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BENEFITS OF RISK BASED INSPECTION PLANNING FOR OFFSHORE STRUCTURES

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ABSTRACT

The economical benefits of applying risk-based inspection planning (RBI) for offshore structures subject to fatigue are evaluated based on experiences from past industrial projects. To this end, the factors influencing the cost of inspection, repair and failure of structures are discussed and realistic values of these costs are presented. These are then applied to assess the expected costs from different inspection strategies, both risk-based strategies as well as inspection strategies with fixed inspection intervals for all potentially critical elements. By comparing these expected costs, the financial benefit of RBI is assessed.

INTRODUCTION

For offshore structures, risk and reliability based inspection planning (RBI) procedures have been developed and implemented since the 1980s, mostly for fatigue deterioration of fixed jacket steel structures, Skjong (1985), Madsen et al. (1989) and Fujita et al. (1989), but more recently also for ship and floating production storage and offloading systems subject to corrosion and fatigue, Lotsberg et al. (1999) and Goyet et al. (2004). While the significant computational efforts required by RBI hindered the applications in the past, this restriction has been resolved with the development of the generic approach to RBI, see Faber et al. (2000), Straub (2004), Faber et al. (2005) and Straub and Faber (2006), which facilitates the highly efficient application of RBI for portfolios of offshore structure.

Although it has been observed that RBI in general reduces the amount of inspections considerably, Moan et al. (2000), the financial benefits of applying RBI strategies for offshore structures have not been systematically quantified in past publications. Furthermore, in the public domain little information is available on realistic estimates of costs related to the structural integrity management of these structures. As an example, in Dalane et al. (1990) the resulting expected cost for different designs and inspection strategies are compared for example details in fixed and floating offshore structures, yet without presenting the underlying cost model.

In this paper, the factors influencing the costs of inspections and repairs are reviewed. Based on past experience, typical costs of different types of inspections and repair actions are presented for fixed and floating offshore steel structures, including FPSO's, subject to fatigue damages. Furthermore, the factors influencing the cost of a failure in the structure are discussed. On this basis, the financial benefits of performing risk based inspection planning are determined for some typical cases by comparing the associated expected costs with the expected cost of an inspection strategy with fixed, predefined inspection intervals. This assessment is based on the generic approach to RBI.

INSPECTION STRATEGIES

The potential inspection strategies can be divided into three groups, namely prescriptive strategies, qualitative strategies and quantitative risk-based strategies.

Prescriptive (or rule-based) inspection planning

Prescriptive inspection plans require that inspections are performed for all joints in the structure at fixed intervals in time. Such rule-based inspection planning is still commonly applied in the offshore industry. Its main advantage is that it does not require further structural and risk analysis of the structure. Additionally, it may facilitate the planning of the logistic aspects of the inspection campaigns, because the number of inspections in each campaign can easily be adjusted to the available inspection capacities. Rule-based strategies are thus defined completely by the inspection interval ΔT_{Insp} .

Partly risk-based inspection strategies (qualitative or semi quantitative risk-based strategies)

Some owners and operators of offshore structures implement an inspection policy which corresponds to a combination of the rule-based and the RBI approach, i.e., they apply inspection strategies which are partly risk-based. These strategies prescribe inspection intervals separately for groups of joints, in accordance with the considered qualitative and/or quantitative risk indicators. As an example, in Pemex (2000), inspection intervals are determined for fixed steel platforms as a function of various indicators, including the member importance (primary, secondary or tertiary member) and the calculated fatigue life.

These partly risk-based inspection strategies are not considered explicitly in this paper. It is argued that although strategies based on qualitative indicators are preferable to purely prescriptive inspection planning strategies, they do have similar disadvantages. This holds in particular when considering fatigue deterioration, as qualitative indicators are poor in describing fatigue performance. Partly risk-based inspection strategies, which are based on quantitative indicators (such as the calculated fatigue life) are not treated in the following, as it is argued that with the availability of these indicators it is preferable to perform a fully quantitative RBI, as, once the indicators are available, the additional effort for such an analysis is small, as outlined in the following section.

RBI strategies (quantitative risk-based strategies)

RBI strategies are based on the priorization of inspection efforts in accordance with the risk reduction efficiency of the different alternative inspection actions. Ideally, such strategies should be based on the preposterior analysis of the Bayesian decision theory. In the following, the RBI model presented in Straub (2004) and Straub and Faber (2006) is summarized and subsequently applied for the numerical investigations; the practical application of similar models has been reported in, e.g., Pedersen et al (1992), Moan et al. (2000), Faber et al. (2005) or Chakrabarti et al. (2005).

The deterioration mechanisms are represented by stochastic models of the defect size as a function of time, $\mathbf{S}(t)$. For fatigue, $\mathbf{S}(t)$ is the crack depth and length as evaluated by a probabilistic fracture mechanics based model. Inspection qualities are commonly represented by a Probability of Detection (*PoD*) curve and a Probability of False Indication (*PFI*), which describe the likelihood of an inspection outcome given the state of the inspected component. Based on the *PoD* and *PFI*, structural reliability analysis or simulation techniques facilitate the updating of any deterioration model in the presence of an inspection outcome through the application of Bayes' rule, as demonstrated by Madsen (1987). Through the assumption of no-indication at the inspections, the required inspection times to comply with a given threshold on the acceptable annual failure probability can be determined, as illustrated in Figure 1 for thresholds 10^{-3} yr^{-1} and 10^{-4} yr^{-1}. The assumption of no-indication implies that mitigation measures (repair, monitoring, follow-up inspections) are taken in case a defect is indicated at any of the inspections. The fact that inspection intervals increase with time reflects the increased confidence in the fatigue performance of the hot spot after the inspections.

