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INSPECTION COST REDUCTION FOR FIXED OFFSHORE PLATFORMS BASED ON RISK BASED INSPECTION APPROACH THROUGH ADVANCED FATIGUE ANALYSIS

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Synopsis

It is a common offshore practice to define the inspection plan for condition monitoring based on simplified standards recommendations and engineering judgment / experience. As results of the inspection program, a general visual inspection associated with a more accurate method is commonly selected by owners / operators in order to inspect critical components based mainly on platform qualitative risk categorization and structure integrity assessment. Considering the high influence of fatigue degradation on the safety of fixed installations, standards consider this failure mechanism as the key aspect to define an inspection plan. Aiming inspection cost reduction, a risk based inspection approach was proposed. Risk Based Inspection (RBI) provides a consistent framework for decision making under uncertainties in which the optimal inspection strategy can be selected based on the risk it implies. The cost reduction is even more evident when the RBI is associated with advanced fatigue analysis. In contrast with the traditional fatigue analysis, the main focus of this paper is to show the advantages of performing advanced analyses in order to reduce the conservatism in the calculation and, consequently, to acquire a more accurate fatigue life. With the purpose of identifying the influence of the proposed advanced approach in the inspection cost reduction against the traditional approach, a case study was developed and comparison is presented in this paper.

1. Introduction

Inspections are the basis for assessing the condition of a fixed platform installation and thus form a cornerstone in the Inspection, Maintenance and Repair (IMR) activities. The objective of inspection planning is to identify an inspection strategy that in a cost efficient way ensures that legislative and operator requirements to safety are fulfilled and can be documented.

In current offshore operations it has been a common practice to define a program for condition monitoring based on simplified standards recommendations and engineering judgment / experience. Besides the annual general visual inspection, a more accurate method is commonly selected by owners / operators in order to inspect safety critical components based mainly on platform risk categorization and structure integrity assessment.

Fixed offshore platforms are usually designed to reduce fabrication and installation costs, implying in an optimized structural design associated to the minimum requisites required by standards. The consequence of these optimized structural designs is the elevated costs associated to maintenance of the platforms as commonly it is necessary to inspect a high number of joints several times during the life cycle.

Aiming inspection cost reduction, a risk based inspection approach associated with an advanced fatigue analysis is proposed in the present study.

Risk Based Inspection (RBI) provides a consistent framework for decision making under uncertainties in which the optimal inspection strategy can be selected based on the risk it implies. Risk may be assessed for the safety of personnel, impact on environment, as well as for monetary costs or any other criterion of relevance for the installation. In the RBI approach the inspection effort is adapted to the condition of the item and prioritized in accordance with its importance and the different deterioration mechanisms. The objective of the RBI methodology is to give feedback on where, what, how and when to inspect in a cost efficient way. RBI theory is summarized in Section 2.

The cost reduction is even more evident when the Risk Based Inspection (RBI) is associated with advanced fatigue analysis. In contrast with the traditional fatigue analysis defined by standards, the purpose of the advanced methodology is to reduce the conservatism in the calculation and consequently acquires a more accurate fatigue life through several additional fatigue analyses. Thus, it is possible to develop a detailed program for condition monitoring focusing only on the safety critical areas; no effort is dedicated to the non-relevant elements. Proposed advanced fatigue analysis is detailed in Section 3.

The recommended methodology presented herein was implemented in a case study as illustrated in Section 4.

2. Risk Based Inspections Applied to Jacket Structures

For managing safety, environmental and financial risks over the lifetime of a jacket platform structure, inspections of the structure are addressed. Inspections shall be planned in a practical way, with a strategy capable of maintaining minimum cost and guaranteeing acceptable risk levels.

Underwater inspections are very expensive and the best way to reduce costs while controlling risk is by doing appropriate probabilistic analysis and applying risk based inspections (RBI), focusing inspection effort on the critical structural elements. Detailed inspections are then applied on items with high risks while General Visual Inspections (GVI) are kept to the rest of the structure guaranteeing no gross errors or non-predicted failure, for example dropped objects and ship collision, are occurring during analyses.

