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*Published in:*  
Proceedings of OMAE'08

*Publication date:*  
2008

*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. (2008). Risk Based Inspection Planning of Ageing Structures. In *Proceedings of OMAE'08: 27<sup>th</sup> International Conference on Offshore Mechanics and Arctic Engineering : June 15-20, 2008, Estoril, Portugal* American Society of Mechanical Engineers.

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OMAE08-57404

## RISK BASED INSPECTION PLANNING OF AGEING STRUCTURES

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### ABSTRACT

There are an increasing number of older installations in use on the Norwegian Continental shelf. Inspections are a key issue in ensuring the safety of an older installation, and the inspection intervals, inspection methods and its reliability are clearly influencing the safety of the installations. Different approaches for updating inspection plans for older installations are considered in order to achieve decreased inspection intervals as the structure are ageing. The most promising method consists in increasing the rate of defects / crack initiation at the end of the expected lifetime.

Different system aspects are considered incl. assessment of the acceptable annual probability of failure for one component dependent on the number of critical components. 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. An example indicates that a high degree of correlation between the uncertain parameters in different components is needed in order to obtain substantial information which can be used in inspection planning.

Fatigue failure of one (or more) components does not necessarily imply total collapse of the structure. The importance of each component can be measured by the *RIF* (Residual Influence Factor) for each component and is illustrated by examples. When an installation becomes older then the number of fatigue critical components can be expected to increase. If the maximum acceptable annual system probability of failure is the same as for a new installation, this implies that the acceptable annual fatigue probability of failure decrease, which again implies more inspections.

### INTRODUCTION

The number of older installations is increasing in the Norwegian Continental shelf. The regulation of these older installations is a part of the Petroleum Safety Authority's responsibility, with the intention of ensuring that also older

installations can be regarded as safe. Inspections, maintenance and repair of the installations are a key issue in ensuring the safety of older installation, and the inspection intervals, inspection methods and its reliability are clearly influencing the knowledge of the safety of the installations. Development of a risk based inspection approach for aging platforms taking into account that for aging platforms several small cracks can be expected – implying an increased risk.

Reliability and Risk Based Inspection (RBI) planning for offshore structures have been an area of high practical interest over the last decades, especially within inspection planning for welded connections subject to fatigue crack growth in fixed steel offshore platforms. The basic assumption made in RBI 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 often 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 with time. It is noted that RBI planning for future inspections are based on predefined 'decision rules' on repair / maintenance when inspection results become available.

Further, inspection planning based on the RBI approach implies that single fatigue critical 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 [1], Skjong [2], Sørensen, Faber, Rackwitz & Thoft-Christensen [3], Ersdal [4], Sørensen, Straub & Faber [5], Moan [6], Straub & Faber [7], Faber, Sørensen Tychsen & Straub [8] and PIA [9].

For aging installations an increasing amount of small defects / cracks are expected to be observed when the installation approaches the design lifetime implying an increased risk for defect / crack initiation (and coalescence of small defects / cracks) and increased crack growth. An increased crack initiation rate should imply shorter inspection time intervals for ageing installations.

In this paper it is assumed that installations in life extension should have the same reliability level as installations in the design life, thus giving the same safety for people and environment. A sufficient safety level in life extension can be obtained by reduced uncertainty about the installation due to knowledge from operation, dedicated maintenance with respect to ageing, modifications of structure, change from ‘safe life thinking’ to ‘damage tolerant thinking’ and/or by an appropriate risk-based maintenance approach. This paper considers different ways of formulating a risk-based maintenance approach for inspection planning of ageing installations.

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

- 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.
- 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.
- Fatigue failure of one (or more) components does not necessary imply total collapse of the structure. The importance of each component can be measured by the *RIF* (Residual Influence Factor) for each component. How many components fail by fatigue before total collapse of structure?
- When an installation becomes older then the number of fatigue critical components can be expected to increase. If the maximum acceptable annual system probability of failure is the same as for a new installation, this implies that the acceptable annual fatigue probability of component/fatigue failure decrease.

## INSPECTION PLANNING FOR OLDER INSTALLATIONS

Various investigations in reliability-based inspection planning for aging installations have been considered and analyzed in Sørensen & Ersdal [10] especially with the aim to

discuss and investigate how decreased inspection time intervals could be obtained when time approaches and goes beyond the design lifetime.

The following models are considered for modifying inspection intervals for older installations:

- Increase of expected value of initial crack size with time – due to coalescence of smaller cracks.
- Non-perfect repairs - by detection of cracks the repair is not perfect, and a new crack is initiated.
- Human errors in inspections (beyond uncertainty included in *POD*-curves).
- 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).

Table 1. Stochastic model for SN-approach in examples. D: Deterministic, N: Normal, LN: LogNormal.

Variable	Distribution	Exp. value	Standard deviation
$\Delta$	LN	1	0.2
$Z_{SCF}$	LN	1	$COV = 0.10$
$Z_{wave}$	LN	1	$COV = 0.30$
$T_L$	D	25 years	
$T_F$	D	75 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			

Table 2. Uncertainty modeling used in the fracture mechanical reliability analysis. W: Weibull.

Variable	Dist.	Expected value	Standard dev.
$N_I$	W	$\mu_{I0}$ (fitted)	$COV = 0.35$
$a_0$	D	0.4 mm	
$\ln C$	N	$\mu_{\ln C}$ (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	
$\ln C$ and $N_I$ are correlated with correlation coefficient $\rho_{\ln C, N_I} = -0.5$			

Representative examples are used to evaluate the different models, see [10]. The results indicate that model d) is the most

promising. In the following example the extra cracks in the fatigue critical area are assumed to initiate following a linear model in the time interval  $[T_0, T_E]$  and that the expected number of extra cracks is  $1 - \delta/\delta$  ( $0 < \delta \leq 1$ ) implying a crack initiation rate  $\alpha_I = 2(1 - \delta)/(T_E - T_0)$  at  $T_E$ .