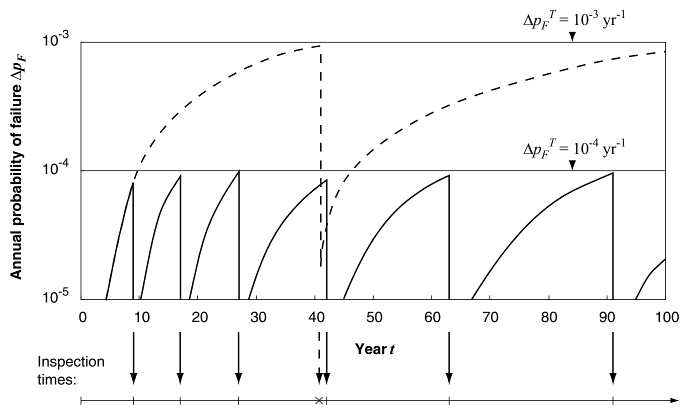

Figure 1. Inspection times as determined from the application of Bayes' rule, from Straub (2004)

The calculated probabilities can be applied to determine inspection strategies that comply with given risk acceptance criteria. Additionally, it is possible to assess the expected costs associated with a given threshold and therefore identify the optimal threshold (and thus the optimal inspection strategy), as illustrated in Figure 2. This optimization follows the principles of the Bayesian preposterior decision analysis according to Raiffa and Schlaifer (1961).

The probability calculations required for RBI are computationally very demanding, especially for fatigue problems. In the past, this has hindered the application of the RBI methodology in practice. The generic approach to RBI was developed to overcome these limitations. The core of the generic approach to RBI is the pre-fabrication of inspection plans for generic hot spots which are representative for the particular hot spots[1] in the considered structures. These pre-fabricated plans are termed *Generic Inspection Plans*. All hot spots that are represented by the model are fully described by the so-called generic parameters. These are the input parameters to the model that vary from one hot spot to the next and which are indicators of the relevant deterioration mechanism. For structures subjected to fatigue, typical

[1] Hot spots are the potential locations for fatigue failures.

examples of such generic parameters are, e.g., the calculated design fatigue life T_{FL} (respectively the dimensionless Fatigue Design Factor FDF^2), other loading characteristics (such as the shape of the distribution describing the stress ranges at the hot spots), the applied SN curve (which is representative for the detail type and the environment) and geometrical parameters such as the wall thickness at the hot spot.

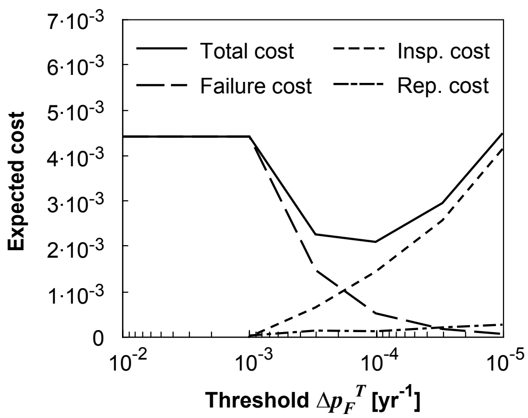

Figure 2. Optimization of inspection efforts, from Straub (2004).

Once the generic inspection plans are calculated, the inspection plans for the specific hot spots in a structure can be obtained by an interpolation of the generic plans, see Straub and Faber (2006) for details on the procedure. For this task, software tools such as iPlan, see Faber et al. (2005), can be developed. Because the generic parameters are obtained from standard fatigue evaluation procedures, the RBI can, in principle, be performed without specialist knowledge once the generic inspection plans are available. In this way, the RBI is easily integrated in the daily asset integrity management procedures of the owner or operator of the structure.

As an example consider Figure 3: The inspections required to comply with given acceptance criteria are here shown as a function of the generic parameter *FDF*, i.e., for fixed values of all other parameters, the inspection times are obtained as a function of the *FDF*. Similarly the expected costs can be expressed as a function of the *FDF*, Figure 4. The calculations are based on marginal costs of failure $C_F = 1$, cost of repair $C_R = 0.01$, cost of inspection $C_I = 0.001$ and an interest rate $r = 0.05\text{yr}^{-1}$.

[2] The *FDF* is a deterministic safety factor, defined as the ratio of the calculated design fatigue life to the design service life.

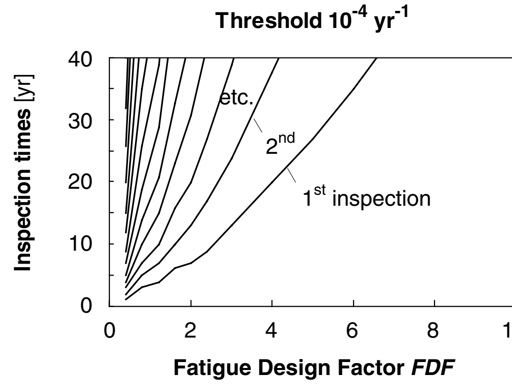

Figure 3. Inspection times as a function of the *FDF* for a target reliability 10^{-4} yr^{-1}, Straub (2004).

