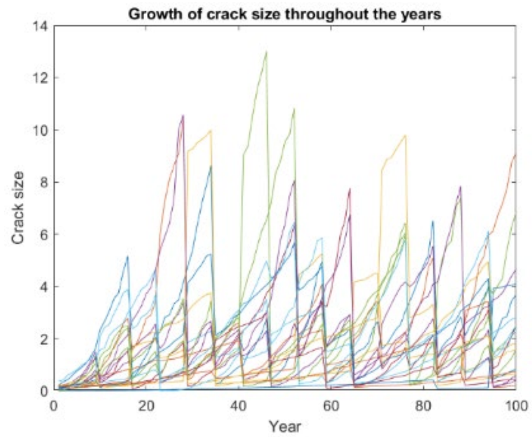

Figure 6. Crack growth using the proposed method for updating after inspections [8].

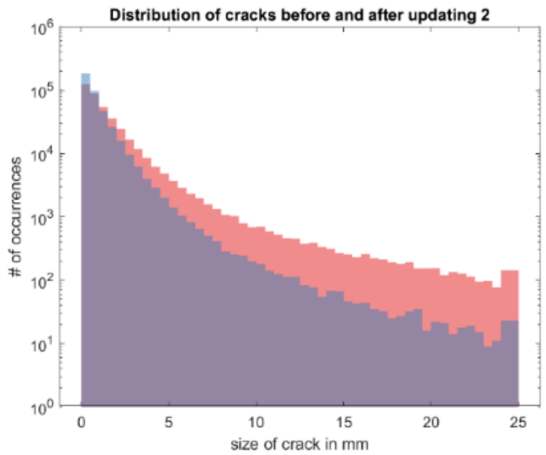

Figure 7. Examples of distribution of crack sizes before and after updating due to inspection for second inspection [8].

Essentially, the distributions of crack sizes before and after inspection turns out to be very similar at all inspections by using the proposed method for updating, as shown in Figure 7. This is the underlying reason for the time history of probability of failure (through thickness crack) as shown in Figure 8. As indicated in Figure 8 this method seems to always provide constant inspection intervals after the first inspection. Hence, this process will produce one "mean" inspection interval in addition to the time to the first inspection. The time to the first inspection is relevant from a methodical point of view but in practise, inspections prior to the calculated first inspection will be needed (e.g. base line inspection) to determine gross errors, fabrication defects and other outliers.

As an additional benefit the likelihood of a crack being detected during the inspection (in Figure 9 called repair required) can be calculated using this simulation method. The trend indicated in Figure 9 is quite similar in all cases simulated. For CVI the curve typically flattens out at a plateau of 0.4 and for MPI (also representative for Eddy Current inspections) at a plateau of 0.6-0.67 as shown in Figure 9.

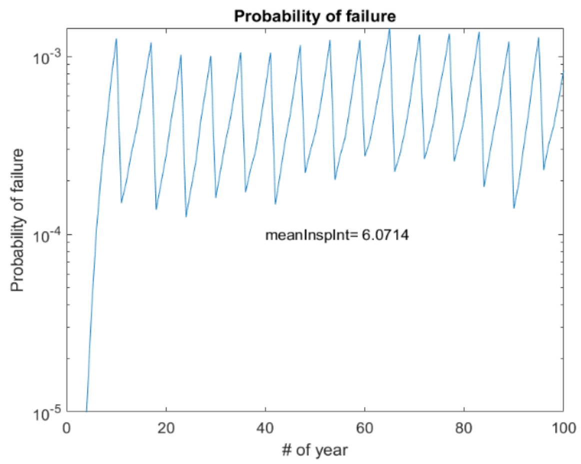

Figure 8. Probability of failure as a function of time with updates.

