Acceptable fatigue crack occurrence rate

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Abstract. In fatigue management, it is essential to know the fatigue crack growth potential. The lessons learned from use of refined fatigue analyses, fracture mechanics and probabilistic methods for platforms in-service are presented. For ageing offshore units of semi-submersible design, the inspection history of more than 20 000 NDT inspections and detection of close to 1000 fatigue cracks, are used in this study. These experience data are used to assess the fatigue failure potential. The fatigue crack growth capacities are influenced by the extent of gross errors in the design, construction and operation phase in addition to the normal uncertainties of design, construction and inspection. Corrosion in combination with not detected weakening of the capacity against fatigue crack growth is one of the main challenges. Assessments based on collected in-service observations are mandatory.

1. Introduction
Reliability measures may be expressed as component or system failure probabilities. The system failure is represented by sequences of component failure, which involve overload (collapse/fracture) and fatigue failure. In this paper we will focus on the probability for fatigue failure.

It is well known that fatigue analyses give a very uncertain estimate of the fatigue crack growth potential. Since 1989 we have applied a probabilistic model to give prognosis or forecast of the fatigue crack growth occurrence. A probabilistic fracture mechanics model makes it possible to get an updated estimate of the fatigue crack growth potential i.e. updating by use of information from in-service inspection, [12]. Such a method also allows for treatment of the interaction between design, inspection, maintenance and repair requirements, [4, 5, 9, 10].

A project to validate the probabilistic inspection analyses approach for jacket structures, was conducted during the period 1994 to 1999, [1 - 3]. The inspection and crack detection histories of around 40 jacket structures were used to identify the degree of correlation between theoretical predictions and observed fatigue cracks, by expressing predictions in probabilistic terms considering normal uncertainties. A calibrated model for the probabilistic forecast was made. However, validation of the calibrated model has not been done by use of a separate set of observation data. Attempts to update parameters in the probabilistic forecast model are presented in [8, 9]. The results for updated parameters for initial crack depth and probability of detection during an inspection were a significant contribution to the calibration, [8]. The validation of the weld improvement effect by grinding, focused in [9], is also a result included in the model for probabilistic forecast of fatigue cracks used during the last 15 years.

In [13] the conclusions from the validation study for the Jacket structures were discussed based on the collected experience data from 25 Semi-submersible of an average operation history of 20 years in the North Sea. It is significant deviations in the performance of the probabilistic forecast model for
Jacket Structures and Semi-submersibles, [13]. The systematic over prediction of fatigue crack growth in Jacket structures are not present for Semi-submersible. For Semi-submersible it is also a lower per cent of the fatigue cracks to occur on hot spot not scheduled for inspection than for the Jacket structures.

In this paper, we address the potential to obtain measures of the fatigue crack growth potential based on the in-service observations that include the effect of all uncertainties and gross errors not detected during the design, construction and first year in operation as well as corrosion.

The outline of this paper is as follows; Section 3, the next section, deals with the decision model for scheduling inspections, improvements and modifications. We focus the uncertainty elements associated with variation in workmanship and engineering. Section 3 give references to descriptions of probabilistic forecast models and assume familiarity with the concept of probabilistic fracture mechanics crack growth model as presented in [6, 12]. We also include considerations related to grouping of uncertainties and example of how these are included in our model.

Section 4 contains sensitivity studies of the uncertainty level in the fatigue load effect and the bias of calculated fatigue life. Section 4 does not include any updating based on inspection history. Section 5 discusses the selection of target reliability level focusing uncertainties in the fatigue load effect. Section 6 focuses the model including update based on the inspection history of No Find. The consequence of bias and variation in uncertainties for the fatigue load effect and PoD (Probability of Detection) values for the inspections are focused.

In section 7, we summarize the likely possibilities to achieve non-conservative results by use of a probabilistic forecast model. Measures and awareness to avoid non-conservative scope of improvement maintenance and inspection are given. To fully avoid non-conservative decisions we need to validate or calibrate the model forecasting the fatigue crack growth potential by use of in-service observations. Examples of such measures are discussed. Measures that include the added uncertainties and bias by the extent of gross errors in the design, construction and operation phase as well as corrosion.