Mechanical degradations of jacket structures are caused mainly by corrosion and fatigue crack growth. The effect of the degradations by corrosion normally has a gradual development easier to be controlled, as the structures usually count with corrosion allowance or a protection system. However, fatigue cracks in welded connections caused by loading from waves are critical for jacket structures, for the reason that cracks can result in a sudden rupture when subjected to large number of stress cycles. Additionally, cracks are hard to be detected because they have a small size for a significant part of the crack growth time. From propagation of a crack causing loss of one single element, the structure as a whole (or partially) may fail, leading to production loss, fatalities and environmental impacts.

Thus, when considering probabilistic methods for planning inspections on jacket structures, the objective of the analysis is to quantify risk in terms of probability and consequence of fatigue failure for the overall structural integrity, and to establish an inspection schedule for individual joints that throughout the considered service life of the platform maintains an acceptable risk level.

From 2011 to 2013, a joint industry project (JIP) was performed on use of probabilistic methods for planning of inspection for fatigue cracks in offshore structures including assessment for jacket structures. The inspection planning methodology covered in this paper is in accordance with the recent released document, reference [3], which is based on the results from the JIP.

2.1 Risk Definition

The risk was defined as the product of the probability of fatigue failure times the probability of having a severe event influenced by the fatigue failure, like collapse of the structure or hydrocarbon leakage which may be ignited and lead to fire and/or explosion. Thus the following relations need to be established (example assuming structural collapse as consequence of fatigue failure):

- Structural strength in damaged condition expressed in terms of the Reserve Strength Ratio (RSR) which is used as a measure of the consequence of failure:

  → Conditional pF: Probability of collapse given fatigue failure, pFcollapse|fatigue

- Fatigue life:

  → Probability of failure: pFfatigue

- Risk is then obtained as the product of probability of fatigue failure and probability of collapse given fatigue failure:

  → Risk = pF = pFfatigue · pFcollapse|fatigue.

It is possible to observe that the event of total collapse of the structure is defined as either of the two following events:

- Collapse of an intact structure - calculated as the marginal probability that the annual extreme loading exceed the structural capacity;

- Combined event of fatigue failure and collapse of a damaged structure (caused by fatigue) - calculated as the joint probability that the structure is damaged caused by fatigue at time T, (i.e. accumulated probability) and the probability that the extreme loading in year [T to T +1] exceed the structural capacity for the damaged structure.

2.2 Acceptance Criteria

According to [5] with respect to fatigue endurance, the operator should define minimum Design Fatigue Factors (DFF) for the different areas dependent of consequence of failure, accessibility for inspection, inspection method, maintenance philosophy, etc. When considering consequence of failure also economic consequences with respect to possible maintenance and repair should be included. From a life cycle cost consideration, it may be beneficial to design for higher DFF's than the minimum required by standards. The cost consequences of increased DFF's may be relatively low compared with the gained reduction in In-service Inspection, Maintenance and Repair cost.

Reference [5] specifies the design fatigue factors given in Table 1 for joint locations with no access.

Table 1 Design fatigue factors for joints with no access, according to reference [5]

Classification of structural components based on damage consequence	Design Fatigue Factor (DFF)
Without substantial consequences	3
Substantial consequences	10

The applied acceptance criteria (target failure probability level) for use in the RBI analyses are based on the following 3 criteria, see Figure 1:

- Criterion 1 – General risk criterion: is the general target risk taken as the maximum acceptable annual probabilities of failure corresponding to a design fatigue factor DFF = 10;

- Criterion 2 – Upper limit on accumulated fatigue probability: is the upper limit of the fatigue probability in order to avoid a situation where several joints develop fatigue cracks. This limit is taken as the accumulated fatigue probability corresponding to a Design Fatigue Factor DFF = 3 for all platforms;

- Criterion 3 – Lower limit on accumulated fatigue probability: is the lower limit of the fatigue probability. According to the NORSOK code inspections are not required if DFF ≥ 10 regardless of consequence of failure. Hence, the lower limit is taken as the accumulated fatigue probability corresponding to a Design Fatigue Factor DFF = 10.