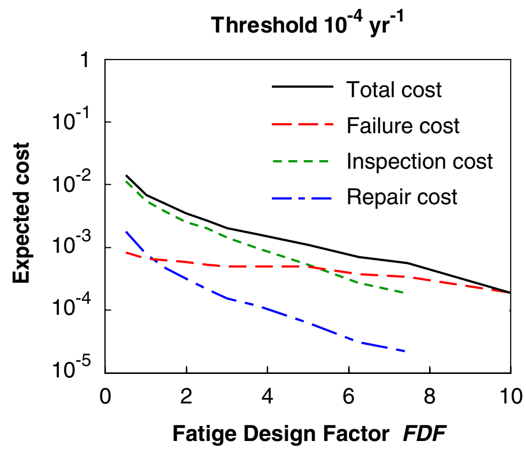

Figure 4. Expected cost as a function of the *FDF* for a target reliability 10^{-4} yr^{-1}, Straub (2004).

CHARACTERISTICS OF FATIGUE PERFORMANCE IN OFFSHORE STRUCTURES

Offshore structures are subject to fatigue mainly due to environmental loads (waves). In addition, parts of the structure are subjected to fatigue loads from machinery or other operational loadings. Typically, fatigue performance is assessed in terms of the fatigue design life (or the *FDF*) as calculated using the SN approach. The *FDF* is a main indicator for the fatigue performance and the required inspection efforts. In the following, we focus entirely on the *FDF* when describing the fatigue performance of offshore structures. Other generic parameters (such as the uncertainty in the load modeling) also have a large influence on the fatigue performance and/or the required inspection times, however, these other parameters often are the same for the entire structure or do not vary much from one hot spot to the next. For the comparative study presented later, it is sufficient to assume that these other parameters are the same for all fatigue hot spots in the structure.

Fixed steel structures

As an example, Figure 5 shows the distribution of *FDF*s calculated for 4 steel jacket structures built in the late 1970s in the Gulf of Mexico. The platforms are all eight-leg drilling platforms with an anticipated service life of 35 to 36 years. The fatigue calculations were performed as part of the reassessment study described in Chakrabarti et al. (2005). A majority of the hot spots have a *FDF* larger than 10. For those, no inspections will be required according to the RBI (see Figure 3), but also according to standards such as NORSOK (1998) or API (2002). The distribution of the *FDF*s provides an indication of the fatigue strength of the installation and will be decisive for the required inspection efforts following an RBI approach.

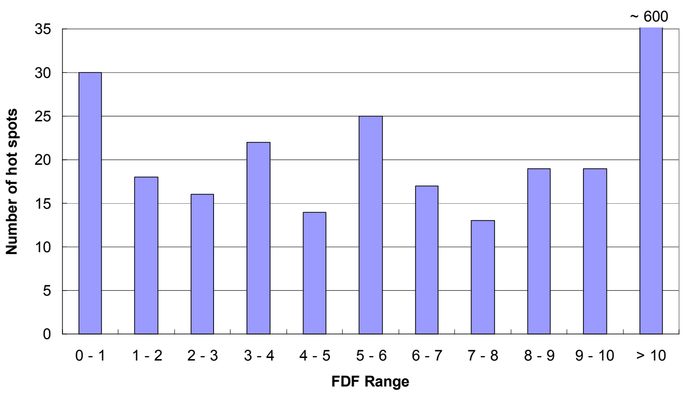

Figure 5. Distribution of *FDF*s observed on 2 steel jacket structures.

It is noted that the fatigue performances of the individual hot spots are dependent, in particular for similar types of details in adjacent locations in the structure. This inter-dependency allows considering system effects in the planning of inspections, which may reduce the amount of required inspections, see Straub and Faber (2005).

Floating structures

Floating structures include FPSOs (Floating Production, Storage and Offloading units) but also semi-submersible platforms. Whereas the fatigue assessment for floating platforms can be considered in analogy to the assessment for fixed structures, the fatigue assessment for FPSOs is different due to the large amount of hot spots (potential locations of fatigue failures) in the structure and due to the large redundancy of the structure. For the same reasons, the consideration of inter-dependency between the fatigue performances of the individual hot spots is even more relevant for floating structures than for fixed structures.

Figure 6 shows exemplarily the distribution of *FDF*s as calculated for 2 units. The first one is a conversion, i.e. a tanker converted into a FPSO, while the second is a purpose-built FPSO. For the conversion, the presented *FDF* values represent hot spots in 3 cargo tanks located in the aft part, the midship part and the fore part respectively. The number of the web frames in these 3 tanks is 9 (3 per tank) and the total number of welded connections is slightly higher than 1050. The fatigue calculations underlying these *FDF* values are described in Goyet et all. (2004). Based on the results of these calculations, only 96 welded connections (about 9% of the total) were considered in the detailed RBI analysis (all hot spots with *FDF*<8). Thereby, the critical welded connections in this FPSO are situated as follows:

- Side shell longitudinals: 71
- Longitudinal bulkhead longitudinals: 23
- Bottom longitudinal: 1
- Bracket toe weld: 1

In the second FPSO, the *FDF* values presented in Figure 6 are located in a condensate tank and a water ballast tank. The number of the web frames is 11 and the total number of welded connections is higher than 1500. The fatigue calculations lead to a selection of 294 welded connections (about 19% of the total) for further detailed RBI analysis, which are situated as follows:

- Side shell longitudinals: 74
- Longitudinal Bulkhead (side) longitudinals: 5
- Bottom longitudinals: 215

It is pointed at the fact that the critical connections are located at different areas in the two FPSOs (in the side shell longitudinals respectively the bottom longitudinals). This indicates the difficulty in identifying the relevant hot spots for inspection without detailed fatigue calculations.

