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Risk based fatigue inspection planning – state of the art

Tom Lassen*

University of Agder, Faculty of Engineering and Science, N 4890 Grimstad, Norway
Affiliated with National Oilwell Varco – APL, N4816 Kolbjornsvik, Norway

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Abstract

The present paper presents the methodology and the practical calculations for risk based inspection planning of fatigue cracks in welded offshore steel structures. Due to the uncertainty in the variables involved in the problem the planning has to be carried out by stochastic modeling and risk based assessments. Scatter in potential crack growth has to be analyzed by applied probabilistic facture mechanics and the uncertainty in the performance of the actual inspection technique has to be determined. With given risk acceptance criteria the practical outcome of the analyses is recommended inspection techniques and associated planned inspection time intervals. The classical theory is briefly outlined and the latest recommendations from a Joint Industry Project recently completed in Norway are included. A practical case study for life extension of an oil loading system in the North Sea is presented.

Keywords: Fatigue cracks in welds;Inspection planning,Risk assessments;Aging of offshore Structures

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1 Introduction

High fatigue reliability is one of the most important design criteria for welded offshore steel structures. Due to repeated wave loading fatigue cracks may initiate and grow in welds that are important for the integrity of these structures. The final fracture may lead to total collapse for non-redundant structures. In 2010 it was 30 years since the Alexander Kielland disaster occurred in the North Sea. A semi-submersible platform capsized due to a fatigue fracture in the welded tubular structure. The accident lead to 123 casualties and made a paradigm shift in fatigue design and inspection planning for steel structures in the North Sea.

* Corresponding author. Tel.:+47 98233288; *E-mail address:* tom.lassen@uia.no

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Lessons learned within these issues were revisited in 2010, Ref. [1]. The knowledge on fatigue of welded structures has evolved vigorously since the disaster and the first important progress was published in 1985, Ref. [2]. Recommendations for improved fatigue design and life predictions were given, and the work was supplemented by probabilistic fracture mechanics for in-service inspection planning, Ref. [3]. To avoid fatigue fractures the potential crack growth has to be modeled and planning of detailed scheduled inspection to detect the cracks in time has to be carried out for critical welded joints. The problem is especially important for aging structures that are being used beyond their original target design life. This is the case for several installations in the North Sea at present. Whereas the guidance and recommendations on how to carry out fatigue life predictions based on the S-N approach at the design stage is very well documented, Refs. [2, 4, 5], the recommended practice for risk based inspection planning has been less conclusive, Refs. [6, 7, 8 and 9]. The recommendations for applied fracture mechanics is very well documented in Ref. [6] but the issue of how to tackle uncertainty is not included in the document. For this reason a large Joint Industry Project (JIP) on the use of probabilistic methods for planning inspection for fatigue cracks in offshore structure has recently been carried out in Norway, Ref. [10]. The results from that work have not yet been published but DNV and NORSOK are planning to update their recommended practice, Refs. [7, 8] based on the results from the JIP. In the present work a short review of life models often employed for fatigue reliability assessments is given. Two stochastic models for the random evolution of the fatigue damage are discussed. These models are:

- The stochastic process model
- The random variable model

The first approach is treating the damage evolution directly based on experimental measurements of crack growth and associated uncertainties. Instead of applying fracture mechanics and carrying out the integration of the Paris law with associated variables, the stochastic waiting time between discrete damage states is modeled based directly on experimental data. The approach applies a Markov Chain model for the purpose. The damage states are related to given crack depth in the welded joint. The purpose of the model is a relatively simple approach used as a tool for preliminary decisions regarding inspection planning. It gives a generic reliability model that can be used for risk-based inspection planning for most welded joints where cracks are propagating from the weld toe. The model is a direct supplement to the S-N life predictions and the Design Fatigue Factor (DFF) is used as a key to the analysis. In cases that need more attention due to smaller safety margins and critical consequences of fracture, a more advanced random variable model in combination with Monte Carlo simulation is suggested. This is the classical approach based on Linear Elastic Fracture Mechanics (LEFM) where the involved parameters are treated as stochastic variable. This approach is in agreement with the latest proposal for standard guidelines recommended in a recent JIP, Ref. [10].