Monte Carlo simulations are used to estimate the reliability as function of time by the SN-approach / Miners rule and by the fracture mechanics approach (FM) calibrated to the SN-approach. For illustration a 1-dimensional fracture mechanics model is used. The stochastic models used are shown in tables 1 and 2, see details in [10].  $\Delta$  models the uncertainty related to Miners rule;  $Z_{SCF}$  and  $Z_{wave}$  model uncertainty related to the stress analysis and to the wave load;  $T_L$  and  $T_F$  are the design life and the fatigue life;  $m_1$  and  $m_2$  are the upper and lower slopes of a bilinear SN-curve;  $\log K_1$  and  $\log K_2$  are the corresponding intersection with the  $\log S$  axis where  $S$  is the stress range. In the FM approach  $N_I$  is the number of cycles to crack initiation;  $a_0$  is the initial crack length;  $m$  and  $\ln C$  are the parameters in Paris equation;  $a_c$  is the critical crack length and  $Y$  is a geometry function. The parameters in the fracture mechanical model are calibrated to  $\mu_{I0} = 5$  years and  $\mu_{\ln C_c} = -25.5$ .

The reliability index (based on accumulated probability of failure) is shown in figure 1. It is seen that a satisfactory agreement between the SN and the FM approach is obtained.

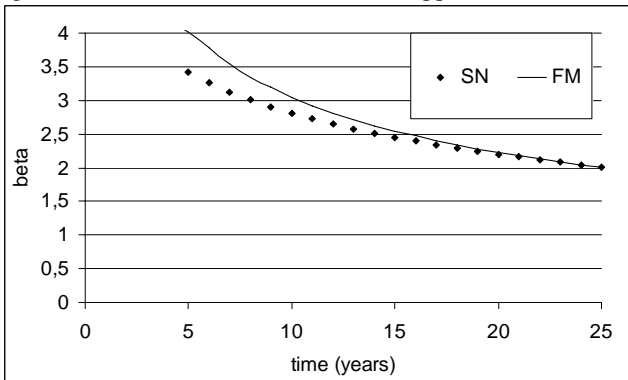


Figure 1. Reliability index (accumulated) as function of time for SN approach and calibrated FM-approach.

RBI planning with no modifications results in the inspection times shown in table 3 for  $\Delta P_F^{\max} = 10^{-4}$ . It is seen that 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.

Table 3. Inspection times and inspection time intervals in years. ‘No modification’.  $\Delta P_F^{\max} = 10^{-4}$ .

Inspection time	6	7	9	11	14	18	22	29	39	53
Inspection interval	6	1	2	2	3	4	4	7	10	14

Table 4. Inspection times and inspection time intervals in years.

Inspection time	6	8	9	11	13	17	22
Inspection interval	6	2	1	2	2	4	5
	30	38	43	48	53	58	
	8	8	5	5	5	5	

As an example for application of model d) extra cracks are assumed to initiate with  $\delta = 0.25$  and  $[T_0, T_E] = [25-60]$ . From the results in table 4 it is seen the inspection time intervals decrease. Similar results are obtained for  $\Delta P_F^{\max} = 10^{-3}$ .

### SYSTEMS EFFECTS – INSPECTION PLANNING WITH CORRELATION BETWEEN COMPONENTS

This section describes the effect of correlation between fatigue failure in different components due to common loading, common model uncertainties and correlation between inspection qualities. The 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.

As an example two fatigue critical components with limit state equations  $g_1(t) = 0$  and  $g_2(t) = 0$  are considered. The events corresponding to detection of a crack at inspection time  $T$  can similarly be modeled by  $h_1(T) \leq 0$  and  $h_2(T) \leq 0$ .

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

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

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

$$P_{F,2|1} = P(g_2(t) \leq 0 | h_1(T) > 0) \quad (3)$$

$$P_{F,1|2} = P(g_1(t) \leq 0 | h_2(T) > 0) \quad (4)$$

(1) and (2) represent situations where a component is updated with inspection of the same component. (3) and (4) 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.

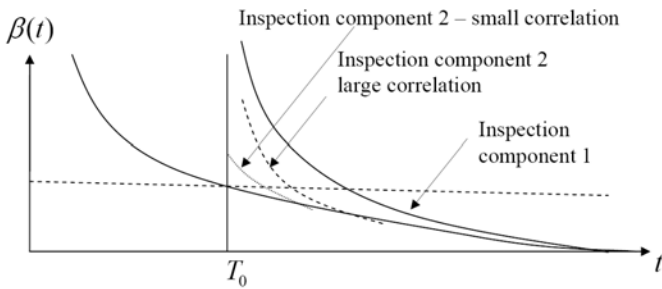


Figure 2. Reliability index as function of time for component no. 1 and updated reliability if inspection of component no. 1 at time  $T_0$ , or of component no. 2 at time  $T_0$  with large and small positive correlation with component no. 1.

In figure 2 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.

As an example two components are considered with same stochastic model as in the previous section. It is assumed that component 1 is inspected, and if a crack is detected, then both component 1 and 2 are repaired. Further it is assumed that each of the stochastic variables  $Z_{SCF}$ ,  $Z_{wave}$  and  $Y$  are fully correlated in the two elements.  $N_i$  and  $\ln C$  are assumed independent in the two components. No extra cracks are initiated and  $\Delta P_F^{\max} = 10^{-3}$ . Inspections should be performed at year 14, 23 and 35. In figure 3 is shown the accumulated probability of failure for the two components. It is seen that the probability of failure for component 2 decrease compared with no inspection, but is much higher than for the inspected component 1.