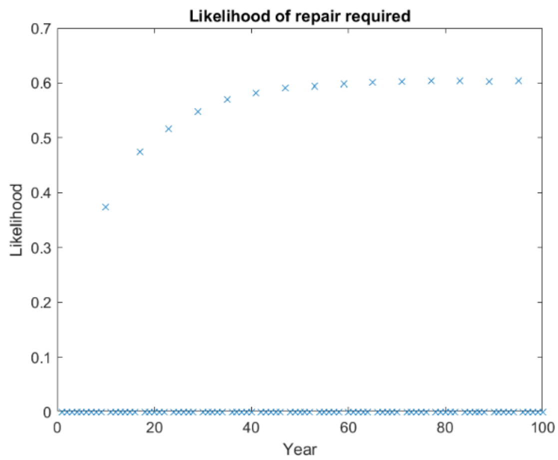

Figure 9. "Likelihood of repair required" using MPI is illustrating the probability that an indication of a crack is detected during the inspection.

The calculated likelihood of finding an indication of a crack (LoIC) as shown in Figure 9 can be used to verify the input parameters to the analysis and possibly the condition of the structure. For example, if the LoIC is calculated to be 0.5 for 20 "identical" details (identical with respect to geometry, stress level etc.) are inspected, we would expect to find 10 cracks. If more that 10 cracks are found it may be an indication of a problem that is not included in the analysis. If less that 10 cracks are found it may be an indication that the analysis is on the conservative side, the inspection quality is lower than predicted by the PoD curves, that the fabrication quality is better than assumed or that the weather that the structure has experienced has been less than predicted from the long-term distribution of sea-states used in the analysis.

A parameter sensitivity study is performed including the model uncertainty (load and crack growth model and the initial crack size). The model uncertainty is included by stochastic variables with mean value of 1.0 and a coefficient of variation (CoV). The model uncertainty in the load model is modelled by a stochastic variable that is kept for the full life of the simulation (GCoV) and a stochastic variable that is changed every year (YCoV) as shown in Equation 7. Each of these are modelled with a CoV in the range of 0.0-0.3. The model uncertainty in the initial crack size is modelled by a stochastic variable with a CoV in the range of 0.0-0.2.

$$\frac{da}{dN} = A \cdot \left[\alpha_G \cdot \alpha_Y \cdot \Delta\sigma_{eq} \cdot F \cdot \sqrt{\pi \cdot a}\right]^{m_a} \tag{7}$$

In addition, the effect of two probability levels for when inspections should be performed is studied ($P_{acceptance}$ equal to 0.01 or 0.001). The $P_{acceptance}$ values are based on normally used acceptance criteria for important and medium important structural nodes and members.

In Table 3 the base case is given with a yearly load model uncertainty (CoV) of 0.15, a general load model uncertainty (CoV) of 0.15 and, a model uncertainty in the initial crack size (CoV) of 0.1.

Table 3: Overview of results from Neeraas (2019) for inspection intervals for a jacket structure

FL	P_{ACC}	Y_{COV}	G_{COV}	$A0_{COV}$	CVI INT	MPI INT	$A0_{COV}$	CVI INT	MPI INT
23	0.01	0	0	0	7.4	11.17	0.1	8	11.33
23	0.01	0.15	0	0	7.4	10.57	0.1	7.6	10.57
23	0.01	0	0.15	0	6.67	10.71	0.1	6.67	10.86
23	0.01	0.15	0.15	0	6.38	9.6	0.1	6.23	9.6
23	0.01	0	0.3	0	5.18	7.9	0.1	5.8	7.9
23	0.001	0	0	0	4.7	7.3			
23	0.001	0.15	0.15				0.1	3.6	6
41	0.01	0	0	0	14.5	22	0.1	16	22
41	0.01	0.15	0	0	14	19.7	0.1	13.5	20.7
41	0.01	0	0.15	0	13.2	17.75	0.1	12.8	18.3
41	0.01	0.15	0.15	0	11.33	18.3	0.1	12	17.8
41	0.01	0	0.3	0	9.4	14.6	0.1	9.3	14
41	0.001	0	0	0	8.75	13.4			
41	0.001	0.15	0.15				0.1	6.75	10.25
60	0.01	0	0	0	22	35	0.1	24	34
60	0.01	0,15	0	0	22.5	32	0.1	22	33
60	0.01	0	0.15	0	20	31	0.1	20.5	32
60	0.01	0.15	0.15	0	18.7	27.5	0.1	18	27.5
60	0.01	0	0.3	0	14	21	0.1	15	21.3
60	0.001	0	0	0	13.25	23			

