



**AALBORG UNIVERSITY**  
DENMARK

**Aalborg Universitet**

## **Safety and Inspection Planning of Older Installations**

Sørensen, John Dalsgaard; Ersdal, G.

*Published in:*

Risk, Reliability and Societal Safety

*Publication date:*

2007

*Document Version*

Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

*Citation for published version (APA):*

Sørensen, J. D., & Ersdal, G. (2007). Safety and Inspection Planning of Older Installations. In T. Aven, & J. E. Vinnem (Eds.), Risk, Reliability and Societal Safety (pp. 2535-2542). Marcel Dekker Incorporated.

### **General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- ? Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- ? You may not further distribute the material or use it for any profit-making activity or commercial gain
- ? You may freely distribute the URL identifying the publication in the public portal ?

### **Take down policy**

If you believe that this document breaches copyright please contact us at [vbn@aub.aau.dk](mailto:vbn@aub.aau.dk) providing details, and we will remove access to the work immediately and investigate your claim.

## Safety and inspection planning of older installations

J.D. Sørensen

*Aalborg University, Aalborg, Denmark*

G. Ersdal

*Petroleum Safety Authority, Stavanger, Norway*

**ABSTRACT:** A basic assumption often made in risk/reliability based inspection planning is that a Bayesian approach can be used. This implies that probabilities of failure can be updated in a consistent way when new information (from inspections and repairs) becomes available. The Bayesian approach and a no-crack detection assumption implies that the inspection time intervals usually become longer and longer. For aging platform several small cracks are often observed – implying an increased risk for crack initiation (and coalescence of small cracks) and increased crack growth. This should imply shorter inspection time intervals for ageing structures. Different approaches for updating inspection plans for older installations are proposed. The most promising method consists in increasing the rate of crack initiations at the end of the expected lifetime – corresponding to a bath-tube hazard rate effect. The approach is illustrated for welded steel details in platforms. Systems effects are considered including use of dependence between inspection and failure events in different components for inspection planning.

### 1 INTRODUCTION

Reliability and Risk Based Inspection (RBI) planning for offshore structures have been an area of high practical interest over the last three decades. The first developments were within inspection planning for welded connections subject to fatigue crack growth in fixed steel offshore platforms. This application area for RBI is now the most developed. In the beginning practical applications of RBI required a significant expertise in the areas of structural reliability theory and fatigue and fracture mechanics, see e.g. PIA (1990). This made practical implementation in industry difficult. Recently generic and simplified approaches for RBI have been formulated making it possible to base inspection planning on a few key parameters commonly applied in deterministic design of structures, e.g. the Fatigue Design Factor (FDF) and the Reserve Strength Ratio (RSR), see Faber et al. (2000), (2005).

The basic assumption made in risk/reliability based inspection planning is that a Bayesian approach can be used. This implies that probabilities of failure can be updated in a consistent way when new information (from inspections) becomes available. Further, the RBI approach for inspection planning is based on the assumption that at all future inspections no cracks are detected. If a crack is detected then a new inspection plan should be developed. The Bayesian approach and the no-crack detection assumption imply that the

inspection time intervals usually become longer and longer.

Further, inspection planning based on the RBI approach implies that single components are considered, one at the time, but with the acceptable reliability level assessed based on the consequence for the whole structure in case of fatigue failure of single components.

Examples and information on reliability-based inspection and maintenance planning can be found in a number of papers, e.g. Madsen, Sørensen & Olesen (1989), Madsen & Sørensen (1990), Fujita, Schall & Rackwitz (1989), Skjong (1985), Sørensen, Faber, Rackwitz & Thoft-Christensen (1991), Faber & Sørensen (1999), Ersdal (2005), Sørensen, Straub & Faber (2005), Moan (2005), Straub & Faber (2005), Faber, Sørensen Tychsen & Straub (2005), PIA (1990) and Faber, Engelund, Sørensen & Bloch (2000). Important aspects are systems considerations, design using robustness considerations by accidental collapse limit states and use of monitoring by the “leak before break” principle to identify damage.

Based on the above considerations the following two aspects are considered in this paper with the aim to develop further the risk based inspection approach, namely

- 1) For aging installations several small defects/cracks are often observed – implying an increased risk for

defect/crack initiation (and coalescence of small defects/cracks) and increased growth – thus modeling a bath-tub effect. This should imply shorter inspection time intervals for ageing installations.

- 2) Systems effects: Due to common loading, common model uncertainties and correlation between inspection qualities, it can be expected that information obtained from inspection of one component can be used, not only to update the inspection plan for that component, but also for other nearby components. Such system effects can also lead to increased probability of simultaneous failure in nearby correlated components.