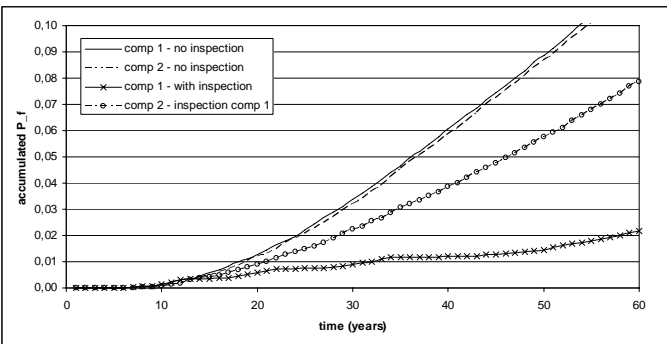


Figure 3. Accumulated probability of failure as function of time.

Next it is assumed that the stochastic variable  $\ln C$  is fully correlated in component 1 and 2. In figure 4 is shown the accumulated probability of failure for the two components. It

is seen that now the probability of failure for component 2 is almost the same as for component 1.

These results indicate that a relatively high degree of correlation between the uncertain parameters in different components is needed in order to obtain substantial information which can be used in inspection planning.

Next, the effect is considered of requiring that the calculated fatigue of a non-inspected detail should be at least 3 times longer than the hot spot that is inspected. Provided that fatigue cracks are not detected at the region with a short calculated life, it is also likely that the considered hot spot has sufficient fatigue capacity (due to correlation in load action). Component 1 and 2 are calibrated such that component 1 has  $FDF = 3$  ( $T_L=25$  years;  $T_F=75$  years) and component 2 has  $FDF = 9$  ( $T_L=25$  years;  $T_F=225$  years). Three examples are considered with max annual probability of failure  $\Delta P_F^{\max} = 10 \cdot 10^{-4}$ ,  $5 \cdot 10^{-4}$  and  $2.5 \cdot 10^{-4}$ .

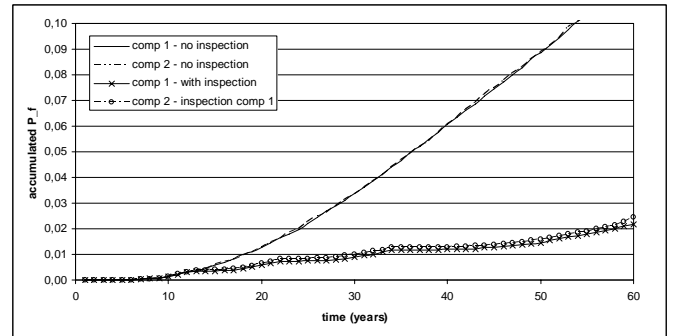


Figure 4. Accumulated probability of failure as function of time.

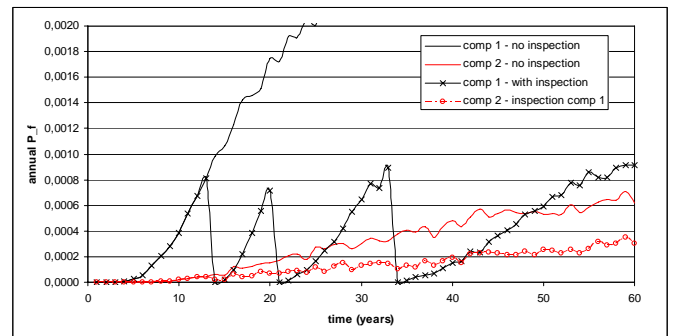


Figure 5. Accumulated probability of failure as function of time. Without extra crack initiation and  $\Delta P_F^{\max} = 10 \cdot 10^{-4}$ .

Case 1)  $\Delta P_F^{\max} = 10 \cdot 10^{-4}$ : Inspections of component 1 are necessary at years 14, 21, 34. Annual probabilities of failure as function of time are shown in figure 5. For component 2:  $\Delta P_F(25) = 0.9 \cdot 10^{-4}$ ;  $\Delta P_F(60) = 3.3 \cdot 10^{-4}$ , i.e. the reliability level of component 2 is satisfactory.

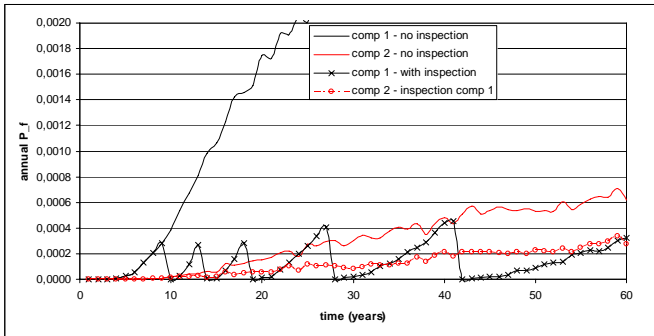


Figure 6. Accumulated probability of failure as function of time. Without extra crack initiation and  $\Delta P_F^{\max} = 5 \cdot 10^{-4}$ .

Case 2)  $\Delta P_F^{\max} = 5 \cdot 10^{-4}$ : Inspections of component 1 are necessary at years 10, 14, 19, 28, 42. Annual probabilities of failure as function of time are shown in figure 6. For component 2:  $\Delta P_F(25) = 1.0 \cdot 10^{-4}$ ;  $\Delta P_F(60) = 3.1 \cdot 10^{-4}$ , i.e. the reliability level of component 2 is satisfactory.

Case 3)  $\Delta P_F^{\max} = 2.5 \cdot 10^{-4}$ : Inspections of component 1 are necessary at years 8, 10, 13, 17, 23, 32, 44. Annual probabilities of failure as function of time are shown in figure 7. For component 2:  $\Delta P_F(25) = 0.6 \cdot 10^{-4}$ ;  $\Delta P_F(60) = 3.0 \cdot 10^{-4}$ , i.e. the reliability level of component 2 is satisfactory at time  $T_L = 25$  years, but not at the extended lifetime  $T_L = 60$  years.