2. The decision model for scheduling inspection, improvements and modifications

Figures 1 is a schematic illustration of how information from inspection and fatigue analyses results are combined for a specific hot spot location. The upper part of the figure illustrates the simulated crack size distribution and the lower part illustrates the development of the estimated probability of a fatigue failure to occur. This illustration is based on an inspection with result No Finding i.e. the event of crack smaller than the detectable crack size, is used for the probability update.

After updating, the estimate of the fatigue crack growth potential is improved. Updating based on inspection result of detecting a fatigue crack, will increase the probability of fatigue failure and not reduce the fatigue failure probability as shown in Figures 1.

The model and philosophy described in [4, 5] has since 1999 been applied for scheduling inspections, improvements and modifications for offshore floating structure. The used probabilistic fracture mechanics model gives results that are comparable with the probabilistic fracture mechanics model recommended used in [6]. Figures 2 contains comparison with curves in Figure 8-1 in [6].

The curves presented in Figures 2, are initially considered as notional probability levels. For these probabilistic fracture mechanics models to represent frequency of occurrence, we need to validate them by use of experience data. The validation is done by comparison of observed frequency of fatigue crack occurrence and forecasted probability of fatigue cracking. The presence of methodology presented in Figure 1 includes the normal uncertainties and not the influenced by the extent of gross errors in the design, construction and operation phase. The observed frequency of fatigue failure will however include the influence by the gross errors present but not detected.
Modelling the uncertainties in loads and resistances for a hot spot in an offshore structure is a crucial task. The system approach in addition requires an estimate of the uncertainty of the system model as well as the correlation between variables in the different failure functions that represent the system. We will in our discussion only focusing the use of these probabilistic models for prognosis or forecast the fatigue crack growth potential. The system aspect and potential correlation effects are not included. The load and resistance uncertainties are of the same order of magnitude in fatigue crack potential in offshore structures. The uncertainties may in general be grouped as, [6]:

- Physical uncertainty, also known as inherent or intrinsic uncertainty which is a natural randomness of a quantity such as variability in current, uncertainty in yield stress etc.
- Statistical uncertainty is uncertainty due to limited amount of information such as a limited number of observations. Unlike physical variability, the statistical uncertainty arises solely because of lack of sample data. Hence, it will decrease and finally vanish as the amount of data increases.
• Measurement uncertainty is uncertainty caused by imperfect instruments and sample disturbance when observing a quantity such as a fatigue crack size.

• Model uncertainty is uncertainty due to imperfections and idealizations made in the applied physical and probabilistic models and reflects a general confidence in the model to describe "real life". It may further account for unknown effects of other variables and their interaction, which are not included in the analysis model.

• Bias is in general defined as difference or a ratio between expectation of an estimator \( \hat{e} \) and the quantity \( e \) being estimated. When assessing load effect and fatigue capacity it may be practical to use the ratio between these two parameters. In order to avoid misunderstanding it is recommended to define the nominator and the denominator in each case where bias is used.

• Gross errors are uncertainties related to human errors and normally not covered within the framework of structural reliability.

It is not straight forward to group the uncertainty elements present and implementing them in the probabilistic model. Traditionally the uncertainty elements grouped as gross errors are not included in the probabilistic forecast for fatigue crack growth. However, the effect of poor workmanship in design, structural analyses, construction, inspection and the in-service assessment are to be included in our probabilistic model to get reliable forecast on the fatigue crack growth. At least we need to understand how we potentially get non-conservative forecast on fatigue development by neglecting these effects. We will address the challenges of the following uncertainty elements:

a) Deviations between As-Is or As-Constructed and the model for calculation of fatigue life
b) Local design and fabrication quality
c) Inspection quality and QA (Quality Assurance) process for the construction work
d) Inspection quality for the In-service inspection
e) The estimate of accumulated fatigue damage at time of inspection

The fatigue crack growth is highly affected by the local design and the fatigue capacity is presented by different class of SN-curves. The probabilistic fracture mechanics crack growth models are calibrated towards a selected SN-curve [6]. To avoid model calibration towards a high number of SN-curves we use an adjustment on the model for the fatigue load effect.