Initiation of several small defects/cracks implies that these can coalesce to larger defects/cracks which can grow and become critical. The many small defects/cracks also implies that larger defects/cracks can initiate at more than one position, i.e. a systems effect along e.g. a welding can be of importance depending on the length of the weld and the dependence between the defects/fatigue cracks.

This paper is a summary of a project performed by John Dalsgaard Sørensen for the Petroleum Safety Authority in Norway within their Aging Installations project.

## 2 RISK BASED INSPECTION PLANNING

In risk based inspection planning (RBI) the inspection plan is determined such that the annual probability of failure is less than a maximum acceptable annual probability of failure,  $\Delta P_F^{\max}$  which is dependent on the consequences of fatigue failure on total collapse of the structure. Further, the inspection plan should be determined such that the lifetime total expected costs to inspection, repair, strengthening and eventual failure are minimised.

In generic inspection planning a database of inspection plans are made once and actual inspection planning is made by interpolation in the database, see e.g. Faber et al. (2000). For given

- Type of fatigue sensitive detail – and thereby code-based SN-curve
- Fatigue strength measured by *FDF* (Fatigue Design Factor)
- Importance of the considered detail for the ultimate capacity of the structure, measured by e.g. *RIF* (Residual Influence Factor) and *RSR* (Reserve Strength Ratio)
- Member geometry (thickness)
- Inspection, repair and failure costs

the optimal inspection plan i.e. the inspection times and inspection qualities can be determined. This inspection plan is generic in the sense that it is

representative for the given characteristics of the considered detail, i.e. SN-curve, *FDF*, *RSR* and the inspection, repair and failure costs.

This inspection planning procedure requires information on costs of failure, inspections and repairs. Often these are not available, and the inspection planning is based on the requirement that the annual probability of failure in all years has to satisfy the reliability constraint implied by  $\Delta P_F^{\max}$ . Further, in risk-based inspection planning the assumption that no cracks are found at the inspections is usually made. If a crack is found, then a new inspection plan has to be made based on that observation.

The reliability of inspections can be modelled in many different ways. Often *POD* (Probability Of Detection) curves are used to model the reliability of the inspections.

In order to model the influence of inspections and estimate the probability of failure, a probabilistic fracture mechanical (FM) model is needed. This model is often calibrated such that it gives the same reliability level as a code based probabilistic SN-approach using Miner's rule of linear accumulation of damage.

If a bilinear SN-curve is applied, the SN relation can be written:

$$N = K_1 (\Delta s)^{-m_1} \quad \text{for } N \leq N_C \quad (1)$$

$$N = K_2 (\Delta s)^{-m_2} \quad \text{for } N > N_C \quad (2)$$

where  $\Delta s$ : stress range,  $N$ : number of cycles to failure,  $K_1, m_1$ : material parameters for  $N \leq N_C$ ,  $K_2, m_2$ : material parameters for  $N > N_C$ ,  $\Delta s_C$ : stress range corresponding to  $N_C$ .

The probability of failure is calculated using the limit state equation

$$g = \Delta - \sum_{s_i \geq \Delta s_C} \frac{n_i T_L}{K_1 (X_S s_i)^{-m_1}} - \sum_{s_i < \Delta s_C} \frac{n_i T_L}{K_2 (X_S s_i)^{-m_2}} \quad (3)$$

where  $\Delta$  is model uncertainty related to Palmgren-Minners rule for linear damage accumulation and  $T_L$  is the service life.  $s_i$  is the stress range in group  $i$ ,  $X_S$  is a stochastic variable modeling model uncertainty related to waves and *SCF* (wave load response).  $X_S$  is assumed Log-Normal distributed with mean value = 1 and  $COV = \sqrt{COV_{wave}^2 + COV_{SCF}^2}$ . The coefficient of variation  $COV_{wave}$  models the uncertainty on the wave load, foundation stiffness and stress ranges.  $COV_{SCF}$  models the uncertainty in the stress concentration factors (SCF) and local joint flexibilities (LFJ).  $\log K_i$  is modeled by a Normal distributed stochastic variable according to a specific SN-curve.

Using the illustrative stochastic model in Table 1 based on Faber et al. (2005) and Equation (3) the probability of failure in the service life and the annual

Table 1. Example of stochastic model for SN-approach. D: Deterministic, N: Normal, LN: LogNormal.