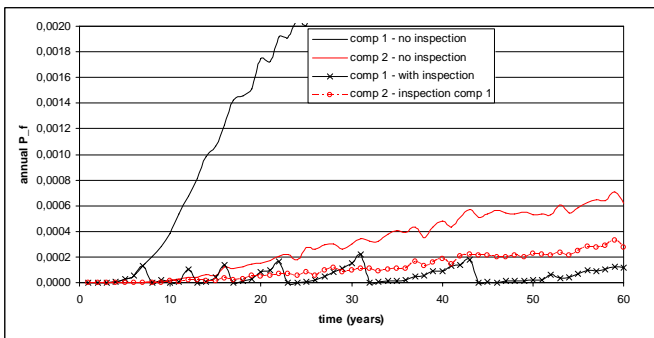


Figure 7. Accumulated probability of failure as function of time. Without extra crack initiation and  $\Delta P_F^{\max} = 2.5 \cdot 10^{-4}$ .

### SYSTEM EFFECTS – ACCEPTANCE CRITERIA DEPENDING ON NUMBER OF COMPONENTS

In regard to fatigue failures the requirements to safety are typically given in terms of a required Fatigue Design Factor (*FDF*). As an example NORSOK [11] specifies the *FDF*'s in Table 3.

From the *FDF*'s specified in Table 5 it is possible to establish the corresponding annual probabilities of failure for a specific year. For the joints to be considered in an inspection plan, the acceptance criteria for the annual probability of fatigue failure may be assessed through the *RSR* (Reserve

Strength Ratio) given failure of each of the individual joints to be considered together with the annual probability of joint fatigue failure. If the *RSR* given joint fatigue failure is known, it is possible to establish the corresponding annual collapse failure probability given fatigue failure,  $P_{COL|FAT}$ .

Table 5. Fatigue Design Factors. Factors relate to 'mean  $\div$  2 standard deviation' SN-curves.

Classification of structural components based on damage consequence	Access for inspection and repair		
	No access or in the splash zone	Accessible	
		Below splash zone	Above splash zone
Substantial consequences	10	3	2
Without substantial consequences	3	2	1

In order to assess the acceptable annual probability of fatigue failure for a particular joint in a platform the reliability of the considered platform must be calculated conditional on fatigue failure of the considered joint. The importance of a fatigue failure is measured by the Residual Influence Factor defined as

$$RIF = \frac{RSR^{\text{damaged}}}{RSR^{\text{intact}}} \quad (5)$$

where  $RSR^{\text{intact}}$  is the *RSR* value for the intact structure and  $RSR^{\text{damaged}}$  is the *RSR* value for the structure damaged by fatigue failure of a joint. The principal relation between RIF and annual collapse probability is illustrated in Figure 8.

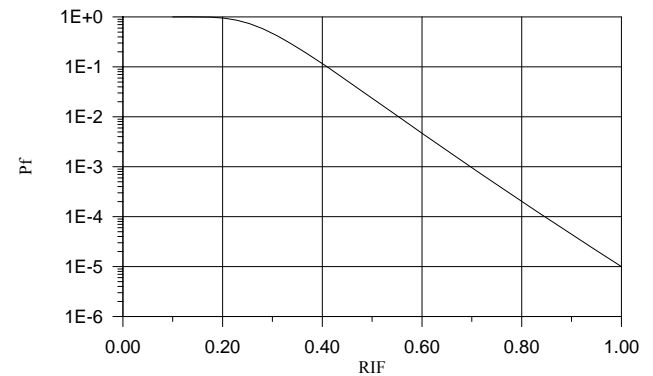


Figure 8. Example relationship between Residual Influence Factors (RIF) and annual collapse probability of failure -  $P(COL|FAT)$ .

The implicit code requirement to the safety of the structure in regard to total collapse may be assessed through the annual probability of joint fatigue failure (in the last year

in service)  $P_{FAT_j}$  for a joint for which the consequences of failure are “substantial” (i.e.  $FDF = 10$ ). This probability can be regarded an acceptance criteria i.e.  $P_{AC}$ . A typical maximal allowed annual probability of collapse failure is in the order of  $P_{AC} = 10^{-5}$ .

A general relation between  $RSR$  and the probability of failure can be obtained considering e.g. the following limit state function:

$$g(x) = R - bH^a \quad (6)$$

where  $R$  is the effective capacity of the platform,  $a$  is a shape factor typically equal to 2,  $b$  is an influence coefficient taking into account model uncertainty parameter and  $H^a$  is a stochastic variable modeling the maximum annual value of the environmental load parameter. The  $RSR$  value as evaluated by a push-over analysis can be related to characteristic values of  $R$ ,  $a$ ,  $b$  and  $H$  i.e.  $R_C$ ,  $b_C$  and  $H_C$ . The characteristic value for  $R$ ,  $b$  and  $H^a$  could be defined as 5%, 50% and 99% quantile values of their probability distributions.

It is assumed that  $R$  and  $b$  can be modeled probabilistically as LogNormal distributed random variables and  $H^2$  as a Gumbel distributed random variable. The coefficients of variation are chosen to  $COV_R = 0.10$ ,  $COV_b = 0.10$  and  $COV_{H^2} = 0.214$ . Using these values  $RSR = 1.79$  and the annual probability of failure (collapse)  $P_{COL} = 10^{-5}$  are obtained.

In the following three approximations are considered to assess the maximum annual probability of fatigue failure,  $\Delta P_{FAT,j}^{\max}$ . It is assumed that  $N$  components/members are critical, the members contribute equally to the probability of failure and only one fatigue critical component fails before total collapse:

- Simple upper bound on the system probability of failure
- An approximate estimate of the system probability of failure assuming that fatigue failure implies load bearing capacities correlated due to common loading
- An approximate estimate of the system probability of failure assuming that fatigue failure in different components is correlated due to common model uncertainties.