Figure 3 illustrate the stress categories to be considered, [14]. In addition to the element of local geometry as shape of stiffener ending, weld profile, mismatch in the angular and linear alignment the uncertainty model for fatigue load effect to include potential presence of undercut, weld porosity, weld remains and scars from disk grinder that contribute to selection of SN-curve.
In offshore structures there are a high number of details that not fully are in accordance with the required fabrication quality. These mainly minor deviations according the requirement of fabrication are in the construction phase mainly assessed according the ULS (Ultimate Limit State) requirements. FLS (Fatigue Limit State) and fatigue crack growth potential is highly affected by measures in the operation phase. Hence, the fatigue challenges related to minor deviations according the requirement of fabrication, are often classified as a challenge to handle in the operation phase. The documentation of deviation reports and fitness for service assessments from the construction phase are traditionally not properly transferred from the construction project to asset integrity responsible in the operation phase. At hot spot level the analyses model frequently shows deviation with the As-Is condition. This is a model uncertainty we for practical reasons includes in the uncertainty level for the fatigue load effect. Without a detailed As-Is inspection and related adjustment of the calculated fatigue life, a higher level of uncertainty in the fatigue load effect is proposed, [13]. The As-Is mapping is also used to remove the deviations between As-Constructed and the construction drawings used as bases for the structural analyses models.

Table 1 and 2 contain results from the reported detection of crack indications. Hence, all flaws not visually detectable but reported by the in-service inspection of NDT (Non Destructive Testing). Table 1 contains data from inspection on Jacket structures and Table 2 contains data from inspection on Semi-submersible.

**Table 1.** Summary of the collected experience data used for the jacket validation study in [1], from 40 jacket structures in the North Sea. A total of 3366 NDE inspections have been reported.

|                      | Non propagating cracks | Potentially propagating cracks | Most likely propagating cracks | Total number of cracks |
|----------------------|------------------------|-------------------------------|-------------------------------|------------------------|
| Number of cracks     | 228                    | 124                           | 159                           | 511                    |
| Percentage of inspections with cracks | 6,77 % | 3,68 % | 4,72 % | 15,2 % |

**Table 2.** Summary of the collected experience data from 12 semi-submersible with more than 20 years of operation time in the North Sea. A total of 22282 NDE inspections have been reported.

|                      | Non propagating cracks | Potentially propagating cracks | Most likely propagating cracks | Total number of cracks |
|----------------------|------------------------|-------------------------------|-------------------------------|------------------------|
| Number of cracks     | 205                    | 324                           | 622                           | 1164                   |
| Percentage of inspections with cracks | 0,92 % | 1,45 % | 2,79 % | 5,22 % |

The study presented in [14] is based on the data collected from Jacket structures in Table 1. According [14] the average initial crack size of the fatigue cracks observed was close to 0.9mm. The average size of the fabrication defects detected had also an average depth of close to 0.9mm, [14]. The tubular joint in a Jacket structures are fabricated in a well-controlled environment that according [6] have an inspection quality of PoD (Probability of Detection) value of 0.4. An inspection with PoD of 0.4 has a 90% confidence to detect a crack of depth 0.9mm. Hence, the observed fatigue crack growths in the Jacket structures have started from flaws assumed detected and removed in the construction phase.

Similar studies for the collected experience data for the Semi-submersible are yet not done. However, observations related initial crack size for Jacket structures are most likely also valid for Semi-submersible. As part of the data collected for Semi-submersible, closely 15 000 hot spot given a detailed As-Is mapping, have revealed a large number of deviations between actual fabrication quality and the
bases for the structural analyses. Of the more than 1000 detected fatigue cracks in the Semi-submersible, closely to 500 are related to hot spot where the As-Is mapping shows deviations towards the assumptions in the calculation of fatigue life. Hence, the as-is mapping has resulted in change of selected SN-curve or SCF value estimated by the hot spot method.

According [8] the estimated PoD (Probability of Detection) value for the collected inspection data for Jacket structures was 1.9 i.e. an inspection quality of 90 per cent confidence to detect a fatigue crack of length 60mm. The recommendation in [6] is to use PoD values in the range 0.4 to 1.2 i.e. inspection quality of 90 per cent confidence to detect a fatigue crack of length 13 and 38mm.

From closely 25 yard stays and management of the inspection process for re-classification of mobile offshore drilling units of Semi-submersible design we experience a high scatter in the in-service inspection quality. The management and QA-process for the inspection process will affect the PoD values for the inspection. It is likely to assume a variation from 0.3 to 2.0 in the PoD value as function of the management and quality assurance in the inspection process i.e. the 90 per cent confidence limit to detect the fatigue crack will vary between crack length of 7 and 70mm.