Variable	Distribution	Expected value	Standard deviation
$\Delta$	LN	1	0/0.3
$Z_{SCF}$	LN	1	$COV_{SCF}$
$Z_{wave}$	LN	1	$COV_{wave}$
$m_1$	D	3	
$\log K_1$	N	12.048	0.218
$m_2$	D	4	
$\log K_2$	N	13.980	0.291

$\log K_1$  and  $\log K_2$  are assumed fully correlated

probability of failure can be obtained. It is noted that the stochastic model for  $\log K_1$  and  $\log K_2$  is based on fatigue tests with variable amplitude load.

A fracture mechanical modeling of the crack growth is applied assuming that the crack can be modeled by a 2-dimensional semi-elliptical crack. It is assumed that the fatigue life may be represented by a fatigue initiation life and a fatigue propagation life:

$$N = N_I + N_P \quad (4)$$

where  $N$  is the number of stress cycles to failure,  $N_I$  is the number of stress cycles to crack propagation and  $N_P$  is the number of stress cycles from initiation to crack through.

The number of stress cycles from initiation to crack through is determined on the basis of a two-dimensional crack growth model. The crack growth can be described by the following two coupled differential equations.

$$\begin{aligned} \frac{da}{dN} &= C_A (\Delta K_A)^m & a(N_0) &= a_0 \\ \frac{dc}{dN} &= C_C (\Delta K_C)^m & c(N_I) &= c_0 \end{aligned} \quad (5)$$

where  $C_A$ ,  $C_C$  and  $m$  are material parameters,  $a_0$  and  $c_0$  describe the initial crack depth  $a$  and crack length  $c$ , respectively, after  $N_I$  cycles. The stress intensity ranges are  $\Delta K_A$  and  $\Delta K_C$ . The crack initiation time  $N_I$  is modeled as Weibull distributed with expected value  $\mu_{I0}$  and coefficient of variation equal to 0.35, see e.g. Lassen (1997). The limit state function is written

$$g(\mathbf{x}) = N - nt \quad (6)$$

where  $t$  is time in the interval from 0 to the service life  $T_L$ .

In order to model the effect of different weld qualities, two different values of the crack depth at initiation

Table 2. Example uncertainty modeling used in the fracture mechanical reliability analysis. D: Deterministic, N: Normal, LN: LogNormal, W: Weibull.

Variable	Dist.	Expected value	Standard deviation
$N_I$	W	$\mu_{I0}$	$0.35 \mu_0$
$a_0$	D	0.1 mm/0.5 mm	
$\ln C_C$	N	$\mu_{\ln C_C}$	0.77
$m$	D	$m$ - value corresponding to the low cycle part of the bi-linear SN-curve	
$Z_{SCF}$	LN	1	
$Z_{wave}$	LN	1	
$a_c$	D	T (thickness)	
$Y$	LN	1	0.1

$\ln C_C$  and  $N_I$  are correlated with correlation coefficient  $\rho_{\ln(C_C), N_I} = -0.5$

Table 3. Example cases.

Case	$COV_{wave}$	$COV_{SCF}$	$T$ [mm]	$T_F$ [year]
Case 1	0.1	0.15	20	100
Case 2	0.1	0.15	20	120
Case 3	0.1	0.15	20	140
Case 4	0.1	0.15	20	160
Case 5	0.1	0.15	20	180
Case 6	0.1	0.15	20	200

$a_0$  can be used: 0.1 mm and 0.5 mm corresponding approximately to high and low material control. The critical crack depth  $a_c$  is often taken as the thickness of the tubular member. An example of a probabilistic modeling used in a fracture mechanical reliability analysis is shown in Table 2.

The parameters  $\mu_{\ln C_C}$  and  $\mu_0$  are fitted such that difference between the probability distribution functions for the fatigue live determined using the SN-approach and the fracture mechanical approach is minimized as illustrated in the examples above.

A steel jacket structure with service life  $T_L = 40$  years and located in the North Sea is considered. The characteristics for some fatigue sensitive details are shown in Table 3, where  $T_F$  is the fatigue lifetime for deterministic design. The resulting inspection intervals are shown in Table 4 for a maximum acceptable annual probability of failure,  $\Delta P_F^{\max} = 10^{-5}$ . It is seen that the time to first inspection increases with the Fatigue Design Factor,  $FDF = T_F/T_L$ , and that after the first inspection, the inspection time intervals generally increase with time, but for low  $FDF$ 's it decrease in the first part of the design lifetime.

Table 4. Example inspection time intervals in years.