Model 1) simple upper bound on the system probability of failure:

$$P_F^{\text{sys}} \cong N \cdot P(COL \cap FAT_j) = N \cdot P(COL|FAT_j) \cdot P(FAT_j) \quad (7)$$

implying:

$$\Delta P_{FAT}^{\max} = \frac{1}{N} \frac{P_{AC}}{P_{COL|FAT}} \quad (8)$$

$\Delta P_{FAT}^{\max}$  is shown in figure 9 and 10 for  $P_{AC} = 10^{-5}$  and  $P_{AC} = 10^{-4}$ , and for  $N = 1, 2, 5$  and 10 critical components.

Model 2) approximate estimate of the system probability of failure assuming that fatigue failure implies load bearing capacities correlated due to common loading:

$$P_F^{\text{sys}} = P(\{COL|FAT_1\} \cup \{COL|FAT_2\} \cup \dots \cup \{COL|FAT_N\}) \cdot P(FAT_j) \quad (9)$$

implying

$$\Delta P_{FAT}^{\max} = \frac{P_{AC}}{P_{SYS}} \quad (10)$$

where  $P_{SYS} = 1 - \Phi_N(\beta_1, \beta_2, \dots, \beta_N; \rho)$  with the reliability index for each member given fatigue failure is  $\beta_i = -\Phi^{-1}(P_{COL|FAT_i})$  and the correlation coefficients in the correlation coefficient matrix,  $\rho$  are obtained assuming that only the wave loading is common in different components, i.e. the load bearing capacities are independent in case of fatigue failure of different members.  $\Delta P_{FAT,j}^{\max}$  estimated by (10) is shown in figure 11 and 12 for  $P_{AC} = 10^{-5}$  and  $P_{AC} = 10^{-4}$ , and for  $N = 1, 2, 5$  and 10 critical components.

Model 3) approximate estimate of the system probability of failure assuming that fatigue failure in different components are correlated due to common model uncertainties:

$$P_F^{\text{sys}} = P(COL|FAT) \cdot P(FAT_1 \cup FAT_2 \cup \dots \cup FAT_N) \quad (11)$$

implying that the maximum acceptable probability of member fatigue failure is obtained from the requirement:

$$P(COL|FAT) \cdot \Delta P_{FAT} \leq P_{AC} \quad (12)$$

where  $\Delta P_{FAT} = 1 - \Phi_N(\beta_1, \beta_2, \dots, \beta_N; \rho)$  with the reliability index for each member given fatigue failure is  $\beta_j = -\Phi^{-1}(\Delta P_{FAT,j}^{\max})$  and the correlation coefficients in the correlation coefficient matrix,  $\rho$  are obtained assuming that only the fatigue model uncertainties are common in different fatigue critical components, i.e. the fatigue strength modeled are independent in case of fatigue failure of different members. The simple relationship between  $P(COL|FAT)$  and

$RIF$  in figure 13 is used.  $\Delta P_{FAT,j}^{\max}$  estimated by (13) is shown in figure 14 and 15 for the common correlation coefficients  $\rho = 0.5$  and for  $P_{AC} = 10^{-5}$  and  $P_{AC} = 10^{-4}$ .

Model 3 is considered the most reasonable, but from the results it is seen that the simple upper bounds in figure 3 for  $N = 1, 2, 5$  and 10 critical components give conservative

estimates of the acceptable annual probability of fatigue failure.

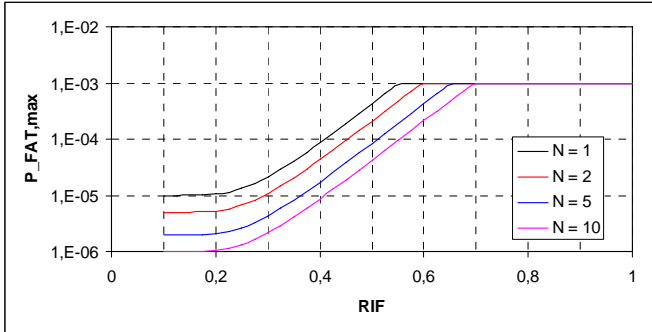


Figure 9. Model 1 - maximum acceptable annual probability of fatigue failure,  $\Delta P_{FAT}^{max}$  for each fatigue critical detail as function of  $RIF$  (Residual Influence Factor).  $P_{AC} = 10^{-5}$ .

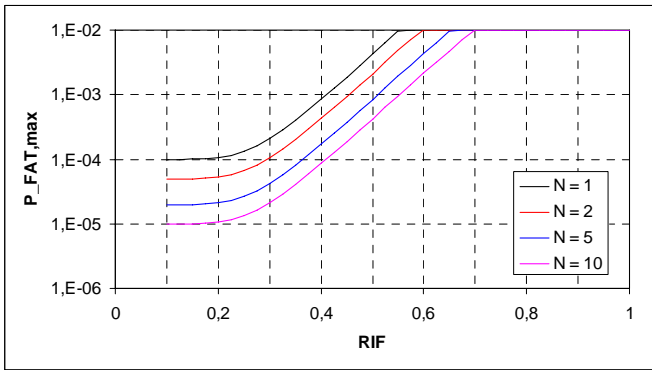


Figure 10. Model 1 - Maximum acceptable annual probability of fatigue failure,  $\Delta P_{FAT}^{max}$  for each fatigue critical detail as function of  $RIF$  (Residual Influence Factor).  $P_{AC} = 10^{-4}$ .