Traditional design and construction focus to document sufficient long calculated fatigue life estimates. For non-critical areas these estimates may be very conservative. As highlighted in [6] the input to the probabilistic forecast models from the structural analysis are to be unbiased estimates of calculated fatigue life. For a Semi-submersible, it is typically more than 1000 hot spots assessed for a detailed follow-up scope. It is extremely time consuming to get accurate calculated fatigue life for all of these hot spots. Hence, it is impractical to secure unbiased and accurate calculated fatigue life for all hot spots. The hot spot with the highest fatigue failure consequence potential are focused.

For mobile offshore drilling units operating in the North Sea it is common to estimate the long-term distribution of the fatigue loading based on the worldwide sea scatter diagram i.e. the North Atlantic long-term sea scatter diagram. In our probabilistic models including updating based on years in service, we assume the experienced fatigue loading to be according the North Atlantic scatter diagram and not the sea scatter diagram of the location of operation i.e. a biased and increased model uncertainty for the North Sea operated units.

Based on the discussion above, we may have the following hypothesis: The probabilistic forecast model of fatigue cracks will normally have an unrealistic low uncertainty level and a conservative mean value in the model for the fatigue load effect.

In the following sections, we will use this assumption as a premise and investigate the potential to obtain non-conservative conclusions in our models for scheduling inspections and improvement maintenance.

3. No previous inspections and no probabilistic updating

Figure 4 shows the reliability index for fatigue failure as function of calculated fatigue life for 5 and 10 years additional service. The intersection with the target reliability level defines the limit of calculated fatigue life for inspection interval of 5 or 10 years. The curves denoted “PaFa-0,1 5 year”, “PaFa-0,2 5 year” and “PaFa-0,3 5 year” give the limit for 5 year interval for inspection. The different curves represent st. dev. 0.1, 0.2 and 0.3 for the Ln(A), where A is the Weibull scale parameter of the long term distribution of the fatigue load effect. The curves in Figure 4 are used when we have a predefined follow up regime by inspection interval of 5 and 10 years.

For the uncertainty level in the fatigue load effect of st.dev. Ln(A) of 0.1, the limits for calculated fatigue life are 18.3 and 36.6 years, ref. the curves “PaFa-0,1 5year” and “PaFa-0,1 10year” Hence, all hot spots with calculated fatigue life shorter than 18.3 years are scheduled for modification to get an improved fatigue capacity. Hot spots with calculated fatigue life between 18.3 and 36.6 years get an inspection interval of 5 years. Hot spots with fatigue life longer than 36.6 years are recommended an inspection interval of 10 years. The limit values for calculated fatigue life are 30.8 and 61.7 years for st. dev. Ln(A) of 0.2. The limit values for calculated fatigue life are 76.3 and 153 years for st. dev. Ln(A) of 0.3. Table 3 summarizes the calculated fatigue life for hot spots in a typical mobile offshore drilling unit of Semi-
submersible design. Table 4 shows the scheduled scope for modification, inspection of interval 5 and 10 years by combining the scheduling criteria in Figure 4 and example data in Table 3. If we underestimate the uncertainty level in the calculated fatigue load effect we will get non-conservative scope for improvement maintenance (modifications) and the extent of inspection. Our hypotheses in section 3 included a conservative mean value of calculated fatigue life. Table 4 shows scope also for a bias value of 2 on the calculated fatigue life. Combining a bias of 2 and increased level of uncertainty by st.dev. Ln(A) of 0.3 and not 0.1, will give a larger scope than bias of 1 and st.dev. Ln(A) of 0.1. The ratio between limit values for calculated fatigue life in Figure 4 give the bias value that balance the non-conservative effect by us of to low uncertainty value for the fatigue load effect. For the cases in Figure 4 these ratios are 1.7(=30.8/18.3=61.7/36.6) and 4.2(=76.3/18.3=153/36.6). Hence, even vary large bias values on the calculated fatigue life will not cancel the non-conservative effects by the underestimation of the uncertainty levels in the fatigue load effect.