2 Defining the problem

The concept of risk based inspection planning is to take decisions regarding a scheduled periodical inspection program based on probability of fatigue failure and the consequence of such a failure. The probability calculation has to include both an analysis of the potential crack growth and the uncertainty in the performance of the actual planned inspection technique. The analysis has to be carried out for all important welded joint in a steel structure. The potential crack growth is shown at the left on figure 2.1 where the crack depth a is plotted as a function of time or number of load cycles N. The curve is usually obtained from fracture mechanics applying the Paris equation. The crack is growing from an initial crack depth of a_0 to a final critical crack depth a_c. The shape of the curve is unfavorable from an inspection point of view; the crack spends most of the time while it is small and hard to detect. The performance of a given inspection technique is shown to the right on the figure where the Probability of Detection (PoD) is plotted as a function of crack depth. This curve is obtained from blind tests with a population of inspectors applying a given inspection technique under a given environmental condition. As can be seen from the figure a simplified measure for the reliability R of the planned inspection program can be estimated once an inspection interval I has been chosen. The probability of missing the crack at all the scheduled inspections is given by:

$$P_f = \prod_{i=1}^{k} (1 - POD(a_i)) \tag{2.1}$$

where i is the number of the current inspection, a_i is the expected crack size at the inspection and k is the total number of planned inspections. In the case shown in Figure 2.1, k is equal to 3. The method is called quasi stochastic due to the fact that scatter in fatigue crack growth is not accounted for. The reliability of the inspection program is simply $R=1-P_f$ .One may argue that for all advances in probabilistic inspection planning methodology, the two simple curves in figure 2.1 will always be used as basis. The target permissible level for probability of failure P_f is given in table 2.1, Ref. [9].

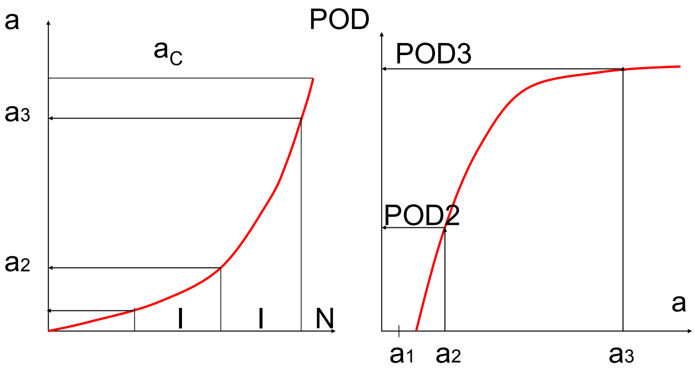

Figure 2.1-Illustration of the quasi stochastic method.

Table 2.1 Acceptable annual probabilities of failure, Ref. [9]

Type of structure	Consequence of failure	
	Less serious	Serious
Redundant structure	10^{-3}	10^{-4}
Non-redundant with Significant warning	10^{-4}	10^{-5}
Non-redundant. No significant warning	10^{-5}	10^{-6}

3 A model for preliminary assessment of fatigue criticality and inspection planning

Before expanding the simple approach described in section 2 we shall look at another simplified approach that takes account for the scatter in the crack growth curves. The method is based on a Markov chain where the crack depth is modeled as descrete damage states, see figure 3.1. As can be seen the fatigue cracks are growing from the weld toe of a fillet weld through the plate thickness T. In the Markov chain model the crack grows through the plate as a random walk phenomenon which respects the crack size mean value and scatter at given times measured during tests, Refs. [11,12]. Hence, this approach avoids the cumbersome time consuming fracture mechanics calculation and simulation. The probability of failure as a function of time is directly given as the probability of ending up in the final absorbing state b which coincides with the critical crack depth $a_b=a_c$. The impact of the chosen Design Fatigue Factors (DFF) and the uncertainty in the applied stresses has to be accounted for. Typical results are shown in

Figure 3.2 where the probability of failure is given as a function of time. The methodology can be regarded as a Damage Tolerance Supplement (DTS) to the design S-N curves for welded joints. The goal is to provide the practicing engineer with simple tools that predict the reliability against fatigue fracture during service life for a given scheduled in-service inspection program.