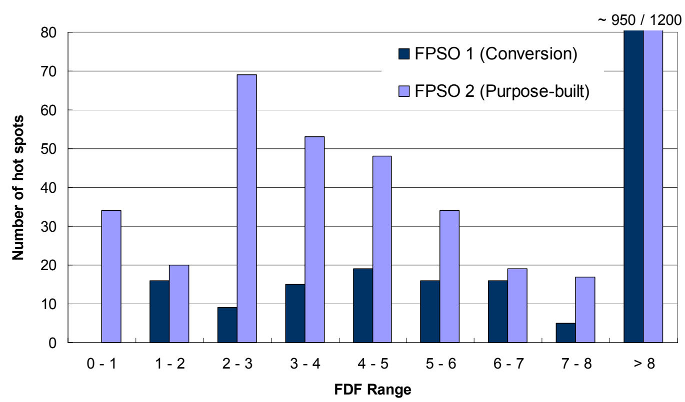

Figure 6. Distribution of *FDF*s observed in 5 different tanks on 2 FPSOs.

COST OF INSPECTION, REPAIR AND FAILURE OF OFFSHORE STRUCTURES

The cost-relevant activities and events included in the optimization of the inspection efforts are the inspections themselves, with associated cost C_I, repair actions with costs C_R and failure of individual hot spots with cost C_F. Inspection planning is a time-dependent problem, as inspections and repairs at an earlier time will prevent failures at a later time. Therefore, an interest rate r is included in the analysis. The cost of the individual actions and events is highly dependent on the type of structure and operation. In the following, the factors influencing the cost of inspection, repair and failure are thus discussed separately for steel platforms and FPSOs.

Cost on offshore steel platforms

A large part of the cost of inspecting joints in steel platforms is related to accessing the hot spots. This holds in particular for the joints which are situated below sea-level and in the splash zone. Below sea level, fatigue inspections require removal of the marine growth, which is a time consuming task. In the splash zone, accessing the hot spots may be very difficult or even impossible, depending on the weather conditions. Because of the limited availability of ships and inspectors, the inspections must be planned well in advance and cannot account for the weather. A main cost factor is the ship which carries both equipment and inspectors. Often a Dynamic Positioning Ship is required, with associated cost in the order of 10'000US$ per day. When inspecting joints below sea-level, approximately 8 joints may be inspected per day, so that, as a rough estimate, it can be assumed that the total cost of inspecting a hot spot, including ship, personnel and equipment cost, is C_I = 2'000US$.

For repair actions, the cost factors are similar to those for inspections, but, depending on the type of repair, the required time to perform a repair can vary substantially. If a small crack is found, it can be removed simply by grinding, which may be performed directly by the inspector in very little extra time. If a larger defect is found, the necessary equipment and personnel may not be available and must be brought to place at an extra cost. Alternatively, an engineering assessment and follow-up inspections may be performed. Considering these factors, it is estimated that the average cost of repairing a major defect is C_R = 20'000US$.

In addition to the direct cost, the inspection and repair activities represent a significant risk for the involved personnel, in particular when joints are inspected by divers. This risk should be taken into account when assessing compliance of an inspection/maintenance strategy with given risk acceptance criteria.

The cost of failure of a hot spot, C_F, depends on the importance of the associated members. The importance of member failure can be expressed by the conditional probability of global collapse given member failure, $p_{COL|F_i}$. This probability can be estimated by the use of a simple indicator; the Residual Influence Factor (*RIF*), see Stahl et al. (2000) and Straub and Faber (2005a). The *RIF* is defined as the ratio between the Reserve Strength Ratio (*RSR*) of the intact structure and the *RSR* of the damaged structure, which is assessed by removing the element i in the pushover analysis. Using a general probabilistic model it is possible to relate the *RIF* for a particular hot spot to $p_{COL|F_i}$, Figure 7. The (expected) cost of the failure of hot spot i is then derived from the cost of structural collapse, C_{COL}, as:

$$C_{F_i} = \left[p_{COL|F_i}\left(RIF_i\right) - p_{COL|\overline{F}}\left(RSR\right) \right] \cdot C_{COL} \qquad (1)$$

Equation (1) is based on the assumption that failures do not occur in several hot spots simultaneously. This assumption does only hold if general visual inspections are held in regular intervals, ensuring the detection of failed members, see Straub and Faber (2003).

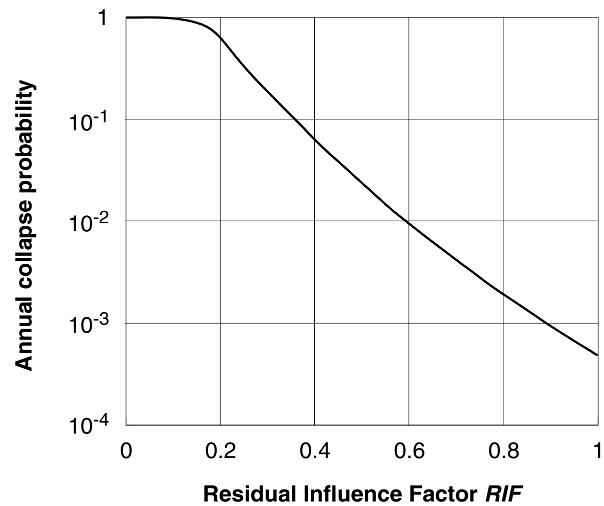

Figure 7. Relation between the *RIF* and the annual probability of collapse for a steel jacket in the Gulf of Mexico with an *RSR* = 1.63.