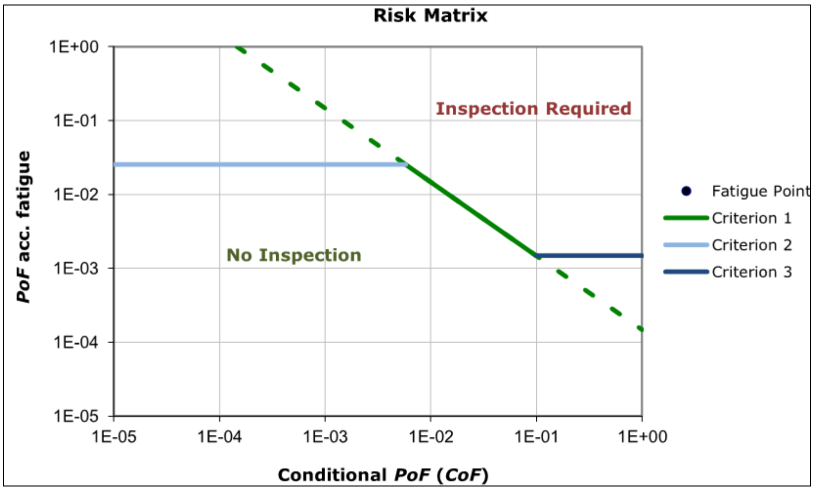

Figure 1 Target probability level for manned installation

2.3 Calculation of probability of Fatigue Failure

The probability of fatigue failure for each considered fatigue point is calculated by ORBIT Structure based on the calculated fatigue life, defined S-N curve, and the established uncertainty parameters. The RBI methodology presented herein, based on the fatigue analyses and derived fatigue lives, is performed as suggested by [3] and [5] using SCF's derived from load path method according to [4].

The uncertainty in the actual analysis method is accounted for when calculating the probability of fatigue failure by the uncertainty parameters denoted as Analysis Methods for Fatigue (AMF). Appropriate AMF's shall be assigned to each individual weld detail by selecting the relevant Fatigue Loading / Location (FL) and Analysis Method (AM), given in Table 2 and 3.

Table 2 Fatigue Loading / Location (FL): Uncertainty in calculated fatigue loading

#FL	Location	CoV
a	20 meters below Mean Water Level (MWL)	0.12
b	Below splash zone down to 20 meters below MWL	0.17
c	Splash zone and above	0.22

Table 3 Analysis Method (AM) Uncertainty in calculated hot spot stress for different analysis methods

#AM	Joint Type	Analysis Method	CoV
1	Tubular joint	Conventional SCF approach	0.20
2	Tubular joint	Load path method	0.16
3	Tubular joint	Generalized influence functions	0.12
4	Tubular joint	Influence coefficients and refined fatigue	0.08
5	Butt weld	Conventional SCF approach	0.05

The resulting uncertainty for the calculated hot spot stress, i.e. CoV(q), is derived from:

$$CoV(q) = CoV_{HS} = \sqrt{CoV_{AM}^2 + COV_{FL}^2} \quad (1)$$

Where: CoVHS is the resulting uncertainty for the calculated hot spot stress; CoVAM is taken from Table 3; CoVFL is taken from Table 2.

The uncertainty parameter for fatigue failure (AMF) for a given weld detail is determined by a combination of FL, AM and failure criterion as given in Table 4.