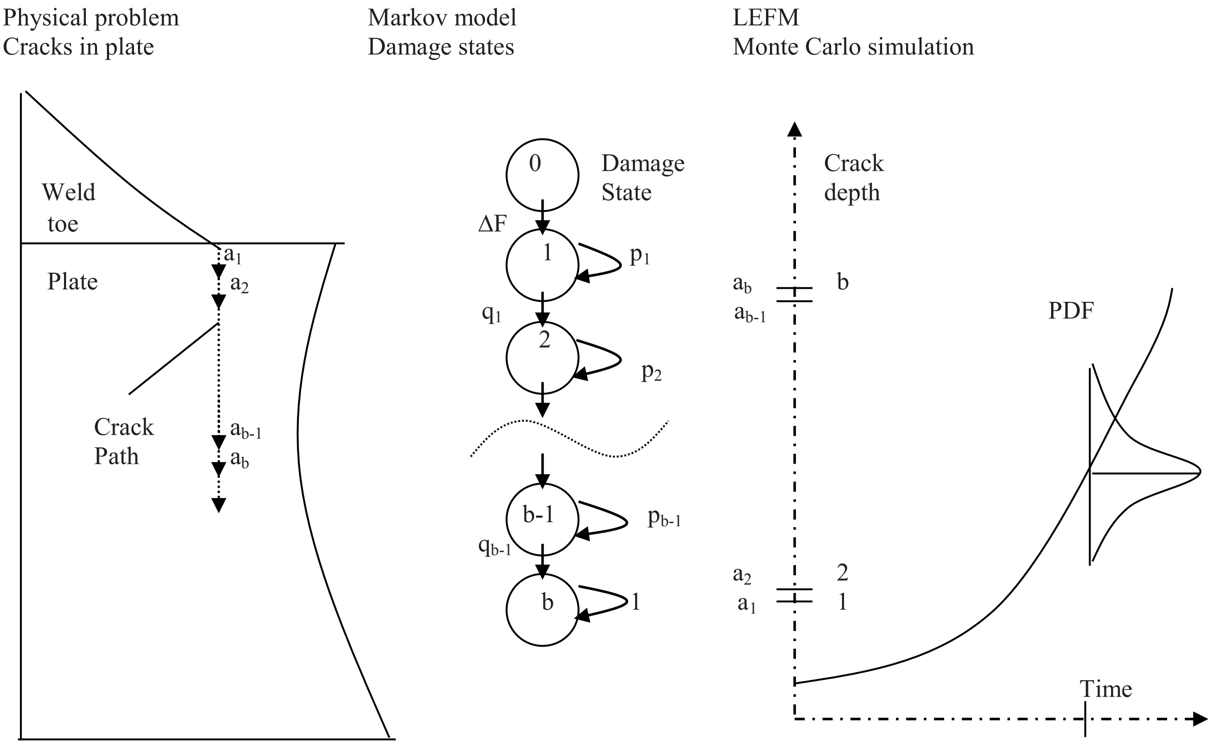

Figure 3.1-Illustration of the stochastic modeling of crack growth. Cracks starting at the weld toe propagating through the plate thickness (left drawing) are related to discrete damage states (middle drawing) or LEFM simulation (right drawing). Note that a_b=T/2.

The results may also be presented as the cumulative probability at the end of the Target Service Life given in Figure 3.2, as shown in Table 3.1 with an uncertainty of 20 percentage in applied stresses, i.e. COV_S=0.2. One may regard Table 3.1 as a decision matrix with columns and rows. If one moves vertically downwards (left column) to obtain high reliability it is the Safe Life (SL) philosophy which is the governing principle, i.e. the probability of cracking during Target Service Life (TSL) is very low. This is preferably obtained by better detail design with low Stress Concentration Factor (SCF). If this strategy gives too large dimensions and heavy weight one may choose to move horizontally right (first row) to achieve high reliability. Then it is the Damage Tolerance (DT) philosophy which is the overriding principle, i.e. cracks are accepted as long as the probability of detection and repair before fracture is high. In most practical cases the designer has to make a trade-off between these two strategies when making the final decision. These types of decision matrices provide useful information to supplement the traditional S-N fatigue life approach. The latter approach does not capture the influence on reliability from chosen DFF's or various inspection strategies. Only in cases with geometries, boundary conditions and loading modes which are not covered by the data base and hence for which the validity of the present Markov Chain model may be questioned, a full Monte Carlo simulation based on Linear Elastic Fracture Mechanics (LEFM) needs to be carried out to substantiate the results. For primary structural details for which failure has a direct bearing on structural integrity and could even endanger human life, it would be cost-effective to gather the necessary information and carry out the numerical efforts for such analyses. Other joints will not merit such attention and the present DTS approach based on the use of tables such as 3.1 is recommended.