5.2. Evaluations of the results of the probability analysis

The results presented in Table 3 gives the probability-based inspection intervals. In practise these are seldom used directly and, as indicated in the principles in section 2 the decision on the time between inspections should also include a discussion of the sensitivity to parameters and models used and the influence of the probability of acceptance. Such a discussion should include the CoV of the crack growth model (YCoV and GCoV), the calculated fatigue life, the CoV of the initial crack size and the influence of the acceptable probability of "failure" ($P_{acceptable}$). Further, the strength of knowledge should be evaluated and taken into account in the decision making as proposed in Table 6.

The load and crack growth model are in most probability-informed inspection planning analysis the primary uncertainty. Other important uncertainties might be:

- The presence of fabrication and design imperfections are not included in the analysis. The presence of gross imperfection is believed to have less impact on later inspection intervals as they most likely will materialize at an earlier stage. However, fabrication standards at different yards may have influence on later inspection intervals.
- The cyclic stress distribution is a part of the uncertainty in the fatigue analysis modelled by the mentioned CoV's.
- The initial crack sizes in the welds is studied by Neeraas [8] and is shown to have minor impact on late inspection intervals.
- The crack growth parameters in the Paris crack growth law is based on a calibration towards SN-fatigue curves. These SN-fatigue curves do also have significant uncertainty. However, it is believed that the SN-curves used are most likely to be conservative and it is believed that inspections results can be used to validate the crack growth and possibly the crack growth model parameters.
- Detection accuracy of the inspection method is believed to be modelled reasonable with the probability of detection curves in DNVGL RP-C210. However, there exist experience indicating that these curves may be non-conservative.

It is believed that the CoV's described in DNVGL RP-C210 [11] is reasonable for this purpose. However, if the strength of knowledge is stronger than assumed in DNVGL RP-C210 it can be argued to decrease the respective CoV's. The square root of sum of squares combination of GCoV and YCoV can be seen in the context of uncertainty as described by DNVGL [11] where the model uncertainties as shown in Table 4 are suggested depending on the quality of the analysis determining the long-term distribution of stress ranges.

Table 4. Suggested model uncertainties [11].

Uncertainty of fatigue and hot spot stress calculation	COV	Combinations of GCoV and YCoV
High (simplified)	0.3	YCoV = 0.3, GCoV = 0.0
		YCoV = 0.0, GCoV = 0.3
Medium (parametric)	0.2	~YCoV = 0.15, GCoV = 0.15
Low (finite element calculation)	0.15	YCoV = 0.15, GCoV = 0.0
		YCoV = 0.0, GCoV = 0.15

In Figure 10 and Figure 11 the calculated inspection intervals for CVI and MPI respectively is presented by increasing CoV in accordance with DNVGL. In addition to the proposed CoV's from DNVGL the base case with CoV = 0.0 is included primarily for comparison. As expected, the time between inspections decreases with increasing CoV and more frequent inspections are needed for lower values of P_{acc}.

There is a slight tendency for longer inspection intervals as ratio of the calculated fatigue life (CFL) when the CFL is increasing. The minimum values indicated in Figure 10 and Figure 11 are as a result of this representing the lowest calculated fatigue life. For longer calculated fatigue lives a slightly higher fraction of the calculated fatigue life is obtained (0.42, 0.44 and 0.46 times CFL for MPI and 0.28, 0.29 and 0.31 times CFL for CVI representing 20, 40 and 60 years CFL respectively).

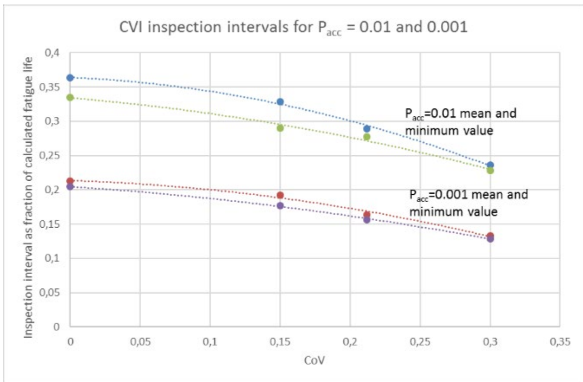

Figure 10. CVI inspection intervals for Pacc equal to 0.01 and 0.001.