**Figure 4.** The reliability index as function of calculated fatigue life. For each of the three different level of uncertainty in the fatigue load effect the reliabilities against fatigue failure after 5 and 10 years additional time of operation are given by the curves “Inter 5 year”, and “Int. 10 year”. The uncertainty levels of fatigue load effect are given by st.dev. of 0.1, 0.2 or 0.3 for Ln(A), where A is the Weibull scale parameter of the long term distribution of the fatigue load effect. Hence, the curve denoted “PaFa-0,1 5 year” are the reliability against fatigue failure after 5 years additional service as function of calculated fatigue life when the uncertainty of the fatigue load effect is given by st.dev. lnA = 0.1.

**Table 3.** Typical example of number of hot spot grouped by range of calculated fatigue life.

| # of Hot Spots within group | Range of Fatigue life in years | Cumulative list # of Hot Spots |
|----------------------------|--------------------------------|--------------------------------|
| 0                          | 1-5                            | 0                              |
| 5                          | 5-10                           | 5                              |
| 5                          | 10-15                          | 10                             |
| 4                          | 15-20                          | 14                             |
| 19                         | 20-30                          | 33                             |
| 50                         | 30-40                          | 83                             |
| 128                        | 40-60                          | 211                            |
| 132                        | 60-100                         | 343                            |
| 205                        | 100-300                        | 548                            |
| 507                        | 300-∞                          | 1055                           |

**Table 4.** Scheduled scope for modifications, 5 years and 10 years inspection interval for different assumption of uncertainty level in the fatigue load effect. A bias value of 2.0 include the assumption...
of systematic conservative calculated fatigue life estimate by a factor 2 i.e. reported calculated fatigue life of 20 year to represent a fatigue life of 40 year upon removal of the conservative assumptions.

| st.dev. Ln(A) | Bias on calculated fatigue life | # for modification | # for 5 year interval | # for 10 year interval |
|---------------|---------------------------------|--------------------|-----------------------|-----------------------|
| 0.1 1.0       | 10                              | 73                 | 64                    |
| 0.2 1.0       | 33                              | 178                | 99                    |
| 0.3 1.0       | 244                             | 201                | 31                    |
| 0.1 2.0       | 5                               | 8                  | 15                    |
| 0.2 2.0       | 10                              | 23                 | 90                    |
| 0.3 2.0       | 74                              | 191                | 93                    |

4. The selection of target level

According to [6] and [7] the target reliability levels are deduced from the selected Design Fatigue Factor, DFF. The time for the first inspections are reached when the accumulated fatigue damage = 1/DFF. For fatigue failure with substantial failure consequence potential the DFF of 10 is used and for a reduced consequence potential we select DFF of 3. From Figure 4 we can identify the reliability level for reaching fatigue damage of 1/10 and 1/3 for the different classes of uncertainty level i.e. st.dev. Ln(A) of 0.1, 0.2 and 0.3. For the curve for 5 years inspection interval the target reliability level is given for the calculated fatigue life of 5*DFF i.e. 15 and 50 year for DFF=3 and DFF=10, respectively. Table 5 contains the target reliability level deduced based on DFF of 3 and 10 for the different assumption of uncertainty in the fatigue load effect.

| st.dev. Ln(A) | DFF = 3 | DFF = 10 |
|---------------|---------|----------|
| 0.1           | 2.4     | 3.4      |
| 0.2           | 2.0     | 2.9      |
| 0.3           | 1.6     | 2.4      |
| Ref. [6]      | 2.5     | 3.7      |

The concept of DFF was introduced before detailed FEM analyses were applied for the fatigue analyses. According [6] these fatigue analyses give uncertainty in the fatigue load effect as st.dev. Ln(A) of 0.3. The traditional class follow up regime of mobile offshore drilling units require inspection by 5-year interval and minimum 20 (15) years calculated fatigue life. From Table 5 the traditional class follow-up regime for mobile offshore drilling units results in reliability indexes as low 1.6. According [6] the target reliability level deduced from the DFF value of 3 and 10 are 2.5 and 3.7. The recommended target safety levels in [6] are based on calculations assuming a very low uncertainty level in the calculated fatigue load. To use the recommendation of target level in [6] as a universal target level is therefore more restrictive than traditional industry practice for operation of offshore structures. As an alternative to use universal target level are the target cases proposed in [4], [5] and [13]. The term target case is used when same probabilistic model is used for calculation of the target level as for the hot spot considered. For the concept of target case, the positive gap between the reliability curve for the hot spot and the target level, have low sensitivity w.r.t. potential variation in basic variables or error in the probabilistic fracture mechanics model, [13]. As long as the probabilistic forecast model for the fatigue crack growth potential not have been validated by use of in-service data the probability or reliability curves are notional values. It is challenging to establish universal target level for acceptable fatigue crack growth potential as we use notional probability estimates, [2]. For monitoring the actual safety level against fatigue crack growth, it is recommended to systematically compare the observed frequency of fatigue crack detection and the forecast from the probabilistic model. According [13] we may need to reconsider our follow up regime and model for estimation of the fatigue crack growth potential if the
The number of fatigue crack detections exceeds 3-15% of the scheduled inspections. The limit of 3-15% is deduced based on the requirements and methodology presented in [6] and [7].