Inspection no.	1	2	3	4	5
Case 1 – $FDF = 2.5$	13	6	5	7	9
Case 2 – $FDF = 3.0$	16	7	7	9	
Case 3 – $FDF = 3.5$	19	9	9		
Case 4 – $FDF = 4.0$	22	10			
Case 5 – $FDF = 4.5$	25	12			
Case 6 – $FDF = 5.0$	28				

It is noted that a basic assumption in the reliability-based inspection planning approach used in this paper is that a Bayesian approach can be used. This implies that probabilities of failure can be updated in a consistent way when new information becomes available. The Bayesian approach is also consistent with rational risk analysis and decision making based on the framework of pre-posterior analysis from classical Bayesian decision theory see e.g. Raiffa and Schlaifer (1961) and Benjamin and Cornell (1970) and implemented as described in e.g. Sørensen et al. (1991). This basic assumption is also very important to understand why longer inspection time intervals are obtained when no-finds at the inspections are assumed.

### 3 INSPECTION PLANNING FOR OLDER INSTALLATIONS

In this section is described various investigations in reliability-based inspection planning with the aim to discuss and investigate how increased inspection time intervals could be obtained when time approaches and goes beyond the design lifetime – this is intuitively what should be expected but as seen above, traditional reliability-based inspection techniques normally result in increasing inspection time intervals with time.

The following observations are included in the considerations for a modified method for reliability-based inspection planning for older installations:

- For aging platform several small cracks are observed – implying an increased risk for crack initiation (and coalescence of small cracks) and growth – thus modeling a bath-tub effect.
- Repair of cracks can imply weakening of the material, implying subsequent crack initiation and growth.
- Observed cracks can be divided in cracks due to fabrication defects and fatigue growing cracks: (1) Fabrication cracks should have been detected by fabrication control and/or an initial inspections, and are therefore not considered in the following; (2) Growing fatigue cracks possibly to be detected by inspections – typically 10% (of welds) is inspected and from these 5% have cracks (defects).

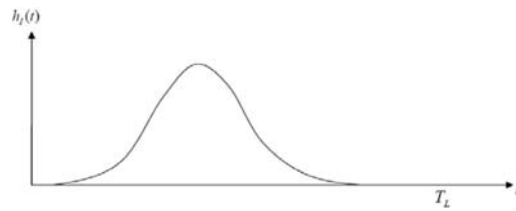


Figure 1. Basic model for defect/crack initiation time.

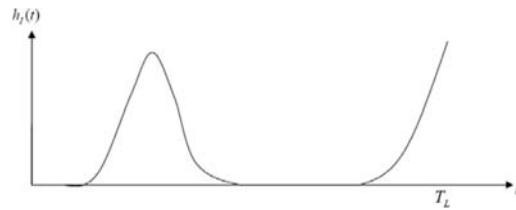


Figure 2. A combined model for damage initiation without initial defects.

The following models for modifying inspection intervals for older installations:

- a. Increase of expected value of initial crack size with time – due to coalescence of smaller cracks.
- b. Non-perfect repairs – by detection of cracks the repair is not perfect, and a new crack is initiated.
- c. Human errors in inspections (beyond uncertainty included in *POD*-curves).
- d. Increased rate of crack initiation – adjustment of the crack initiation time such that initiation of cracks increase with time (bath-tub effect). The increase of crack initiation can be in excess of the crack initiation expected at the design state (and obtained by reliability-based calibration to *SN*-curves) due to the aging effects (e.g. by coalescence of small defects / cracks).

In case of lifetime extension the above effects also applies in the extended lifetime. Representative examples are used to evaluate the different models.

The basic assumption in the RBI approach described in section 2 is that in a critical detail a defect/crack initiate at some time and is modeled by a stochastic variable, see figure 1. However, it is frequently observed that damage initiation rates follow a bath-tub form, see figure 2. Initial damages are mainly due to fabrication/construction defects, and at the end of the expected lifetime the damage rate increase. In figure 2 a combined model is illustrated where the ‘bath-tub’ effect is combined with the ‘usual’ defect/crack initiation model.

In model (d) it is assumed that more defects/cracks initiate when time is approaching the design lifetime (due to weakening by age effects) than assumed in

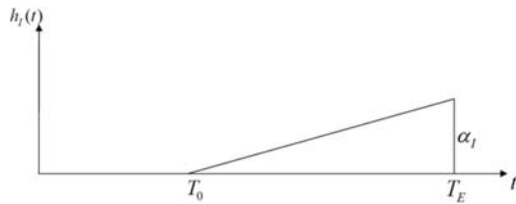


Figure 3. Initiation rate of extra defects/cracks – linear model.

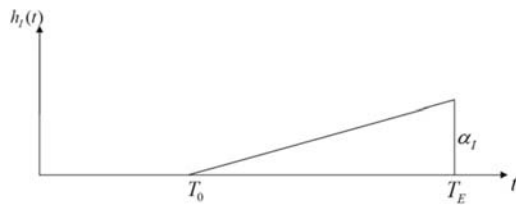


Figure 4. Initiation rate of extra defects/cracks – constant model.