Table 4 Uncertainty parameter for fatigue failure (AMF)

Possible FL’s	Possible AM’s	Joint Type	Weld treatment	Failure criterion
a, b, c	1, 2, 3, 4	Tubular joint	As-welded	Through-thickness crack
				Section failure
			Grinded	Through-thickness crack
				Section failure
	5	Butt weld	As-welded	Through-thickness crack

2.4 Inspection planning

As per [1] the inspection plan defines the frequency and scope of the inspection, the tools / techniques to be used, and the deployment methods.

For each fatigue point inspection planning the following data must be previously established: Thickness (of considered weld detail); Fatigue life; S-N curve; Structural consequences (Member Importance Analyses); Uncertainty of parameters (AMF); Previous inspection history; Member condition (dry, flooded, grouted, etc.); Inspection methods.

Detailed inspections are performed when calculated probability of failure reaches the target probability level presented in Figure 1. Inspection methods are assumed for future NDE (Non-destructive examination) inspections:

– Above water:
  Eddy Current (EC) or Alternating Current Field Measurement (ACFM);

– Below water:
  In general: Flooded member detection (FMD) inspections of all members where FMD can be used, i.e. all empty members below water level.
  If inspections not feasible by FMD (grouted or water filled members): EC or ACFM.
  Chord side of leg tubular joints and leg butt welds: EC or ACFM.
  In addition, periodical (e.g. annually) GVI inspections (below water by ROV) should be performed.

For joints that require more than one inspection, a crack growth model based on fracture mechanics is calibrated to the S-N approach in order to define the inspection intervals. The entire inspection schedule is established such that the failure probabilities do not exceed the selected target value.

Probability of Detection (PoD) curves related to each inspection type is also used for inspection intervals updating. PoD curves distribution functions, as presented in [3] and [7] , are assumed to be similar and can be presented as:

$$PoD(a) = \frac{1}{1 + \left(\frac{1}{X_0} \right)^b} \qquad (2)$$

Where a = crack depth in mm; X0 = distribution parameter (= 50% median value for the PoD); b = distribution parameter.

3. Fatigue Assessment

The method and parameters mentioned in Section 3.1 are basis to develop a traditional fatigue analysis defined by standards which gives trusted and conservative results. In contrast with the traditional fatigue analysis, the main focus of this paper is to show the advantages of performing advanced analyses in order to reduce the conservatism in the calculation and, consequently, to acquire a more accurate fatigue life through several additional fatigue analyses, as detailed in Section 3.2. Both traditional and advanced fatigue analysis are presented hereafter.

3.1 Traditional Fatigue Analysis

During a life cycle of an offshore structure, a typical structural tubular joint could experience hundreds of millions waves induced stress cycle. Due to the large number of stress cycles these joints are susceptible to fatigue cracking which further can cause loss of member stiffness and even its fracture. As crack in welded connections is one of the most common failure modes, fatigue sensitivity is a crucial factor to select known or suspected damage areas to be inspected during the structure operational life.

Fatigue assessment is a relation of the stress range imposed on the structure due to repeated cyclic loads (mostly wave loads) and the element fatigue strength.

In a frequency domain analysis, the sea state and the number of waves acting on the structure is represented by a long-term wave distribution, which is discretized into representative sea-states of short duration and constant intensity. The variable loads due to these waves might excite a dynamic response and amplify the acting inducing stresses. This dynamic response should be accounted for each considered member.

Further the total fatigue damage or expected fatigue life of a structural element can be obtained based on the S-N fatigue approach under the assumption of linear cumulative damage proposed by Palmgren-Miner Rule (1945), see Equation 3.

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{3}$$

Where D = accumulated fatigue life; n_i = number of cycles endured at stress range; N_i = number of cycles to failure obtained from referred S-N curve at constant stress range $\Delta\sigma_i$; k = number of considered stress range intervals.