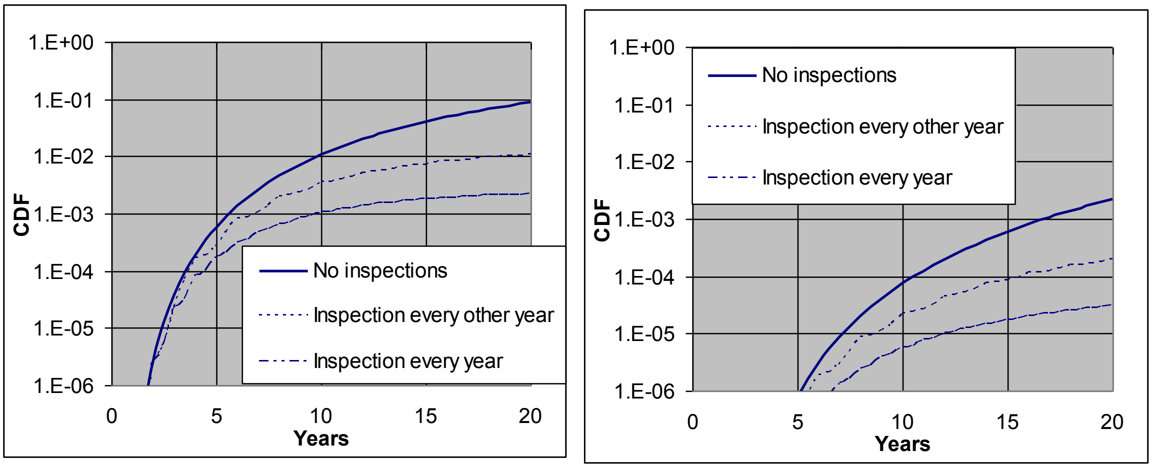

Figure 3.2-Cumulative probability of failure derived by Markov chain model for various DFFs and inspection strategies. Left: DFF=1, Right DFF=3.

Table 3.1 Cumulative probability of failure at the end of TSL(Largest probability in 1/20 fraction of TSL in parentheses) . COV_S=0.2 and Magnetic Particle Inspection under water

DFF	No Inspection	Inspection I=TSL/10	Inspection I=TSL/20
1	$8.8\ 10^{-2}$ ($1\ 10^{-2}$)	$7.2\ 10^{-3}$ ($5\ 10^{-4}$)	$1.1\ 10^{-3}$ ($8\ 10^{-5}$)
3	$2.2\ 10^{-3}$ ($5\ 10^{-4}$)	$1.2\ 10^{-4}$ ($2\ 10^{-5}$)	$1.3\ 10^{-5}$ ($1\ 10^{-6}$)
6	$7.5\ 10^{-5}$ ($2\ 10^{-5}$)	$3.4\ 10^{-6}$ ($9\ 10^{-7}$)	VR
10	$3.2\ 10^{-6}$ ($1\ 10^{-6}$)	VR	VR

4 A full probabilistic model for determining the reliability of an inspection program

A full probabilistic analysis based on LEFM as shown to the right in Figure 3.1 is fully illustrated in figure 4.1. The Paris crack growth law is adopted in combination with Monte Carlo simulations. Initial crack depth and growth parameters are treated as random variables and the result variable N is number of cycles to failure. The crack growth history before reaching N cycles is now random according with experimental measurements and fracture mechanics modeling. The effect of inspections is included through the POD concept.

All possible crack size at the various inspections must be included. The calculation is based on the following assumptions and inspection strategy:

The target service life is given as N_S
Inspection is planned at regular times N_i
C, a_0 and $\Delta\sigma$ are random variables in the Paris law.
The POD curve is known for the selected inspection technique
All cracks detected are to be repaired

Each simulation runs through all planned inspections. At each inspection the crack depth is determined based on the depth at former inspection and the stress level. Hence, the crack depth increases from one inspection to another according to the increment in number of cycle's ΔN corresponding to the inspection interval I. To get a better understanding of the physics in the problem, typical outcomes of three simulations are illustrated by the growth histories in Figure 4.2.