Table 5. Stochastic model for SN-approach in examples.

Variable	Distribution	Expected value	Standard deviation
$\Delta$	LN	1	0.2
$Z_{SCF}$	LN	1	$COV_{SCF} = 0.10$
$Z_{wave}$	LN	1	$COV_{wave} = 0.30$
$T_F$	D	75 years	
$T_L$	D	25 years	
$m_1$	D	3	
$\log K_1$	N	12.048	0.218
$m_2$	D	4	
$\log K_2$	N	13.980	0.291

$\log K_1$  and  $\log K_2$  are assumed fully correlated

the initial calibration of the fracture mechanics model. This model corresponds to the model in figure 2.

In the examples below, the extra cracks are assumed to initiate following a simple linear or constant model in the time interval  $[T_0, T_E]$ , see figures 3 and 4. Extra new defects/cracks could be expected to have the effect that the inspection time intervals decrease.

Monte Carlo simulations are used to estimate the reliability as function of time by the SN-approach and by the fracture mechanics approach (FM) for the models proposed above. In order to reduce the computational effort, a 1-dimensional fracture mechanics model is used. The stochastic models used are shown in tables 5 and 6.

The parameters in the fracture mechanical model are calibrated to

$$\mu_{I0} = 5 \text{ years and } \mu_{\ln C_C} = -26.5$$

Table 6. Uncertainty modeling used in the fracture mechanical reliability analysis. D: Deterministic, N: Normal, LN: LogNormal, W: Weibull.

Variable	Dist.	Expected value	Standard deviation
$N_I$	W	$\mu_{I0}$ (fitted)	$0.35 \mu_0$
$a_0$	D	0.4 mm	
$\ln C_C$	N	$\mu_{\ln C_C}$ (fitted)	0.77
$m$	D	3	
$Z_{SCF}$	LN	1	0.10
$Z_{wave}$	LN	1	0.30
$a_c$	D	T (thickness)	
$Y$	LN	1	0.1
$T$	D	50 mm	
$T_F$	D	$= FDF T_L = 25/50/75$ years	

$\ln C_C$  and  $N_I$  are correlated with correlation coefficient  $\rho_{\ln(C_C), N_I} = -0.5$

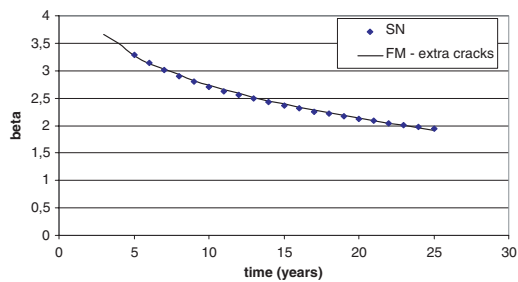


Figure 5. Reliability index (accumulated) as function of time for SN approach and calibrated FM-approach.

The reliability index (based on accumulated probability of failure) is shown in figure 5. It is seen that a good agreement between the SN and the FM approach is obtained.

RBI planning with no modifications result in the following inspection time intervals (in years):

$$4, 1, 2, 2, 3, 5, 6, 9, 9$$

The inspection time intervals increase with time – most of the fastest growing cracks are detected and repaired in the first inspections, and thus only few critical cracks are left when time approaches the design lifetime.

The three models (a), (b) and (c) described above does not result in decreased inspection time intervals. The main reason is believed to be the statistical effect of the inspection, namely that fast growing cracks are detected by the first inspections – if not by the first inspection then by one of the following inspections – and thus resulting in increasing inspection time intervals.

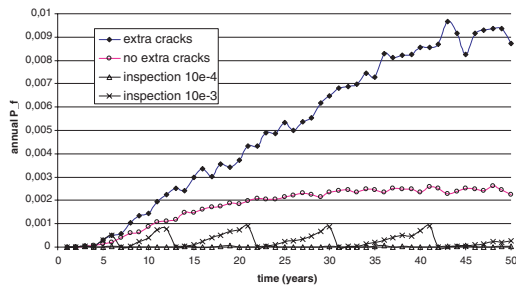


Figure 6. Annual probability of failure as function of time. Without extra crack initiation, with extra crack initiation – Linear [10 ; 25] and  $\alpha_I = 3 \times 2/15$ , and with inspections when  $\Delta P_F^{\max} = 10^{-4}$  and  $\Delta P_F^{\max} = 10^{-3}$ .

In model (d) extra cracks are assumed to initiate in the time interval  $[T_0, T_E]$ , see models in figures 3 and 4.