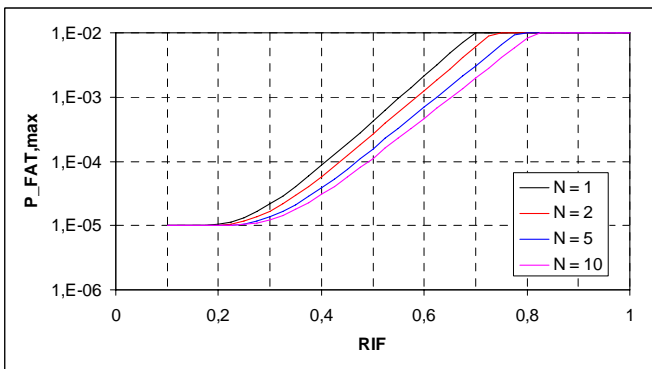


Figure 11. Model 2 - Maximum acceptable annual probability of fatigue failure,  $\Delta P_{FAT}^{max}$  for each fatigue critical detail as function of  $RIF$  (Residual Influence Factor).  $P_{AC} = 10^{-5}$ .

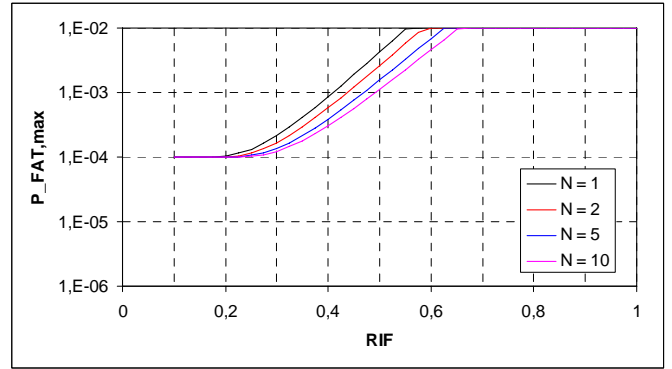


Figure 12. Model 2 - Maximum acceptable annual probability of fatigue failure,  $\Delta P_{FAT}^{max}$  for each fatigue critical detail as function of  $RIF$  (Residual Influence Factor).  $P_{AC} = 10^{-4}$ .

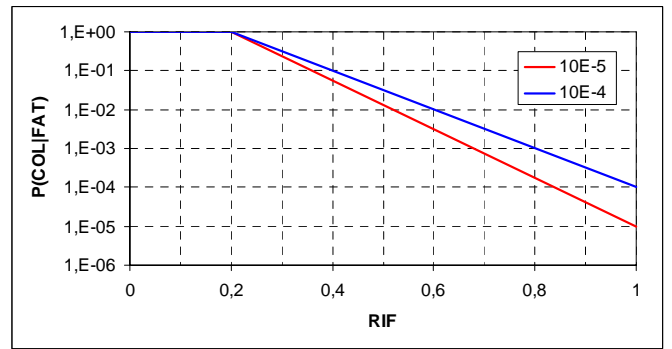


Figure 13. Model 2 - Relationship between  $P(COL|FAT)$  and  $RIF$ .

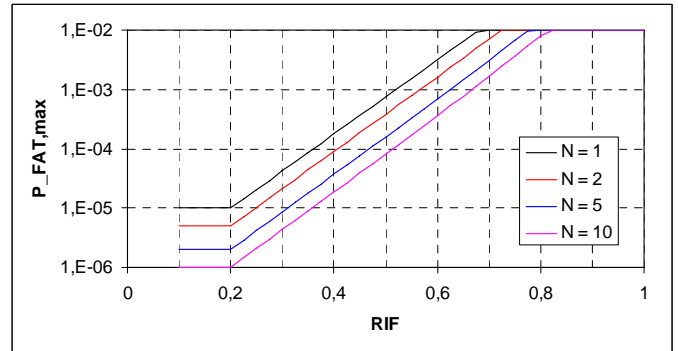


Figure 14. Model 3 - Maximum acceptable annual probability of fatigue failure,  $\Delta P_{FAT}^{max}$  for each fatigue critical detail as function of  $RIF$  (Residual Influence Factor).  $P_{AC} = 10^{-5}$  and  $\rho = 0.5$ .



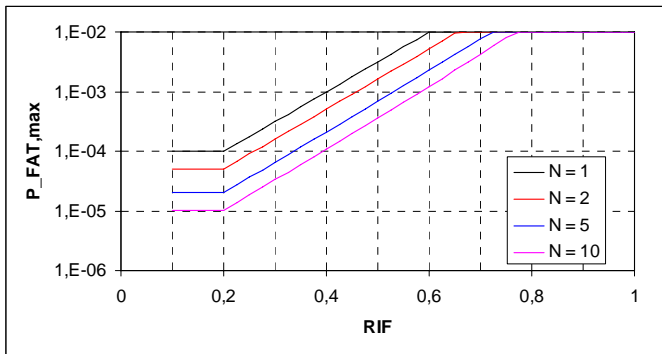


Figure 15. Model 3 - Maximum acceptable annual probability of fatigue failure,  $\Delta P_{FAT}^{\max}$  for each fatigue critical detail as function of  $RIF$  (Residual Influence Factor).  $P_{AC} = 10^{-4}$  and  $\rho = 0.5$ .

### SYSTEM EFFECTS – NUMBER OF COMPONENTS TO FAIL BY FATIGUE BEFORE TOTAL COLLAPSE

In this section it is investigated how many fatigue critical components fail before collapse of the installation. The model for the ultimate load bearing capacity (collapse) described in the above section is used.

$N=5$  fatigue critical components are assumed. Life time realizations of the crack size are generated using the stochastic model described in previous sections. In case of failure of one of the fatigue critical components the load bearing capacity  $R$  is reduced by a factor equal to  $RIF$ . If  $m$  components are failed by fatigue at time  $t$ , then the load bearing capacity  $R$  is reduced by a factor  $RIF^m$ . If a component is inspected and a crack is detected then it is assumed that all  $N$  components are repaired.

Figures 16 and 17 show the expected number of fatigue critical components failed in case of total collapse with  $RIF = 0.3, 0.5, 0.7, 0.8$  and  $0.9$ . It is seen that for  $RIF$  less than approximately 0.4 only one fatigue critical component fail before collapse.