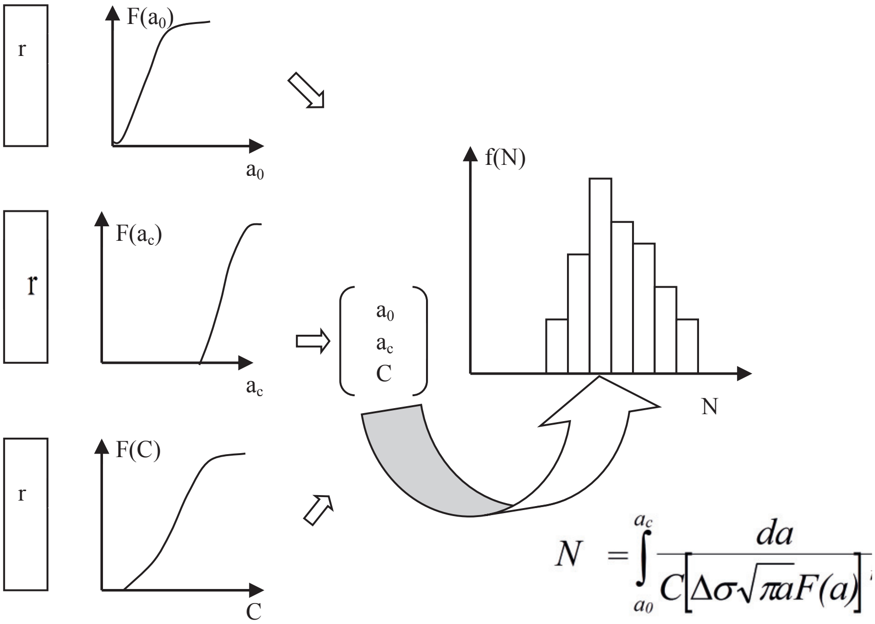

Figure 4.1-Flowchart for simulation model with planned inspections

For simplicity, only two inspections are scheduled before the end of service life. The outcomes are:

Realization 1: Slow crack growth without any crack detection. No failure ($N>N_S$)
Realization 2: Relatively slow crack growth with crack detection and repair at second inspection. No failure ($N>N_S$)
Realization 3: Rapid crack growth without detection at first inspection and failure before the second inspection is reached. Failure ($N<N_S$)

The number of simulations that gives N less than N_S contributes to the failure probability. This is the case for simulation 3. In a large simulation with say M=100 000, there will of course be most realizations of type 1 for a well designed joint where a reasonable requirement for the DFF is met. The total number of simulations of type 3 relative to the total number of simulations M will give us the probability of failure. If DFF is set to 10 there will hardly be any realization of type 2 and 3 and inspection can be avoided. If we let N_S vary the results of the simulation can be presented as curves for the probability of failure as shown in Figure 4.3. Thus far we have treated the likely influence of future planned inspection on the reliability level. It is a characteristic feature for these reliability curves that they are monotonically decreasing as shown in Figure 4.3. When inspection results are available from inspection already carried out all updating must be based on the law of conditional probability:

$$P(E_I \mid E_J) = \frac{P(E_I \cap E_J)}{P(E_J)} \tag{4.1}$$

where the left hand side is the posterior probability of event E_I given that event E_J has occurred.