The inspection time intervals (in years) are with  $\Delta P_F^{\max} = 10^{-4}$  determined to:

Constant [10 ; 25] and  $\alpha_I = 1/15$ :  
4, 1, 2, 2, 3, 4, 5, 6, 7, 6, 9

Linear [10 ; 25] and  $\alpha_I = 6/15$ :  
4, 1, 2, 2, 2, 4, 5, 4, 4, 4, 7, 7

The inspection time intervals (in years) are with  $\Delta P_F^{\max} = 10^{-3}$  determined to:

Linear [10 ; 25] and  $\alpha_I = 6/15$ :  
6, 6, 9, 9, 11

It is seen that the inspection time intervals are unchanged before the time where extra cracks initiate. The inspection time intervals become smaller when more cracks are initiated – but the effect of the inspections imply that when the extra inspections start early, then most of the critical ones are detected and therefore the inspection time intervals can again increase. A large effect is obtained using e.g. a linear model for extra crack initiation rate with extra cracks in the interval [10 ; 25] years. Here the increase in inspection time intervals becomes negligible in the time interval [20 ; 40] years (until the effect of the extra cracks have disappeared).

Figure 6 shows the annual probability of failure as function of time without extra crack initiation, with extra crack initiation (linear [10 ; 25] and  $\alpha_I = 3 \times 2/15$ ), and with inspections when  $\Delta P_F^{\max} = 10^{-4}$  and  $\Delta P_F^{\max} = 10^{-3}$ . The annual probability of failure is seen to increase significantly when extra initiation of cracks is included. Using inspections it is seen that it is possible to obtain a maximum annual probability of failure below  $\Delta P_F^{\max}$ .

Using model (d) the fracture mechanical model could be calibrated to the SN based approach including

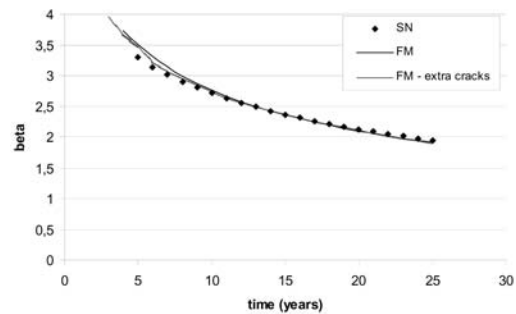


Figure 7. Reliability index (accumulated) as function of time for SN approach and calibrated FM-approach – without and with extra cracks included in calibration.

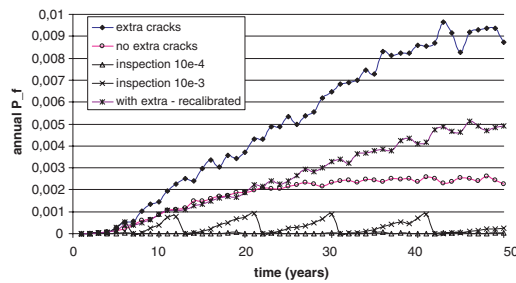


Figure 8. Annual probability of failure as function of time. As figure 6, but with re-calibrated model.

the extra initiation of cracks – linear [10 ; 25] and  $\alpha_I = 3 \times 2/15$ . The parameters in the fracture mechanical model then become:

$$\mu_{I0} = 3 \text{ years and } \mu_{\ln C_C} = -27.5$$

The reliability indices (based on accumulated probability of failure) are shown in figure 7.

Inspection time intervals (in years) with extra initiation of cracks used in re-calibrated model are with  $\Delta P_F^{\max} = 10^{-4}$  determined to:

4, 1, 3, 3, 5, 6, 5, 7, 9

and with  $\Delta P_F^{\max} = 10^{-3}$  to:

10, 12, 14

Figure 8 shows the annual probability of failure as function of time. It is seen that the inspection time intervals are larger with the re-calibrated model, but compared to the model without extra cracks, the inspection intervals have the wanted effect.

Table 7. Stochastic variables for fracture mechanical analysis.

	Variable	Description
Strength Variables	$N_I$	Number of stress cycles to initiation of crack
	$a_0$	Initial crack length
	$\ln C_C$	Crack growth parameter
Load Variables	$Y$	Geometry function
	$Z_{SCF}$	Uncertainty stress range calculation
	$Z_{wave}$	Uncertainty wave load
	$a, b$	Weibull parameter in long term stress range distribution
Inspection quality	$c_d$	Probability Of Detection curve

#### 4 SYSTEMS EFFECTS FOR OLDER INSTALLATIONS

For many installations there will be a (large) number of critical details (components), implying the following important aspects:

- Assessment of the acceptable annual fatigue probability of failure for a particular component can be dependent on the number of critical components. The acceptable annual probability of failure of a component is obtained considering the importance of the component through the conditional probability of failure given failure of the component.
- Due to common loading, common model uncertainties and correlation between inspection qualities it can be expected that information obtained from inspection of one component can be used not only to update the inspection plan for that component, but also for other nearby components. Further, the common history and loading also implies an increased risk of several correlated components fail at almost the same time.
- In some cases the development of a defect/crack in one component causes a stiffness reduction and an increased damping which imply that loads could be redistributed and thereby increase the stress ranges in some of the other critical details.