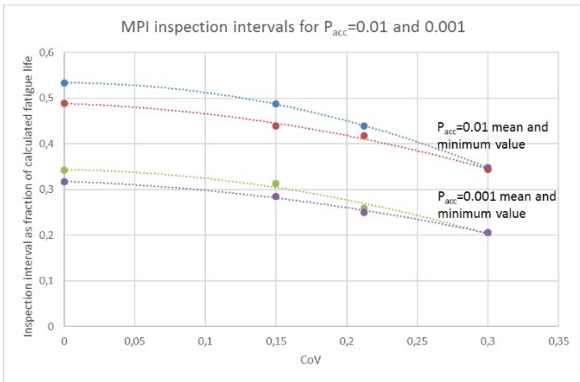

Figure 11. MPI inspection intervals for Pacc equal to 0.01 and 0.001.

The different $P_{acceptable}$ is normally linked to the importance of the structural member or node. In general, the importance is a measure of the consequence of the failure of the member or node. Traditionally a $P_{acceptable}$ equal to 0.001 is used for high consequence of failure members and nodes and $P_{acceptable}$ equal to 0.01 is used for medium consequence of failure members and nodes. For a jacket structure a suggested understanding of medium importance may be that failure of this member increases the utilization check (UC) less than 5% (in any member or node in the structure). Similarly, a failure of a high importance member and node increases the UC less than 25%.

In some cases, reserve strength ratios (RSR) are used to determine the importance of members and nodes. If RSR values are used medium and high important members can be defined as medium important member: reduces the RSR value less than 5% if it fails and high importance member: reduces the RSR value less than 25% if it fails respectively.

5.3. Decision making based on the probability analysis

The aim of this paper is to describe a method for the analysis of inspection intervals and to facilitate decisions-making taking into account the strength of knowledge, assumptions and the parameters importance on the result of the decision. The decision should therefore be based on evaluating observable quantities (inspection intervals), the probability-based analysis, the analysts experience and understanding of the problem, evaluation of strength of knowledge and assumptions. An example of such evaluation is given in Table 6 (based on the parameters and models described in Section 5.1).

The evaluation of strength of knowledge in parameters and models as shown in Table 6 indicates that the calculated probabilities of through-thickness cracks must be seen as indicative and not as absolute values. Hence, the inspection intervals need to be carefully adjusted to experience and continuously monitored in order to within a reasonable level of confidence determine the existence, extent and consequence of damage, degradation and deterioration. For example, information and experience on imperfections from fabrication and design flaws from the relevant yard will be of importance for the final decision-making.

In Table 3 it is shown that for a jacket structure with approximately 20 years fatigue life and design fatigue factor (DFF) of 1, an inspection interval of 3.6 years using CVI for high importance nodes and members is calculated. In practice, such inspection intervals will be rounded to match the inspection campaigns during the summer season. For high importance jacket structural members with a fatigue life of 20 years and DFF of 3 an inspection interval of 10 years for CVI and 16 years for MPI are suggested. Such intervals may be regarded as large; however, it must be admitted that few cracks have been detected in critical areas on jacket structures. Hence, the inspection intervals found in the analysis is regarded as reasonable based on the authors' experience. However, this evaluation does not take into account the fabrication performance of the specific yard.