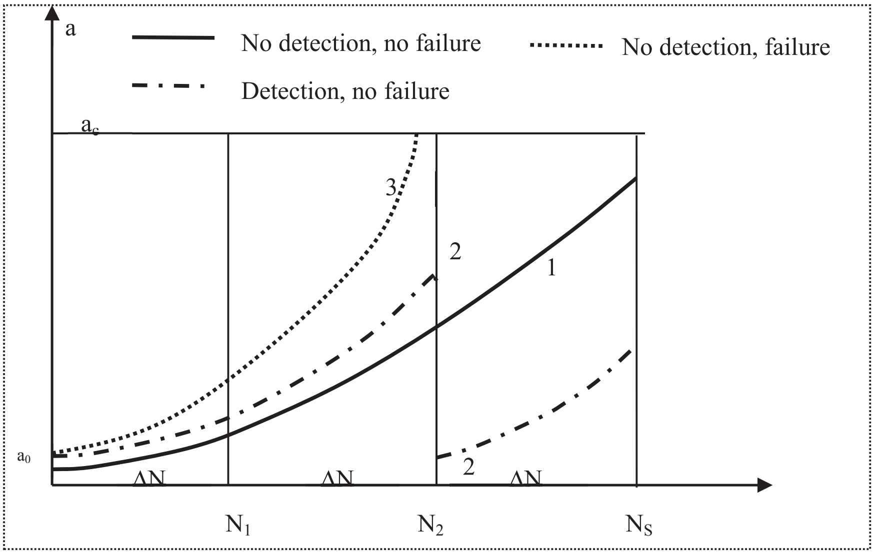

Figure 4.2- Illustration of possible outcomes of the crack growth simulations with planned inspections.

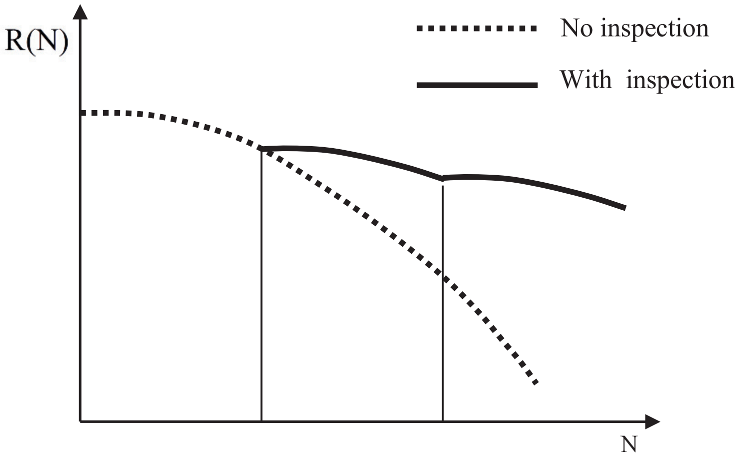

Figure 4.3- Reliability predictions with the most likely influence of future inspections

The following events E_j are considered:

E_0: Failure has not occurred
E_1: No cracks detected.
E_2: Crack detected but not sized or repaired
E_3: Crack detected and sized, but not repaired.
E_4: Repair is carried out.

We must update the calculated crack depth distribution at the time of inspection based on Bayesian equation in 4.1. The distribution for the crack depths must be updated and the reliability function will change as shown in figure 4.4 where results from the first inspection are available. Curve A pertains to the case where cracks are detected and repaired, whereas curve B is for no cracks detected. Curve C is for detected cracks that are left without repair.

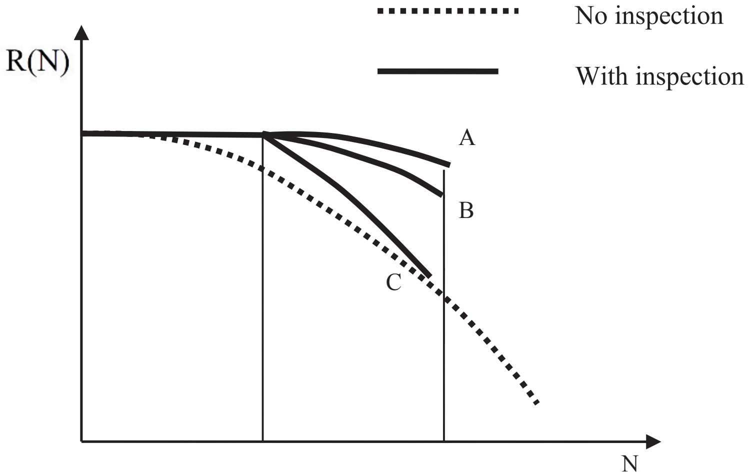

Figure 4.4-Reliability prediction with the influence of updating based on inspection results

5 Guidelines and recommended practice

Despite the documents referenced in 6, 7,8 and 9 there is still a lack for standard and guidelines on the use of probabilistic methods for predicting the effect of a scheduled inspection program for fatigue cracks in offshore steel structures. The basis for the probabilistic methods has been described in the present work in section 2 and 4.
In the recent JIP organized and lead by Det Norske Veritas (DNV) a proposal for standard and guidelines is given, Ref. [10]. The report treats important topics as:

- Fatigue analysis method, particularly based on fracture mechanics (curve figure 2.1, left)
- Effect of methodology/refinement used in fatigue analysis
- Basic distribution function for random variables entering the analysis (figure 4.1, left)
- Detail data the performance of inspection techniques (figure 2.1 right)
- Target reliability levels (table 2.1)
- Fatigue life extension

The main goal of the work is to establish a consistent methodology to obtain optimal allocation of inspection efforts to obtain reliable operation of structure with respect to fatigue cracking. Regarding the fatigue analysis the Paris law for crack propagation is adopted and the given parameters are in agreement with Ref. [6] but some important corrections and extension for the geometry function F(a) is given. Amongst the extensions is specification of geometry functions F(a/T) for ground welded connections. The material constant C and m are also in agreement with Ref. [6] but with some modification for growth in the base material. Furthermore, the work suggests a calibration of the fracture mechanics based crack life against S-N test results to obtain values for the initial crack depth a_0. After having proposed value for all the parameters, distribution types with mean value and standard deviations are given to account for the inherent uncertainty. Finally, data for PoD curves are given for common techniques such as Eddy Current (EC), Magnetic Particle Inspection (MPI) and Alternating Current Field Measurements (ACFM). When DNV in the future will sum-up the work in a recommended practice document, the inspection planner will have everything needed for carrying out the analyses described in section 4 in the present work. The target reliabilities given in table 2.1 are modified for redundant structure as the remaining system reliability after a local fatigue fracture of a welded joint has occurred is explicitly taken into account. The simple and more direct methodology outlined in section 3 is not mentioned in the JIP, but the JIP also uses the DFF from the S-N life prediction as a key parameter to the subsequent inspection planning. Section 3 can be regarded as an intermediate step before going into full probabilistic fracture mechanics model as the JIP recommends. This intermediate step can be an efficient and useful approach as we shall see from the case study in the next section.

6 Replacement and inspection program for an oil loading system in the North Sea

In the present case study an oil loading system in the North Sea is subject to analysis, see illustration in Figure 6.1. The original design life of 20 years has expired and another 20 years in service is planned. The flexible hoses are to be replaced but the steel parts were analyzed to choose between replacements or life extension based on a risk based in-service inspection program, Ref. [13]. Similar systems have earlier been discarded without looking into the possibility of keeping steel components in service based on risk based inspection strategies. The future strategy for the present installation is to replace the flexible hoses every 10 years and the system will be retrieved onshore for the purpose of this replacement. The first task to undertake was to make a re-analysis of the various steel components to predict the fatigue life based on the recent S-N approach, Ref. [5].