When considering fatigue inducing stress ranges, possible stress concentrations and how these modify the predicted values of the acting stress need to be taken into account. Depending on the numerical model used to analyze the structure it may not adequately account for local effects which modifies the stress range near the structural detail. For this reason, a Stress Concentration Factor (SCF) is a usual parameter to be used for each member connection. In general, the use of methods based on the equations presented by [4] is the most common to determine the SCF's at welded tubular connections for typical uni-planar T-Y,X,K and K-T joints, which includes the effects from loads applied to braces. On the other hand, for complex joint which is typically a multi-planar joint, these parametric equations may not be the most recommended method to define SCF's.

The approach mentioned herein stablishes the traditional fatigue analysis defined by standards. Usually this methodology gives trusted and conservative results.

3.2 Additional Fatigue Analysis

Hereafter the proposed studies used to compose the advanced analyses will be presented.

Local joint flexibility:

In fatigue analysis it has been standard practice to model the joints as rigid tubular joints composed by beam elements. In this kind of analysis local distortions of the chord circular cross sections are assumed to be negligible, and for this reason no relative displacements and rotations between the chord and the brace occur. However, simple tubular joints, especially without ring stiffeners, are normally flexible structures since the connection is not properly rigid and the chord deforms locally due to the loads. Therefore, local loading on the tubular members may then be implemented by the use of springs in the joints to account for local flexibility as detached in Figure 2.

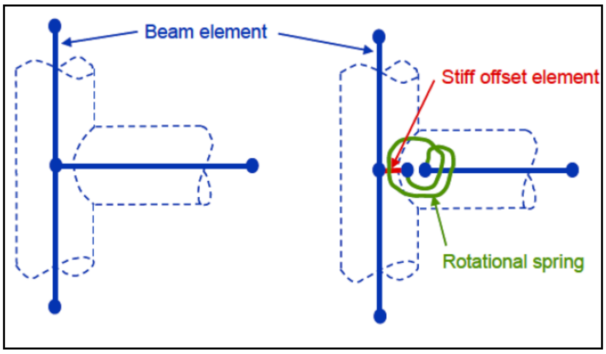

Figure 2 Theory of local joint flexibility

Besides that, flushing the member in order to represent the joint connection properly also provides a positive effect on the representativeness of local loading effects.

The effect of the gap length as well as the interaction effects between the chord and braces on local flexibility leads to more accurate results in the global analysis.

Load study:

The purpose is to identify the sensitivity of the calculated fatigue life for selection of the input parameters used in the load calculation. Specifically for this paper, it was evaluated the influence of marine growth, conductor's layout and long-term wave distribution.

Marine growth represents an additional non-structural mass which leads to increase wave loading on the structure since it increases the effective member diameter as well as the drag coefficient due to additional surface roughness. Besides the uncertainties involved to this parameter, it has been practice to consider the maximum thicknesses defined by standards for the whole platform life cycle, even though it might take several years in order to reach the final thicknesses. Hence, the use of marine growth in a more representative way improves the fatigue results.

Additionally, in order to reduce locally the dynamic bending load effect of the conductors acting on the stub connection and consequently decrease the fatigue damage, one of the studies consists to consider the conductors installation year instead of considering all conductors for the entire fatigue life.

Furthermore, in order to define a long term distribution of wave heights produced for each wave direction in a deterministic fatigue analysis, wave occurrence is considered linearly distributed in a semilogarithmic mapping between wave heights defined in H-T scatter diagrams instead of considering the maximum wave height of each wave interval. This type of approach leads to a smoother distribution of waves occurrence between wave heights.

SN-curve:

Due to the severe environmental condition found in areas such as North Sea and Gulf of Mexico, members are designed with higher thickness and then several S-N curves defined in the standards based on a reference thickness of 32 mm are applied in a conservative practice. Otherwise for instance in Brazil the environmental condition is not as severe as these places making possible to design thinner members and then use SN-curves with smaller reference thickness.