5. Inspection history with no finding

After some years in operation, observations through inspections are obtained. A probabilistic fracture mechanics model makes it possible to get an updated estimate of the fatigue crack growth potential i.e. updating by use of information from in-service inspection, [6]. The calculated reliability against fatigue crack growth varies with the quality of the inspection method, procedure and the skills of the inspection Technicians. According [6] the PoD-value (median crack depth for probability of detection) are in the range 0.4 to 1.2mm for the inspection methods MPI (Magnetic Particle Inspection) and EC (Eddy Current). The study in [8] based on in-service observation indicate a PoD value of 1.9mm.

Figure 5 shows the reliability index for fatigue failure as function of calculated fatigue life for 5, 10 and 15 years additional service after inspection. The curves in Figure 5 are for hot spots that after 20 years’ service have been inspected with the result No Find. The intersections with the target reliability level define the limit of calculated fatigue life for inspection interval of 5, 10 or 15 years.

Figure 5 as Figure 4 are used when we have a predefined follow up regime by inspection interval of 5 and 10 years. The intersections with the target reliability level define the limits for calculated fatigue life for inspection interval of 5, 10 or 15 years. The intersection between the curves and the target value are for the calculated fatigue life of 3, 10 and 40 years. Hence, all hot spots with a calculated fatigue life shorter than 3 years are scheduled for modification to get an improved fatigue capacity. Hot spots with calculated fatigue life between 3 and 10 years have an inspection interval of 5 years. Hot spots with fatigue life between 10 and 40 years have an inspection interval of 10 years.
accumulated fatigue damage, are invariant with years in service to reach the level of accumulated fatigue damage. Hence, the results in the last two columns can be used to obtain a general representation of time to next inspection as function of accumulated fatigue damage at time of inspection with result No Find. The time to next inspection is the product of acceptable additional fatigue damage and calculated fatigue life of the hot spot. We extend the Table 6 with other combination of values for st.dev. Ln(A) and PoD as well as service years before inspection. Based on the last two columns in an extended Table 6 we establish a functional relationship between accumulated fatigue damage at time of inspection with result No Find and the acceptable amount of additional fatigue damage before new inspection is required. See Figure 6.

Each curve represents a combination of uncertainty level in fatigue load effect and PoD value for the inspection method. The PoD values of 0.4, 0.7, 1.2 and 1.6 represent 90% confidence to detect fatigue cracks of length 13, 22, 37 and 51mm. The uncertainty levels in the fatigue load effect vary between st.dev. Ln(A) of 0.1 and 0.3.

According Figure 6 the future inspection intervals are highly affected by the inspection quality. The curves in Figure 6 for equal PoD values have different inclination and these curves have comparable limit for added fatigue damage when the accumulated fatigue damage is approximately 2. As shown in Figure 4 and no updating by inspection, high uncertainties in the fatigue load effect reduce the time to next inspection. However, high uncertainties level in the fatigue load effect will give a higher updating effect by the inspection result No Find. These 2 effects balance for the accumulated fatigue damage of approximately 2 in our model as shown in Figure 6 and the intersection of curves with equal PoD.