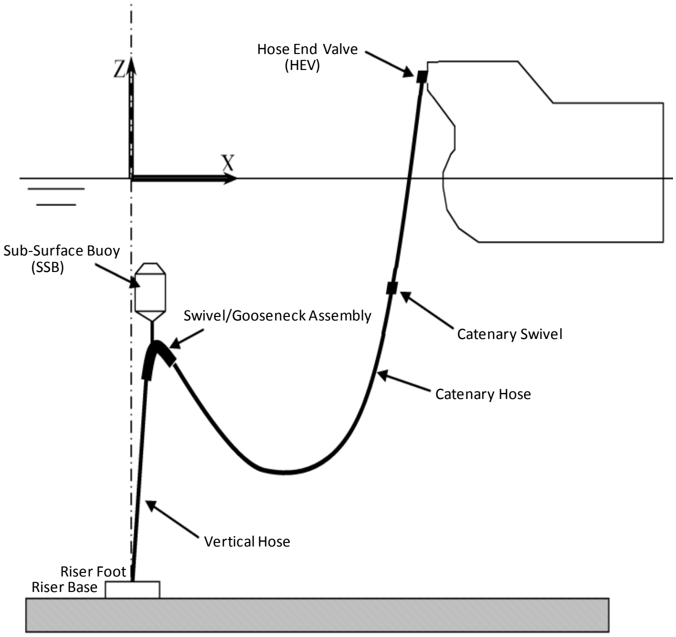

Figure 6.1 Oil loading System in the North Sea

Updated finite element modeling was carried out for the components and the hot spot methods were applied for fatigue life predictions. This methodology was not available at the original design stage. Once the DFF was determined for the various components the components were analyzed based on the simplified methodology described in section 3. For the few critical components revealed a more enhanced simulation was carried out according to section 4. Based on the analysis one of the critical components was identified as the gooseneck underneath the sub-surface buoy. The FEM model of the component is shown in Figure 6.2 right side. The potential crack location was at the surface of the piping at the nose of the vertical suspension plate, see figure 6.2. The analysis for the original as-built gooseneck gave a predicted fatigue life of 130 year. The elapsed service life was 20 years and for 20 more planned years in service this gives a final DFF=3.2 at final planned retirement. Applying table 3.1 as the first approach an accumulated probability of 2.2 10^{-3} or annual probability of 5 10^{-4} are obtained. This was considered too high taking into account that a fatigue crack in the steel pipe leading to leakage will result in shut down of the loading and expensive unscheduled retrieval of the entire system. If MPI is carried out with a 2 years interval it can be seen from table 3.1 the accumulated probability of failure reduces to 1.2 10^{-4} which is regarded as acceptable. However, sub-sea inspection of the gooseneck is not cost efficient. Consequently, the stress situation at the pipe surface was improved by grinding down the nose of the suspension plate. This gives a better detail design that reduces the SCF by more than 30%. As a result the predicted fatigue life increased from 130 years to 350 years. The DFF is then close to 9 for the entire life span. This will give an annual probability close to 10^{-6} in table 3.1 which is acceptable for all consequence groups, see Table 2.1. However, since it was questioned whether the load and stress calculation could have a higher uncertainty than the 20% on which table 3.1 is based it was decided to carry out MPI in favorable shop environment every 10 years when the system was available for inspection anyway due to replacement of the flexible hoses. Even with a stress uncertainty of 30% it was proven by the methodology in section 4 in combination with the recommendation in Ref. [10] that this inspection strategy was satisfactory.

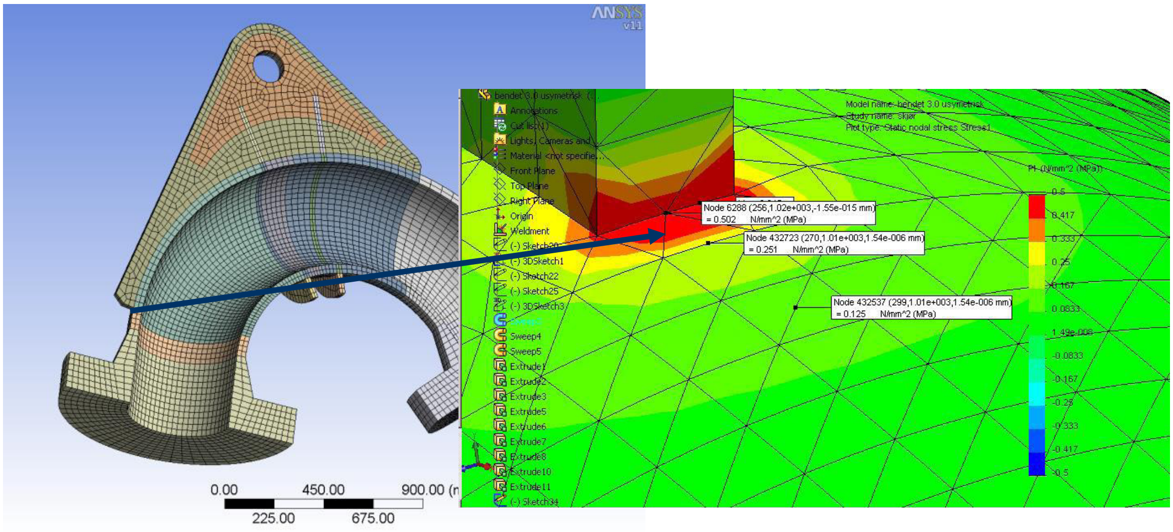

Figure 6.2 finite element models for the gooseneck (left) with stress concentration at suspension plate toe (right)

7 Conclusions

The present paper has presented the methodology and the practical calculations for risk based inspection planning of fatigue cracks in offshore welded steel structures. The practical pragmatic aspects are emphasized and the new guidance from a recent Joints Industry Project is commented. The Markov Chain model is an important tool for screening of the welded structure for fatigue criticality. Subsequently, the application of a probabilistic fracture mechanics model based on Monte Carlo simulations can be applied for the most critical joints of the structure. The methodology is important to ensure reliable extended operation with respect to fatigue damage of aging structures in the North Sea.

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