Table 5: Evaluation of strength of knowledge in parameters and models, assumptions and the parameters and models influence on the result of the probability-informed inspection planning

Parameter	Description	Strength	Influence	Conclusion / comments
H_s	Long-term distribution of significant wave height.	Good	Large	Based on some 50 years of hindcast and measurements. No further action required.
T_Z	Zero-up crossing period in sea-state.	Fair	Minor	Low influence in the uncertain range
$\Delta\sigma_{eq}$	Load model to transfer wave loading to stress in detail	Fair	Large	Model uncertainty is included in the analysis.
a_0	Initial crack size	Fair	Minor	Based on laboratory tests of different welds but assumed to be relevant. However, model uncertainty is included.
log(a)	SN curve parameter	Good	Large	Based on reasonable datasets although
m_{SN}	SN curve parameter	Good	Large	not same steel. No further action required
ln(A)	FM curve parameter calibrated from SN-fatigue calculation	Fair	Large	No further action required. Uncertainty in FM curve parameters
m_a	FM material parameter	Fair	Large	are included by modelling ln(A) as a normal distributed variable
t	Thickness of material	Good	Large	No further action required
PoD	Probability of detection of defects for various NDT methods.	Fair	Large	Based on inspection trials performed in several industry projects included in the proposed PoD curves in DNVGL [11]. Possibly optimistic, and this optimism should be taken into account in the decisions.

It should also be noted that the present revision of NORSOK N-006 [12] requires that inspection intervals on high importance members and nodes in jacket structures should not exceed 5 years independent on inspection method used. Although there are limitations to the strength of knowledge in some parts of these analysis and evaluations, the resulting inspection intervals (the observable quantity) are reasonably in line with current practice and recommendations given in class rules and standards. The experience using such inspection intervals is also reasonably good. Hence, based on these evaluations taking into account the analysis, experience, strength of knowledge, and the understanding of the problem a set of inspection intervals can be developed as indicated in Table 6 for a detail in a jacket node with 20 years calculated fatigue life based on the illustrative and simplified simulations performed by Neeraas [8].

It should be noted that the inspection intervals given in Table 6 is based on sea-states following the given long-term distribution. If several years of worse sea-states are experienced the inspections should be more frequent and special analysis may be required.

Table 6. Proposed inspection intervals given the analysis in Neeraas [8], experience, strength of knowledge and understanding of the problem.

	Importance	
Uncertainty of fatigue analysis	Medium	High
High (simplified)	4 years interval (CVI)	2.5 years interval (CVI)
CoV = 0.3	7 years interval (MPI)	4 years interval (MPI)
Medium (parametric)	5 years interval (CVI)	3 years interval (CVI)
CoV = 0.2	8 years interval (MPI)	5 years interval (MPI)
Low (finite element calculation)	6 years interval (CVI)	4 years interval (CVI)
CoV = 0.15	9 years interval (MPI)	6 years interval[1] (MPI)

1) Note that NORSOK N-006 recommends a maximum of 5 years intervals

6. Conclusion and recommendation and further work

The probability-informed results used in this paper is based on a probabilistic analysis performed as a part of a master thesis by Neeraas [8]. These analyses have limitations and cannot be construed to provide general inspection intervals for jacket structures. The suggested inspection intervals in this paper should be seen as examples and not as recommendations. However, the indications of constant inspection intervals are not affected by this limitation. The process used in the master thesis is based on the method suggested in this paper.

The paper illustrates the importance of taking into account the strength of knowledge, assumptions and the parameters importance on the result of the decision when determining inspection intervals for structures. Further, the importance of basing the analysis and decision-making on evaluating observable quantities as an addition to traditional probability-based analysis is highlighted. Especially, it is highlighted that the analysts experience and understanding of the problem should be taken into account.

The calibration of fracture mechanics parameters from the SN-curves needs further investigation. The calibration is performed with no model uncertainty (CoV = 0.0) for both the fracture mechanics crack growth model and the SN-fatigue model. This choice may not be correct and may be un-conservative.

The calculations performed in the master thesis by Neeraas [8] is based on a model using long-term distribution of sea-states and equivalent stresses. In most cases, probability-informed inspection planning analysis is rather based on a simplified long-term distribution of stress ranges. However, both methods have been shown to provide similar results [9]. A future work to implement the standard long-term stress range distribution into this type of analysis is recommended.

Acknowledgement

The results that is presented in this paper should not be seen as a suggestion for inspection intervals for jacket structures in general. This paper describes a methodology for decision-making of inspection intervals based on a probability- and risk-informed approach.

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