The cost of platform collapse, C_{COL}, is difficult to estimate. Construction costs of typical offshore steel platforms are in the order of 20-30 10^6 US$. However, if the loss of production cannot be compensated by other installations in the field, it may result in costs of an order of magnitude higher. As an example, the cost of the loss of Petrobras' P-36 semi-submersible rig in 2001 has been estimated as 500 10^6 US$, Goldman Sachs (2004). In addition, catastrophic events may also lead to a loss of reputation, which is very difficult to quantify. On the other hand, most structures are insured and failure costs are, therefore, compensated. However, because the insurance premiums will depend on risk mitigation actions implemented by the operator (at least theoretically), it is argued that compensation by insurance companies should not be included in the cost-benefit analysis. For the examples presented in the latter, two cases are considered: C_{COL} = 30 10^6 US$ and C_{COL} = 300 10^6 US$. The cost of a hot spot failure, calculated by applying Equation (1) and the relation given in Figure 7, is given in Table 1 for different *RIF*s:

Table 1. Expected cost of hot spot failure as a function of the RIF and the cost of collapse.

RIF	C_{COL} = 30 10^6 US$	C_{COL} = 300 10^6 US$
0.95	6'000 US$	57'000 US$
0.9	14'000 US$	138'000 US$
0.8	43'000 US$	433'000 US$
0.5	688'000 US$	6'879'000 US$

Note that fatalities are not considered here, as these must be taken care of by risk acceptance criteria, which are based on the preferences of society, see Rackwitz (2002) and Kübler and Faber (2002).

Cost on FPSOs

In analogy to platforms, a major contribution to inspection and repair costs is from assessing the hot spots. The costs for the inspection of an example tank are:

- 8000US$ for COW (Crude Oil Washing), water wash and to purge/gas free the tank, activities which are required for accessing the tank.
- 4000US$ for a visual inspection of the lower area.
- 70'000US$ for visual inspection of the upper area using rope access.
- 5000US$ for Non-destructive testing (NDT) of 10 hot spots in the tank.

Note that these costs are not exclusively related to fatigue inspections, but include inspections for other types of degradation (such as painting/coating checks and thickness measurements). Assuming that all other inspections are fixed, the cost which is associated with the inspection of one hot spot may be estimated as C_I = 500US$.

The cost of a repair is related to the cleaning and the repair action itself. For an example hot spot, the related costs are:

- 2500$ for the local cleaning before the repair.
- 1500$ for a repair including a drill stop, gouging and welding.
- 15'000$ for an insert repair (replacing a steel plate). Note that this cost is dependent on the size of the area which is repaired.

For a minor repair, the associated costs are therefore approximated by C_R = 4'000US$.

A main factor influencing the cost of failure is the unavailability of a tank. Whereas inspections (including subsequent repair) can be planned, failures may lead to an unplanned, immediate shut-down of parts of the installation. The cost of such shut-downs is highly depending on the operation, but in any case these costs will be huge. As a simple example consider a fatigue failure occurring between two consecutive inspection campaigns, which leads to an unavailability (down time) of the corresponding tank for a period of about 10 days. Assuming that the loss of production is equal to 10'000 bbl/day at a rate of 30US$ per bbl, the loss of production over 10 days amounts to: 10'000 x 10 x 30US$ = 3'000'000US$.

In the above it is assumed that a component fatigue failure is followed by an immediate repair in order to prevent any global failure scenario with much higher consequences. The implicit assumption – which is not always realistic – is that the failure is immediately detected and repaired once it occurs. In principle, also the influence of fatigue failures on the overall structural integrity should be (explicitly) accounted for. Clearly, fatigue failures lead to an increased risk of loss of the entire unit, as each failed connection will decrease the global structural resistance to operational and environmental loads and thus increase the probability of structural collapse. However, due to the high redundancy in floating structures, it is not possible to assess the member importance with a *RIF* value (*RIF* values would generally be very close to 1). On the other hand, fatigue failures will be highly inter-dependent and may occur in clusters, which increases the probability of a global collapse of the structure, see also Straub and Faber (2005a) for a discussion. It seems therefore not reasonable to quantify the cost of an individual failure event in a floating structure, as it has been done for platform structures. Instead, as a first approximation it is assumed that all fatigue failures will be detected and immediately repaired. Because this assumption is over-estimating the true costs (not all defects will be detected and repair may take place during the regular inspection campaign), it is considered that this partly accounts for neglecting the effect of the failure on the overall structural integrity. The cost of a failure is thus taken as C_F = 3'000'000 US$.

For some of the hot spots, special failure scenarios become relevant, e.g. when the fatigue failure is located on the side shell and may cause pollution of the environment or for the case where a fatigue failure may trigger an explosion due to the emission of gas, as may be the case for the walls separating the cargo tanks and the water ballast tanks. In that case, these failure costs may be considered explicitly, following a probabilistic consequence assessment.

BENEFITS OF RISK BASED INSPECTION PLANNING

The benefits of performing RBI as compared to prescriptive inspection planning are assessed for examples of fixed offshore steel structures and FPSOs.

Fixed steel structures

In the following, the expected cost of different inspection planning strategies are assessed, based on the probabilistic deterioration model described in Faber et al. (2005) and the cost model presented in the previous section as it applies to platforms. It is assumed that the hot spot has a RIF=0.9. The expected cost of failure (C_F=138'000 US$), the cost of inspection (C_I=2'000US$) and the cost of repair

(C_R=20’000US$) follow from the pervious discussion. Furthermore, an interest rate of $r = 0.03$ is taken into account.