**Table 6** Limits of Calculated fatigue life for scheduling scope for improvement maintenance and inspection. The service period with result, No fatigue crack detection, vary from 25 to 10 years. Inspection quality and uncertainty in the fatigue load effect are given by PoD value 0.7 and st.dev. Ln(A) of 0.7. The last two columns give value of accumulated fatigue damage at service years with the No Find inspection results and the added accumulated fatigue damage before new inspection is scheduled.

| Service years before a “No Find” inspection | Inspection interval (Year) | Sorting Criterion for serv act. for Calculated Fatigue Life | Fatigue damage at last inspection | Added fatigue damage in next interval |
|---------------------------------------------|-----------------------------|-----------------------------------------------------------|---------------------------------|-------------------------------------|
| 25                                          | 5                           | 3                                                         | 8.23                            | 1.65                                |
| 25                                          | 10                          | 8                                                         | 3.22                            | 1.29                                |
| 25                                          | 15                          | 16                                                       | 1.52                            | 0.91                                |
| 20                                          | 5                           | 3                                                         | 6.52                            | 1.63                                |
| 20                                          | 10                          | 10                                                       | 1.99                            | 0.99                                |
| 20                                          | 15                          | 40                                                       | 0.50                            | 0.38                                |
| 15                                          | 5                           | 4                                                         | 3.50                            | 1.17                                |
| 15                                          | 10                          | 18                                                       | 0.84                            | 0.56                                |
| 15                                          | 15                          | 112                                                      | 0.13                            | 0.13                                |
| 10                                          | 5                           | 6                                                         | 1.75                            | 0.87                                |
| 10                                          | 10                          | 29                                                       | 0.34                            | 0.34                                |
| 10                                          | 15                          | 595                                                      | 0.02                            | 0.03                                |
Figure 6. The acceptable level of additional fatigue damage for the scheduled inspection interval as function of the accumulated fatigue damage at time of last inspection with result No Finding.

For the case of no updating based on inspection history it was a non-conservative approach to select a low level of uncertainties in the fatigue load effect. For the cases of updating based on the event of no fatigue crack detection this will not necessarily be correct.

From [8] and [1] the review of in-service data indicates a much higher PoD value for offshore MPI / EC inspection than proposed in [6]. The recommendation in [6] highlights that the recommended uncertainty levels do not include gross errors. The deviation between PoD values from [8] and [6] indicate the effect of including variation in workmanship. The quality controls and management of the inspection campaign are important to focus if the lower PoD values are wanted to obtain. The potential for non-conservative conclusions by selection a too high uncertainty level for the fatigue load effect are also reduced by high PoD values as shown by the curve in Figure 6. If we have high PoD values it is low sensitivity with respect to uncertainties in the fatigue load effect.

Figure 6 may also be used to discuss the systematic bias of assuming fatigue loading of world-wide sea scatter diagram for units operating in the North Sea. The experienced annual fatigue damage of a mobile offshore drilling unit operating in the North Sea will typically be 2 to 4 times lower than the estimates based on the word-wide sea scatter diagram [7]. As long as the units continue to operate in the North Sea the overestimation of fatigue damage at time of inspection with result No Find will be as a systematic conservative bias on the calculated fatigue life. We get non-conservative inspection interval if the unit moves to harsher environment.

6. Example cases
The methodology presented above is used for a number of different semi-submersibles since 2004. The table below shows three cases of units operated more than 20 years in the North Sea. The age, operation history and procedure for fatigue analyses shows high degree of correlation between these units.

The following tables (Table 7 – 12) summarize the collected inspection history of crack detections. The first columns indicate time period. The following three columns group the findings in percent belief of the cracks to be propagating cracks. The following columns contain the number of NDT inspections done i.e. EC or MPI, and the cracks grouped according crack depth. Minor indicate depth less than 40% of the wall thickness, than larger than 40% of wall thickness and finally number of cracks with leakage or leak potential. The columns “Minor”, “>0.4*wt” and “Leakage” exclude the cracks classified with 30% or lower belief to be propagating cracks.
Case 1 presented in Table 7 and 10 shows a limited number of larger fatigue cracks. For the last 5 years in operation it has only been detected smaller cracks. Case 2 presented in Table 8 and 11 had server cracking in the years 1998 to 2007. Efforts implemented in this period were not sufficient to secure per cent of cracking with leak potential to be less than 0.5% according the requirement deduced from the regulations and recommended practice for fatigue management. Additional efforts were required in the period year 2008 to 2010. For the year 2011 to 2014 we secured a sufficient low fatigue crack growth level for unit Case 2. Case 3 presented in Table 9 and 12 have server fatigue cracking in the year 2011 to 2014. The efforts to improve the fatigue capacity implemented in the period 1998 to 2010 were comparable with the investment done for unit Case 1 and 2.