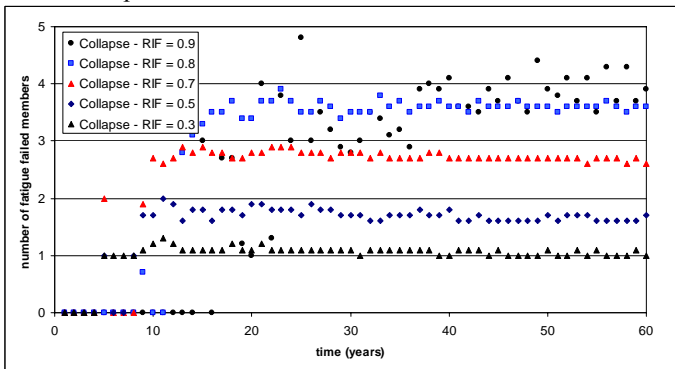


Figure 16. Expected number of components failed by fatigue in case of total collapse failure of structure for  $RIF = 0.3, 0.5, 0.7, 0.8$  and  $0.9$  without inspections.

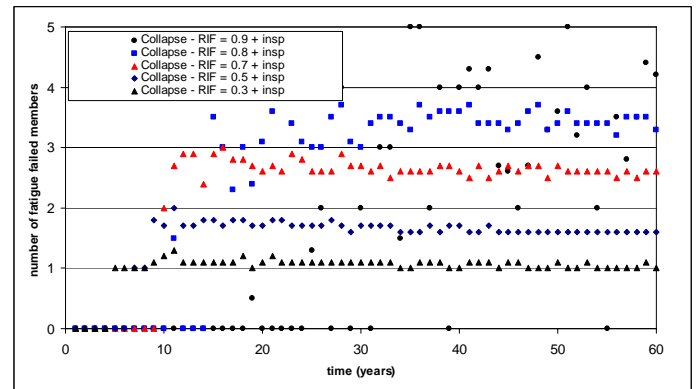


Figure 17. Expected number of components failed by fatigue in case of total collapse failure of structure for  $RIF = 0.3, 0.5, 0.7, 0.8$  and  $0.9$  with inspections.

The above results indicate that for structures with 5 fatigue critical components up to 4 fatigue critical components have to fail before collapse when  $RIF$  is large (larger than 0.8). Only one fatigue critical component has to fail before collapse when  $RIF$  is small (smaller than 0.4). This implies that assessment of the maximum acceptable annual probability of fatigue failure is more complicated than described in the previous section when  $RIF$  is large.

### SYSTEM EFFECTS – INCREASED NUMBER OF FATIGUE CRITICAL COMPONENTS

Table 5. Number of fatigue critical elements:

Year	0-30	30-40	40-50	50-60
Number of elements	10	15	20	25

Table 6.  $\Delta P_{FAT}^{\max}$  as function of  $RIF$ .

$RIF$	$P(C F)$	$\Delta P_{FAT}^{\max}$ [0;30]	$\Delta P_{FAT}^{\max}$ [30;40]	$\Delta P_{FAT}^{\max}$ [40;50]	$\Delta P_{FAT}^{\max}$ [50;60]
0.2	1	$1 \cdot 10^{-4}$	$0.67 \cdot 10^{-4}$	$0.50 \cdot 10^{-4}$	$0.40 \cdot 10^{-4}$
0.4	0.18	$5.6 \cdot 10^{-4}$	$3.7 \cdot 10^{-4}$	$2.8 \cdot 10^{-4}$	$2.2 \cdot 10^{-4}$
0.5	0.075	$13 \cdot 10^{-4}$	$8.9 \cdot 10^{-4}$	$6.7 \cdot 10^{-4}$	$5.3 \cdot 10^{-4}$
0.6	0.032	$32 \cdot 10^{-4}$	$21 \cdot 10^{-4}$	$15 \cdot 10^{-4}$	$13 \cdot 10^{-4}$
0.7	0.013	$75 \cdot 10^{-4}$	$50 \cdot 10^{-4}$	$37 \cdot 10^{-4}$	$30 \cdot 10^{-4}$
0.8	0.056	$178 \cdot 10^{-4}$	$119 \cdot 10^{-4}$	$89 \cdot 10^{-4}$	$71 \cdot 10^{-4}$

Table 7. Inspection time intervals in years.

$RIF$	6	2	2	2	3	4	5	6	8	9	10
0.2											
0.4	10	4	6	9	11	12					
0.5	17	12	12								
0.6	30	20									
0.7	53										
0.8											

When an installation becomes older the number of fatigue critical components can be expected to increase. If the

maximum acceptable annual system probability of failure is required to be the same as for a new installation, this implies that the component acceptable annual fatigue probability of failure decreases. The number of fatigue critical components is expected to develop as shown in table 5 and  $P_{AC}$  is chosen to  $10^{-3}$ .  $\Delta P_{FAT}^{max}$  determined using the simple upper bound approach is shown in table 6, and the corresponding inspection time intervals are shown in table 7.

Table 8. Number of fatigue critical elements.

Year	0-30	30-40	40-50	50-60
Number of elements	10	20	30	40

Table 9.  $\Delta P_{FAT}^{max}$  as function of RIF.