In Figure 8 and Figure 9, the expected cost over the lifetime (40 years) of a hot spot with *FDF*=2 is presented, for a prescriptive and a risk-based strategy respectively. The RBI strategies are given as a function of the maximum annual probability of failure, in accordance with Figure 1 and Figure 2. The inspection times for ACFM inspections corresponding to the RBI strategy are shown in Figure 10.

Although the difference between the prescriptive and the RBI strategies with respect to the expected cost appears small, this is not the case if it is reminded that the inspection plans must also fulfill specified acceptance criteria. In the application presented in Faber et al. (2005), for a hot spot with *RIF*=0.9, risk acceptance criteria demand that the annual probability of failure is lower than 10^{-3} yr^{-1}. For the example hot spot, when applying a prescriptive inspection plan, this would require that the inspection interval is 4 years or lower. In this case, the total expected cost is, according to Figure 8, 17’000US$. The RBI plan fulfilling the acceptance criteria has a total expected cost of 12’500US$, Figure 9.

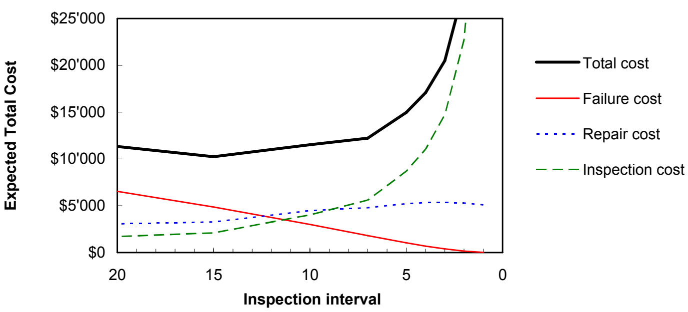

Figure 8. Expected costs for a hot spot with *FDF*=2 for different equidistant inspection strategies.

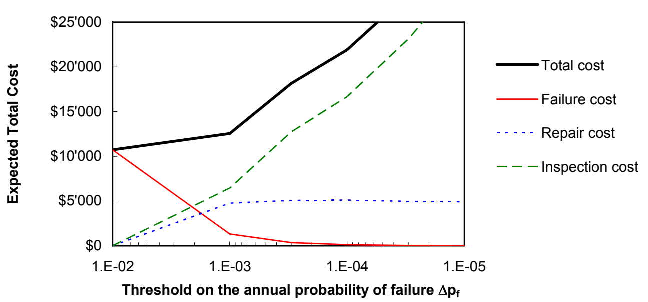

Figure 9. Expected costs for a hot spot with *FDF*=2 for different RBI strategies.

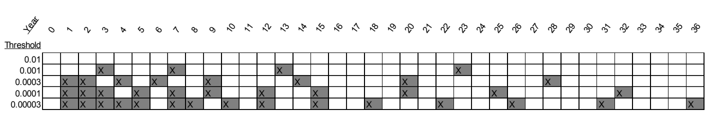

Figure 10. Inspection plans corresponding to different thresholds for a hot spot with *FDF*=2.

Figure 11 and Figure 12 show the expected cost for two different prescriptive inspections plans, with constant inspection intervals of 10 and 4 years. It is reminded that only the second fulfills the acceptance criteria for hot spots with a *FDF*=2 (but not with a *FDF*=1). Figure 13 presents the expected cost for an RBI plan, which fulfills the acceptance criteria for all *FDF*s. It can be observed that the RBI plans lead to significantly lower total expected cost than the prescriptive plans for almost the entire range of *FDF*s, while at the same time ensuring compliance with the acceptance criteria.

Based on the expected costs presented in Figure 11 to Figure 13 and the distribution of *FDF*s for the 4 sample platforms as presented in Figure 5, the total expected costs $\mathrm{E}[C_T]$ for the different inspection planning strategies can be computed. These are

- 10 years fixed interval: $\mathrm{E}[C_T] = 5.2\ 10^6$ US$
- 4 years fixed interval: $\mathrm{E}[C_T] = 11.7\ 10^6$ US$
- RBI plan: $\mathrm{E}[C_T] = 3.8\ 10^6$ US$

It is observed that the application of the RBI plans result in the savings of 1.4 10^6 US$, respectively 7.9 10^6 US$ as compared to the different prescribed inspection plans.

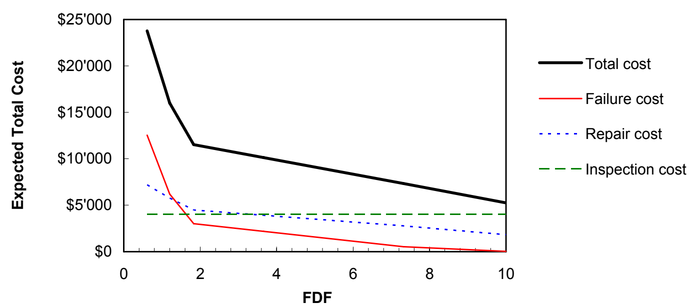

Figure 11. Expected cost as a function of the *FDF* when performing inspections in a constant interval of 10 years.