Table 7 illustrates the stochastic variables typically used in a fracture mechanical model for fatigue analysis, partly based on table 6. Considering as an example two critical components, the limit state equations can be written:

$$g_1(t) = a_{c,1} - a_1(\mathbf{X}_{Load,1}, \mathbf{X}_{Strength,1}, t) \quad (7)$$

$$g_2(t) = a_{c,2} - a_2(\mathbf{X}_{Load,2}, \mathbf{X}_{Strength,2}, t) \quad (8)$$

where  $a_j(\mathbf{X}_{Load,j}, \mathbf{X}_{Strength,j}, t)$  is the crack depth at time  $t$  for component  $j$ ,  $a_{c,j}$  is the critical crack depth for component  $j$ ,  $\mathbf{X}_{Load,j}$  are the load variables ( $Z_{SCF}$ ,  $Z_{wave}$ ,  $a$  and  $b$ ) for component  $j$ ,  $\mathbf{X}_{Strength,j}$  are the strength variables ( $N_I$ ,  $a_0$ ,  $\ln C_C$  and  $Y$ ) for component  $j$ .

The events corresponding to detection of a crack at time  $T$  can similarly be written:

$$h_1(T) = c_{d,1} - c_1(\mathbf{X}_{Load,1}, \mathbf{X}_{Strength,1}, T) \leq 0 \quad (9)$$

$$h_2(T) = c_{d,2} - c_2(\mathbf{X}_{Load,2}, \mathbf{X}_{Strength,2}, T) \leq 0 \quad (10)$$

where  $c_j(\mathbf{X}_{Load,j}, \mathbf{X}_{Strength,j}, c_{d,j}, T)$  is the crack length at time  $T$  for component  $j$  and  $c_{d,j}$  is the smallest detectable crack length for component  $j$ . It is noted that the crack depth  $a_j(t)$  and crack length  $c_j(t)$  are related through the coupled differential equations in (5).

The stochastic variables in different components will typically be dependent. The load related variables can be assumed fully dependent since the loading is common to most components. However, in special cases different types of components and components placed with a long distance between each other can be less dependent. The strength variables  $N_I$ ,  $a_0$  and  $\ln C_C$  will typically be independent since the material properties are varying from component to component. However, some dependence can be expected for components fabricated with the same production techniques and from the same basic materials.

Updated probabilities of failure of component 1 and 2 given no detection of cracks in detail 1 and 2 are

$$P_{F,1|1} = P(g_1(t) \leq 0 | h_1(T) > 0) \quad (11)$$

$$P_{F,2|2} = P(g_2(t) \leq 0 | h_2(T) > 0) \quad (12)$$

$$P_{F,2|1} = P(g_2(t) \leq 0 | h_1(T) > 0) \quad (13)$$

$$P_{F,1|2} = P(g_1(t) \leq 0 | h_2(T) > 0) \quad (14)$$

(11) and (12) represent situations where a component is updated with inspection of the same component. (13) and (14) represent situations where a component is updated with inspection of another component. The above formulas can easily be extended to cases where more components are inspected.

In figure 9 is illustrated the effect on inspection planning for a component if this component is inspected or if another nearby component is inspected. The largest effect on reliability updating and thus inspection planning is obtained inspecting the same component or inspection of another component with a large correlation with the considered component.



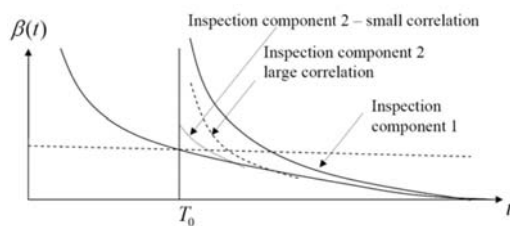


Figure 9. Reliability index as function of time for component no. 1 and updated reliability if inspection of component no. 1 at time  $T_0$ , or of component no. 2 at time  $T_0$  with large and small positive correlation with component no. 1.