RIF	$P(C F)$	$\Delta P_{FAT}^{max}$	$\Delta P_{FAT}^{max}$	$\Delta P_{FAT}^{max}$	$\Delta P_{FAT}^{max}$
		[0,30]	[30,40]	[40,50]	[50,60]
0.2	1	$1 \cdot 10^{-4}$	$0.50 \cdot 10^{-4}$	$0.33 \cdot 10^{-4}$	$0.25 \cdot 10^{-4}$
0.3	0.42	$2.4 \cdot 10^{-4}$	$1.2 \cdot 10^{-4}$	$0.79 \cdot 10^{-4}$	$0.59 \cdot 10^{-4}$
0.4	0.18	$5.6 \cdot 10^{-4}$	$2.8 \cdot 10^{-4}$	$1.9 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$
0.5	0.075	$13 \cdot 10^{-4}$	$6.7 \cdot 10^{-4}$	$4.4 \cdot 10^{-4}$	$3.3 \cdot 10^{-4}$
0.6	0.032	$32 \cdot 10^{-4}$	$16 \cdot 10^{-4}$	$11 \cdot 10^{-4}$	$7.9 \cdot 10^{-4}$
0.7	0.013	$75 \cdot 10^{-4}$	$37 \cdot 10^{-4}$	$25 \cdot 10^{-4}$	$19 \cdot 10^{-4}$
0.8	0.006	$178 \cdot 10^{-4}$	$89 \cdot 10^{-4}$	$59 \cdot 10^{-4}$	$44 \cdot 10^{-4}$

Next the number of fatigue critical components is expected to develop as shown in table 8. The results are shown in tables 9 and 10. The results indicate (as expected) that when the structure is ageing and the number fatigue critical elements increase, and that the inspection time intervals decrease.

Table 10. Inspection time intervals in years.

RIF											
0.2	6	2	2	2	3	4	5	6	7	9	11
0.3	8	2	3	5	6	7	8	11			
0.4	10	4	6	9	9	11					
0.5	17	12	11	13							
0.6	30	13									
0.7	40										
0.8											

### FATIGUE DESIGN FACTORS – IN CASE OF LIFETIME EXTENSION

The problem considered in this section is how to check the design by deterministic calculations when an installation becomes older and lifetime extension is considered. For design of new installations the SN-approach and Fatigue Design Factors ( $FDF$ ) as for example in table 1 can be used.

The following example is considered: the original design lifetime is 25 years, lifetime extension from 25 to 45 years and an inspection (MPI or EC) is performed at year 25 with the result 'no-find'.

A modified  $FDF^{45}$  to be used for the life extension is estimated as follows:

- The reliability index as function of time is determined using the SN-approach and the  $FDF^{25}$  factor for life time = 25 years.
- The fracture mechanics model is calibrated to give approximately the same reliability as function of time.
- The annual reliability index at year 25 is determined:  $\Delta\beta(25)^1$
- The fracture mechanics model is re-calibrated to give the annual reliability index  $\Delta\beta(25)^1$  at year 45 assuming that an inspection with no-find is performed at year 25, i.e. the reliability level during the life extension is at least the same as in the ordinary life. The annual reliability index at year 45,  $\Delta\beta(45)^2$  is determined assuming no inspections
- Using the SN-approach the  $FDF^2$  (with lifetime = 25 year) is determined which give the annual reliability index at year,  $\Delta\beta(45)^2$
- Using  $FDF^2$  a modified  $FDF$  factor related to the whole lifetime 45 is determined:  $FDF^{45}$  (assuming inspection with no-find at year 25).

The result is shown in table 11. It is noted that only in the case of details in the splash zone with substantial consequences a new  $FDF$  factor related to the whole extended life (45 years) is needed. In the other cases the updating effect of the 'no-find' inspection is so large that the reliability in the life extension period is satisfactory (larger than the reliability level after 25 years).

Table 11. Fatigue Design Factors for life extension from 25 to 45 years and inspection (MPI or EC) with 'no-find' after 25 years. The upper index indicate the reference life time for the  $FDF$  factor. Factors relate to 'mean ÷ 2 standard deviation' SN-curves.

Classification of structural components based on damage consequence	In splash zone	Below splash zone	Above splash zone
Substantial consequences	$7^{45}$	$3^{25}$	$2^{25}$
Without substantial consequences	$3^{25}$	$2^{25}$	$1^{25}$

### SUMMARY

Different approaches for updating inspection plans for older installations are considered in order to achieve decreased inspection intervals as the structure are ageing. The most promising method consists in increasing the rate of defects / crack initiation at the end of the expected lifetime. 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. The approaches described are especially developed for inspection planning of fatigue cracks, but can also be used for various other deterioration processes where inspection is relevant.

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. An example indicates that a high degree of correlation between the uncertain parameters in different components is needed in order to obtain substantial information which can be used in inspection planning.

Assessment of the acceptable annual fatigue probability of failure for a particular component can be dependent on the number of critical components. Examples indicate that the acceptable annual probability of failure of a component can be obtained using a simple upper bound.

Fatigue failure of one (or more) components does not necessarily imply total collapse of the structure. The importance of each component can be measured by the *RIF* (Residual Influence Factor) for each component. Results indicate that for structure with 5 fatigue critical components up to 4 fatigue critical components have to fail before collapse when *RIF* is large (larger than 0.8). Only one fatigue critical component has to fail before collapse when *RIF* is small (smaller than 0.4). This implies that assessment of the maximum acceptable annual probability of fatigue failure has to be assessed taking more than one simultaneous component failure into account for *RIF* larger than 0.4.

When an installation becomes older then the number of fatigue critical components can be expected to increase. If the maximum acceptable annual system probability of failure is the same as for a new installation, this implies that the acceptable annual fatigue probability of failure decrease, which again implies more inspections.

Finally, an example of modifying the required Fatigue Design Factors (*FDF*) in case of life extension is shown indicating that only in the case of a detail in splash zone with substantial consequences a new *FDF* factor related to the whole extended life (45 years) is needed. In the other cases the updating effect of the 'no-find' inspection is so large that the reliability in the life extension period is satisfactory (larger than the reliability level after 25 years).

## ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support from the Petroleum Safety Authority Norway (the former Safety Division of the Norwegian Petroleum Directorate). The opinions expressed in this document are those of the authors,

and they should not be construed as reflecting the views of the Petroleum Safety Authority Norway.

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