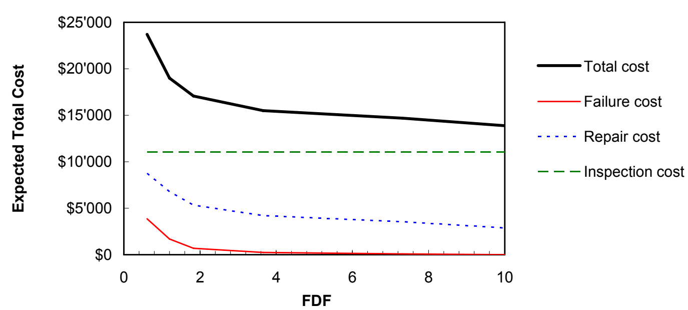

Figure 12. Expected cost as a function of the *FDF* when performing inspections in a constant interval of 4 years.

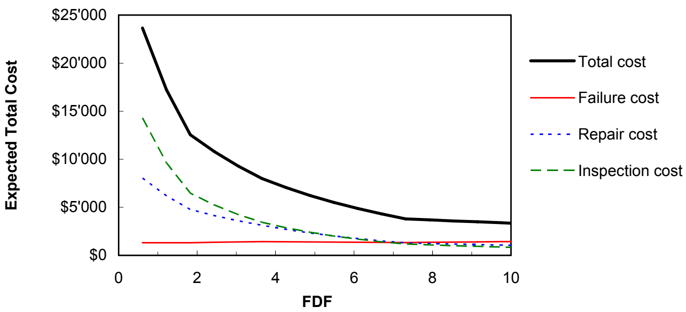

Figure 13. Expected cost as a function of the *FDF* when applying a RBI strategy with a threshold on the annual probability of failure of 10^{-3} per year.

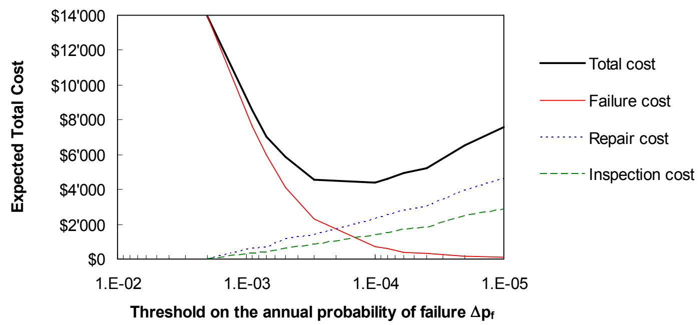

Figure 14. Expected costs for a specific connection on FPSO 1 (with *FDF*=2.41) and various thresholds.

FPSO (Example 1)

Similar calculations as performed in the previous section for fixed steel offshore structures may also be carried out for floating units. The total expected costs of an RBI plan are thereby compared with the total expected cost related to the application of prescriptive rules. In the case of FPSOs, prescriptive rules are the rules issued by the classification societies for maintaining class. According to Bureau Veritas rules (2004), a special survey has to be carried out every fifth year when the unit is younger than 15 years. For older units, the required inspection interval is reduced to 2.5 years. As may be observed from Table 2, the required inspection times (applying Alternate Current Field Measurements, ACFM) vary significantly when applying a RBI strategy, although a direct comparison is not valid, because inspections must also be carried out for assessing other degradation, in particular corrosion. Because a large part of the inspection cost is related to assessing the hot spots, the expected cost related to the different inspections must be considered jointly. However, a RBI study can be performed including all different types of degradation.

Note that the RBI calculations for the FPSOs are based on the probabilistic models presented in Goyet et al. (2004).

Table 2. Inspection times [yr] for 7 representatives FDF values on FPSO 1.

FDF	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1.58				■		■			■			■			
2.51									■						■
3.50								■				■			
4.27								■					■		
5.54											■				
6.45												■			
7.45												■			

As an example, the expected cost for a hot spot with *FDF*=2.4 and service life time 15yr is shown in Figure 14. The costs as utilized in the calculations follow from the previous discussion and are C_F=3'000'000 US$, C_I=500US$ and C_R=4'000US$, the interest rate is $r = 0.03$.

Due to the fact that the times for fatigue inspection for the most critical set of components were found close to the usual inspection times (years 2.5, 5, 7.5, 10, 12.5 and 15), it was decided to fit the fatigue inspections to the usual inspection campaigns required by the class. In addition, it was possible to reduce the amount of inspections by considering systems effects (see, e.g., Straub and Faber (2005b)): As a consequence, only 50% of the NDT inspections must be performed every 2.5 years. Therefore, only 50% of the wing tanks are inspected every 2.5 years, and the inspection interval for those tanks is thus increased to 5 years. Only a reference group of cargo tanks will be inspected directly according to the plan coming from the detailed RBI (as in Table 2), to verify the assumptions made regarding system effects. For ballast tanks, system effects were not considered.

FPSO (Example 2)

FPSO 2 is not under the class regime for in-service life. Therefore, a RBI approach has been applied for determining inspection plans for the unit. Based on *FDF* values shown in Figure 6, the so called "equidistant RBI approach" (see Faber et al., 2000) was used to determine the optimal periodicity of inspection campaigns, i.e., the inspection intervals required for fulfilling the acceptance criteria. The distribution of the inspection intervals calculated for two different tanks is presented in Figure 15. It is required to distinguish the two tanks under consideration:

For the condensate tank almost all of the hot spots require an inspection each 5 years or each 4.3 years.

For the water ballast tank, most of the hot spots require an inspection each 5 years or each 10 years, but a small number of hot spots - basically the ones at the bottom shell connections - require more frequent inspections.