## 5 SUMMARY

The basic principles in reliability and risk based inspection planning are described. The basic assumption made in risk/reliability based inspection planning is that a Bayesian approach can be used. The Bayesian approach and the no-crack detection assumption imply that the inspection time intervals usually become longer and longer. Further, inspection planning based on the RBI approach implies that single components are considered, one at the time, but with the acceptable reliability level assessed based on the consequence for the whole structure in case of fatigue failure of a single component.

The following two aspects are considered with the aim to develop/extend the risk based inspection approach for older installations, namely that for aging structures several small defects/cracks are often observed – implying an increased risk for defect/crack initiation (and coalescence of small defects/cracks) and increased defect/crack growth. This should imply shorter inspection time intervals for ageing structures.

Different approaches for updating inspection plans for older installations are proposed. The most promising method consists in increasing the rate of defects/crack initiation at the end of the expected lifetime – corresponding to a bath-tub hazard rate effect. The approach is illustrated for welded steel details in platforms, and implies that inspection time intervals decrease at the end of the platform lifetime.

It is noted that data is needed to verify the increased crack initiation model. These data can be direct observations of cracks in older installations or indirect information from inspection programs.

The approaches described is especially developed for inspection planning of fatigue cracks, but can also be used for various other deterioration processes where inspection is relevant, including corrosion, chloride ingress in concrete and possible corrosion of reinforcement and wear.

Different system aspects are considered incl. assessment of the acceptable annual probability of failure for one component dependent on the number of critical

components. Common loading, model uncertainties etc. imply that information obtained from inspection of one component can be used not only to update the inspection plan for that component, but also for other nearby components. Further, the common history and loading also implies an increased risk that several correlated components can fail at almost the same time.

## REFERENCES

- Benjamin, J.R. and Cornell, C.A. 1970. Probability, statistics and decision for civil engineers. McGraw-Hill, NY.
- Fujita, M., Schall, G. and Rackwitz, R., 1989. Adaptive reliability based inspection strategies for structures subject to fatigue. In Proc. ICOSSAR89, San Francisco, USA, pp. 1619–1626.
- Ersdal, G. 2005. Assessment of existing offshore structures for life extension. PhD thesis, University of Stavanger.
- Faber, M.H. and Sørensen, J.D. 1999. Aspects of Inspection Planning – Quality and Quantity, Published in Proc. ICASP8, Sidney Australia.
- Faber, M.H., Englund, S., Sørensen, J.D. and Bloch, A. 2000. Simplified and Generic Risk Based Inspection Planning. *Proc. 19th OMAE, Vol. 2.*
- Faber, M.H., Sørensen, J.D., Tyghsen, J. and Straub, D. 2005. Field Implementation of RBI for Jacket Structures. *Journal of Offshore Mechanics and Arctic Engineering, Vol. 127, 220–226.*
- Lassen, T. 1997. Experimental investigation and stochastic modeling of the fatigue behavior of welded steel joints. PhD thesis, Structural reliability theory, paper No. 182, Aalborg University.
- Madsen, H.O., Sørensen J.D. and Olesen R. 1989. Optimal Inspection Planning for Fatigue Damage of Offshore Structures. *Proceedings ICOSSAR 89, San Francisco, pp. 2099–2106.*
- Madsen, H.O. and Sørensen J.D. 1990. Probability-Based Optimization of Fatigue Design Inspection and Maintenance. Presented at Int. Symp. on Offshore Structures, University of Glasgow, pp. 421–438.
- Moan, T. 2005. Reliability-based management of inspection, maintenance and repair of offshore structures. *Journal Structure and Infrastructure Engineering, pp. 33–62.*
- PIA 1990. PIA (Probabilistic Inspection Analysis) Theory Manual, Aker Partner Engineering AS, Oslo, Norway.
- Raiffa, H. and Schlaifer, R. 1961. *Applied Statistical Decision Theory.* MIT Press, Cambridge, Mass.
- Skjong, R., 1985. Reliability based optimization of inspection strategies. In Proc. ICOSSAR 85 Vol. III, Kobe, Japan, pp. 614–618.
- Straub, D. and Faber M.H. 2005. Risk based acceptance criteria for joints subject to fatigue deterioration. *Journal of Offshore Mechanics and Arctic Engineering, Vol. 127, pp. 150–157.*
- Sørensen, J.D., Faber, M.H., Rackwitz, R. and Thoft-Christensen, P.T. 1991. Modeling in optimal inspection and repair. In Proc. OMAE91, Stavanger, Norway, pp. 281–288.
- Sørensen, J.D., Straub D. and M.H. Faber 2005. Generic Reliability-Based Inspection Planning for Fatigue Sensitive Details – with Modifications of Fatigue Load. CD-rom Proc. ICOSSAR'2005, Rome.