Table 7. The collected inspection results for Case 1. The number of cracks detected.

| Year     | < 30% | Between 30-70% | >70% | # of NDT Inspect | Minor | > 0.4* wt | Leakage |
|----------|-------|----------------|------|------------------|-------|-----------|---------|
| 1991-2007| 23    | 16             | 14   | 988              | 21    | 9         | 0       |
| 2008-2012| 27    | 5              | 0    | 955              | 5     | 0         | 0       |
| 2012-2017| 0     | 0              | 19   | 535              | 19    | 0         | 0       |

Table 8. The collected inspection results for Case 2. The number of cracks detected.

| Year     | < 30% | Between 30-70% | >70% | # of NDT Inspect | Minor | > 0.4* wt | Leakage |
|----------|-------|----------------|------|------------------|-------|-----------|---------|
| 1991-2007| 0     | 2              | 19   | 125              | 0     | 21        | 19      |
| 2008-2012| 1     | 4              | 16   | 479              | 10    | 11        | 7       |
| 2012-2017| 13    | 20             | 24   | 516              | 46    | 11        | 0       |

Table 9. The collected inspection results for Case 3. The number of cracks detected.

| Year     | < 30% | Between 30-70% | >70% | # of NDT Inspect | Minor | > 0.4* wt | Leakage |
|----------|-------|----------------|------|------------------|-------|-----------|---------|
| 1991-2007| 26    | 34             | 18   | 451              | 56    | 22        | 5       |
| 2008-2012| 37    | 60             | 27   | 1014             | 110   | 14        | 4       |
| 2012-2017| 4     | 25             | 35   | 937              | 17    | 47        | 22      |

Table 10. The collected inspection results for Case 1. The per cent of inspection to detect crack.

| Year     | # of NDT Inspect | Minor | > 0.4* wt | Leakage |
|----------|------------------|-------|-----------|---------|
| 1991-2007| 988              | 2,13 %| 0,91 %    | 0,00 %  |
| 2008-2012| 955              | 0,52 %| 0,00 %    | 0,00 %  |
| 2012-2017| 535              | 3,55 %| 0,00 %    | 0,00 %  |

Table 11. The collected inspection results for Case 2. The per cent of inspection to detect crack.

| Year     | # of NDT Inspect | Minor | > 0.4* wt | Leakage |
|----------|------------------|-------|-----------|---------|
| 1991-2007| 988              | 0,00 %| 16,80 %   | 15,20 % |
| 2008-2012| 955              | 2,09 %| 2,30 %    | 1,46 %  |
| 2012-2017| 535              | 8,91 %| 2,13 %    | 0,00 %  |

Table 12 The collected inspection results for Case 3. The per cent of inspection to detect crack.

| Year     | # of NDT Inspect | Minor | > 0.4* wt | Leakage |
|----------|------------------|-------|-----------|---------|
Case 1 and 2 have more or less the same number of fatigue cracks detected. However, the number of minor fatigue cracks and cracks reported that is classified with low percent of belief to be propagating, is significant lower for the Case 1 unit. The Case 1 unit has been given a slightly different site follow-up regime during the inspection and implementation of the improvement maintenance scope. A difference with high impact on the operation cost.

7. Considerations
The fatigue crack growth potential is highly influenced by gross errors in the design, construction and operation phase in addition to the normal uncertainties of design, construction and inspection. Collected data and experience indicate that the theoretical predicted fatigue crack growth potentials are generally conservative without including the influence of gross errors. Hence, the safety of the regulatory requirements is in average adequate. However, by use of the probabilistic approach and Bayes updating non-conservative estimates may easily be obtained if the potential influence of gross errors isn’t properly considered. The acceptable fatigue crack growth potential or fatigue failure rate deduced from present codes represents 3-15 percent of the schedules inspections to detect fatigue cracks and 0.5 percent to detect fatigue failure. As long as the inspection history documents a lower percent of detection for the scheduled inspections the failure rate is within the acceptable level. The scheduled inspections represent the inspections selected by the theoretical models as presented.

The observations are the key book. Independent of the calculated characteristic fatigue life a detection percent higher than 3-15 percent of fatigue crack detection and 0.5 percent for fatigue failure indicate a failure rate for fatigue larger than the acceptable limit and actions is required.

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