The thickness effect in the fatigue strength of a welded connection decreases when the thickness of load carrying plate increases. For this reason, selecting a more appropriated S-N curve with reference thickness similar to the element has a significant favorable impact in the fatigue life since thicker elements are more fatigue sensitive and higher probability to initiate a crack, as can be seen in Figure 3.

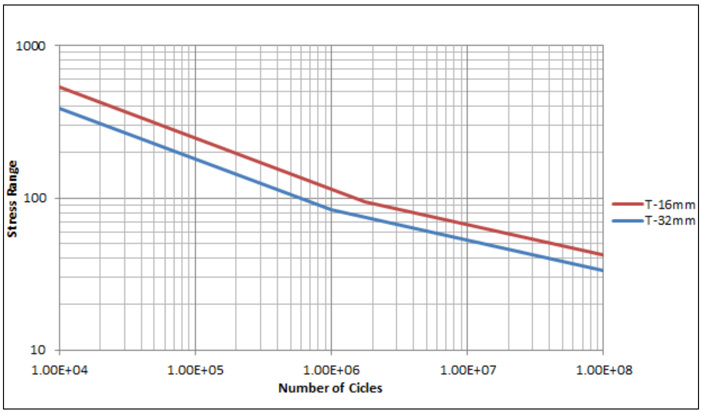

Figure 3 S-N Curves Comparison

Local Finite Element Analysis (FEA):

The advantage of this additional analysis is to check the structural behavior and stress levels along a specific joint connection through a detailed local finite element model (FEM) in shell integrated into the global beam model in order to determine its fatigue resistance. This kind of analysis reduces the uncertainties on the local behavior of the element when compared to a beam model analysis.

Joints presenting a high damage should be chosen to evaluate the fatigue life, which are directly obtained by a FEA. It was noticed that the fatigue damage reduced significantly applying this study, even more for complex joints. The improvement is a consequence of using a FEM to directly calculate fatigue life, instead of considering a conservative parametric SCF equation in the beam model. As mentioned in the Section 3.1 and noted in the performed local analysis, SCF equations predicted to a typical multi-planar joint may not be the most recommended method to define SCF's, being conservative.

4. Case Study

With the purpose of identifying the influence of the proposed advanced approach in the inspection cost reduction compared with the traditional approach, a case study for a fixed offshore platform was developed covering the following activities, as illustrated in Figure 4:

– Inspection plan based on the traditional approach – international standard recommendations;

– Inspection plan based on risk based inspection approach;

– Inspection plan based on risk based inspection approach through advanced fatigue analysis.

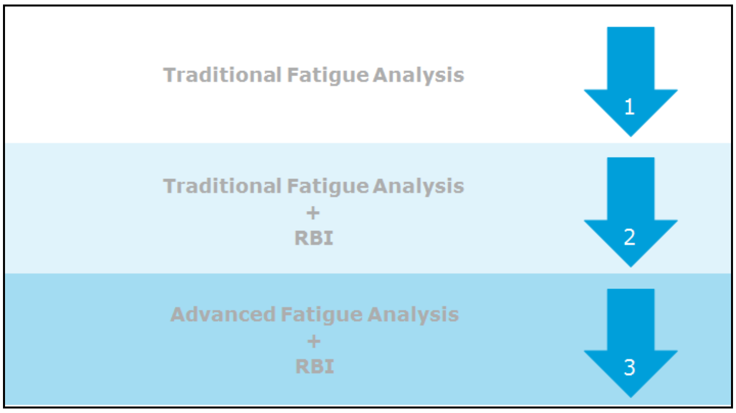

Figure 4 Proposed analyses workflow (right)

As per [1] the inspection is defined by the visit to the platform and the associated survey activities for purpose of collecting data required in evaluating its structural integrity for continued operation. Structural Integrity Management (SIM) provides a process for understanding the effects of deterioration, damage, changes in loading, and accidental overloading defining a framework for inspection planning of platforms.