The inspections times were determined for close visual inspection, which is the usual way of inspection in maritime transportation. In a second step, other, more accurate NDT techniques with higher probability of detection (*PoD*) were used to extend the frequency of inspection of the most critical components. This illustrates the flexibility of RBI, which allows for adaptations and modifications when required.

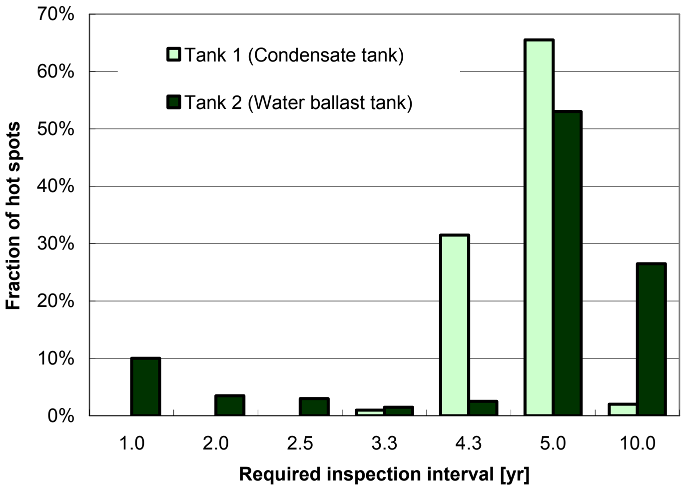

Figure 15. Distribution of the inspection (close visual) periodicity as determined for 2 tanks on FPSO 2.

DISCUSSION

In the paper, the benefits of RBI are presented for examples of fixed steel structures as well as floating structures (FPSOs). For fixed structures it has been demonstrated that the application of RBI plans may lead to significant economical benefits, which are in the range of one to several million US$ for the four example platforms, depending on the alternatively applied prescribed inspection plans. In addition, the RBI plans ensure that the acceptance criteria with respect to risk to personnel and the environment are fulfilled, which is not the case when prescriptive inspection planning is performed. For FPSOs, it has been outlined on two examples that the application of RBI plans facilitates the targeted application of inspections. Only the detailed fatigue calculations, which are performed as part of the RBI study, allow the identification of the critical details (hot spots) in the structure. These have been found to be different ones for the two considered FPSOs (the side shell longitudinal connections in the conversion FPSO and the bottom longitudinal connections in the purpose-built FPSO). On this basis, a significant reduction of inspection efforts on the non-critical elements has been achieved, while ensuring sufficient inspection coverage of the critical hot spots. The examples underline the fact RBI allows to fit inspection efforts to the requirements in terms of acceptance criteria for each component individually and thus leads to a significant (economical) benefit.

In addition to a direct reduction of the total expected cost, RBI enhances the understanding of the structural integrity. Because RBI requires a detailed analysis of the structure, the deterioration processes as well as the inspection performances, it helps to identify the "weak points" of the structure. For some structures, the RBI study may thus result in a recommendation for additional mitigation measures, which are more efficient than an increased inspection effort. Following the same line-of-thought, it would also be highly beneficial to perform a RBI study already during the design of a new structure. Considering the examples presented in this paper, it would, e.g., be possible to identify a cost optimal *FDF* values for the hot spots, when the construction cost is included in the analysis.

For most new-built fixed offshore structures, fatigue calculations are performed at the design stage for all hot spots. For existing structures, however, such calculations are often not available and are thus carried out as part of the RBI study. For FPSOs, fatigue calculations are generally available only for a selection of hot spots which are considered critical, although there is a tendency towards demanding more extensive fatigue assessments. Independently of whether or not fatigue calculations are available for all hot spots, RBI procedures are based on a model of the structure which is not perfect. This is reflected by the fact that fatigue cracks occur at hot spot areas where they were not expected. It is thus of utmost importance that besides the detailed inspections planned according to RBI, general (visual) inspections are performed to ensure the validity of the assumptions made in the RBI analysis. The inspection planning procedures must then ensure that fatigue calculations and consequently the RBI analyses are revised when such general inspections reveal defects which were not anticipated.

It is noted that RBI is increasingly required by owners and operators of offshore structures. For owners and operators, the primary objective of RBI is to maximize safety, to minimize costs and to gain a technical understanding of the behavior and performance of the facilities. It can be observed from the calls for tenders that operators are moving from a reactive to a proactive vision through the introduction of risk-based, optimized inspection programs. In the case of FPSOs, risk-based schemes are implemented as an alternative to or in parallel with class inspection rules and flag state requirements. This is also true for fixed steel offshore structures, where RBI and certification are related integrity management tools. Furthermore, many call for tenders nowadays explicitly require the demonstration of compliance with risk acceptance criteria. These prescribe that risks to personnel arising from consequences of loss of pressure containment or structural failure have to be retained below some limits as specified by national authorities or operators and owners. Such acceptance criteria may be expressed for example in terms of average FAR, location-specific FAR or individual risk, Straub and Faber (2005a). It is clear that only inspection plans based on RBI are able to demonstrate compliance with the acceptance criteria.

CONCLUSIONS

By consideration of examples of fixed offshore steel structures and FPSOs subject to fatigue deterioration, the benefits of RBI are presented and discussed. It is demonstrated that the financial benefits in terms of the expected total life-cycle cost are huge. Furthermore, it is observed that only RBI plans ensure compliance of the structures with risk acceptance criteria and its documentation. Finally, the analyses required by RBI enhance the understanding of the relevant degradation processes and may thus lead to an improved structural integrity management beyond the optimization of inspection activities.

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