4.1 Inspection Plan based on traditional approach

It is a common offshore practice to define the inspection plan for condition monitoring based on simplified standards recommendations and engineering judgment / experience. Some recommended activities consist of collecting all platform data, evaluating the structural integrity, stablishing an overall inspection strategy and then defining an inspection program within detailed work scope for inspection. As results of the inspection program, a general visual inspection associated with a more accurate method is commonly selected by owners / operators in order to inspect critical components based mainly on platform qualitative risk categorization and structure integrity assessment.

Considering that the fatigue degradation mechanism has high influence on the safety of fixed installations and by compromising safety, not only the production can be lost but also fatalities and environmental impacts can be expected, standards considers this failure mechanism as the key aspect to define the inspection plan.

It is possible to observe that the inspection plan based on traditional approach described in Section 3.1 does not consider any sophisticated risk methodology, being fundamentally defined by fatigue lives. Thereby, aiming to apply this approach to the analyzed jacket structure it is essential to be acquainted with the fatigue life of all main joints.

A structural fatigue assessment was performed through the SESAM software, according to [2]. Stress concentration factors for joints were defined based on the equations presented in [4], while butt welds and conical transitions were calculated according to [2].

As consequence of the fatigue results, an inspection plan based on the traditional approach and standards recommendation lead to a large number of joints requiring detailed inspection methods such as Flood Member Detection (FMD) and / or Non Destructive Test (NDT).

As mentioned before, the selection of the critical joints considering the approach mentioned herein does not take into account any advanced risk evaluation, slightly considering or even disregarding probability and consequence of failure. As the current offshore industry is experiencing, the traditional approach usually leads to inconsistent inspections planning, which can result in costly inspection at non critical areas, or worse, no inspection at critical areas.

4.2 Inspection Plan Based on Risk Based Inspection Approach

Risk Based Inspection (RBI) provides a consistent framework for decision making under uncertainties in which the optimal inspection strategy can be selected based on the risk it implies. Risk may be assessed for the safety of personnel, impact on environment, as well as for monetary costs or any other criterion of relevance for the installation. In the RBI approach the inspection effort is adapted to the condition of the item and prioritized in accordance with its importance and the different deterioration mechanisms.

By applying the RBI methodology described in Section 2 and considering the fatigue results used in Section 4.1, the inspection plan revealed that eight (8%) from the total of main joints / butt weld required NDT (EC) inspections, while twenty percent (20%) required to be inspected by FMD. Compared with the traditional approach presented in Section 4.1, it was observed a significant reduction of detailed inspection by applying RBI methodology, giving a more reliable feedback on where, what, how and when to inspect in a cost efficient way. Figure 5 summarizes the joints / members probability of failure results compared to the acceptable risk target, defining the details requiring inspections as those above the line as per Section 2.2.

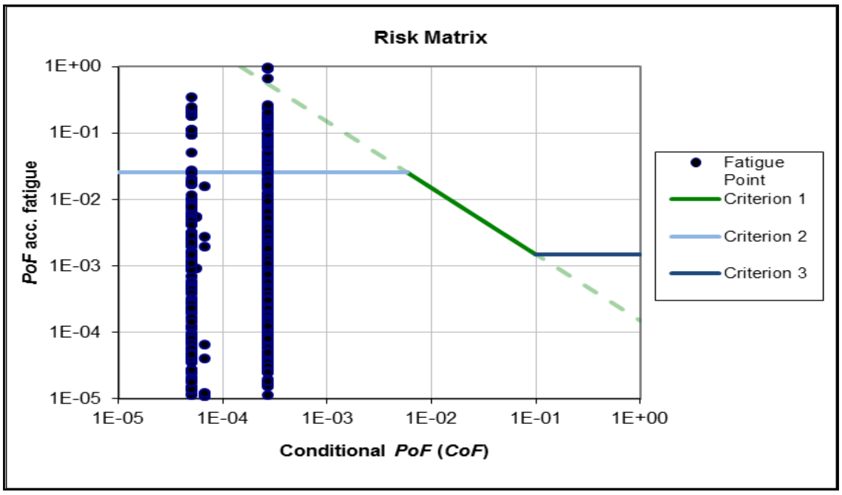

Figure 5 Risk Matrix and joints / members probability of failure results – RBI with traditional fatigue approach

4.3 Inspection Plan Based on Risk Based Inspection Approach Through Advanced Fatigue Analysis

The cost reduction showed to be even more evident when the Risk Based Inspection (RBI) was associated with advanced fatigue analysis. In contrast with the traditional fatigue analysis defined by standards, the advanced methodology reduced the conservatism in the calculation and consequently acquired a more accurate fatigue life. It was observed that the fatigue damage significantly decreased by performing the analysis as described in Section 3.2.

By applying the RBI approach through advanced fatigue analysis described in Sections 2 and 3.2, the inspection plan revealed that no main joint / butt weld required NDT (EC) inspections. Only one and a half percent (1.5%) from the total of main joints / butt weld are to be inspected by FMD as illustrated in Figure 6, reducing drastically the associated cost of inspection compared to the two inspection plans mentioned in Sections 4.1 and 4.2.

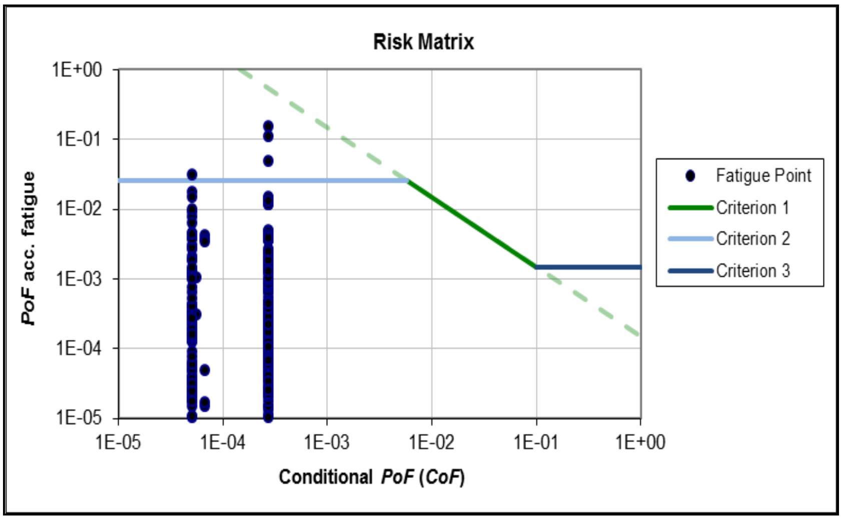

Figure 6 Risk Matrix and joints / members probability of failure results - RBI with advanced fatigue approach

5. Conclusion

The recommended risk based inspection approach through advanced fatigue analysis presented herein was implemented as a case study in a fixed offshore platform and, as per results presented in Section 4, implied in an expressive inspection cost reduction.

As presented in Section 4.2, the inspection plan revealed that eight (8%) from the total of main joints / butt weld required non-destructive Eddy Current (EC) inspections, while twenty percent (20%) required to be inspected by Flooded Member Detection (FMD) based on RBI with the traditional fatigue approach analysis. By applying the proposed advanced methodology as described in Section 4.3, the inspection plan revealed a significant improve with no main joint / butt weld requiring NDT (EC) inspections and only one and a half percent (1.5%) from the total of main joints / butt weld to be inspected by FMD, giving a reduction of one hundred percent (100%) and ninety-three percent (93%) respectively.

It is even more advantageous when comparing the proposed advanced methodology to the traditional approach presented in Section 4.1, since costly inspection were dedicated to non-critical areas and no attention was given to critical areas.

Cost reduction was also expressive when looking to the platform life cycle, since the inspection frequency significantly reduced when performing the approach presented herein.

6. References

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