Flexible Approaches to Risk-Based Inspection of FPSOs


Abstract

As the FPSO fleet matures, the challenge of how to more rationally and efficiently manage the life-cycle integrity of an FPSO attracts more attention. Risk and reliability based approaches are regarded as very powerful tools to help optimize an integrity program and offer flexibility in helping better manage the integrity management regime.

ABS has developed a multi-level risk-based inspection methodology ranging from simplified deterministic approaches using standard design analysis up to sophisticated probabilistic approaches. Each approach has various levels of usefulness ranging from the definition of critical areas for a single inspection campaign up to the generation of an optimized inspection schedule and work scope covering the entire lifecycle of a particular unit. These RBI methodologies have been successfully applied in inspection planning for several FPSO installations. A wide range of engineering analyses were involved, depending on the needs of individual projects and client requests, inspection objectives, condition of the asset, availability of design analysis information, etc.

In line with the various levels of assessment defined above, ABS has also started developing an automated RBI assessment tool which is discussed at the end of this paper.

Introduction

As experience with the current FPSO fleet grows, it has become common knowledge that there are fundamental differences in the way FPSOs are operated compared with trading tankers. Therefore, it is not surprising that the survey practice normally applied to tankers does not always suit FPSO operations. For example, dry docking of a vessel, a procedure routinely conducted in trading tankers, would only be considered in extreme circumstances for FPSOs. For this and other reasons, it is desirable to have more flexible inspection approaches.

While there remains a strong need for traditional rule-based and prescriptive approaches [1], offshore units are becoming more complex and have a higher degree of novelty. Many aspects of their designs are falling outside of traditional Class rules. The ever-expanding offshore oil and gas frontier demands the adoption of new and advanced technology. Risk and reliability technology [3] is finding increased application given the current demands from clients for more flexibility in the way classification services are provided as well as the greater use of performance-based criteria. Offshore exploration and production in deeper water require novel installation configurations and lighter structure and moorings (newer materials). In addition, commercial pressures are driving changes in FPSO operating practices:

- Vessels (e.g. tankers converted to FPSO service) are being kept in service beyond their service lives
- The standard survey cycle does not always align well with operating practice
- The industry needs more efficient and rational ways for maintaining machinery and structures

Traditional practice as exemplified by prescriptive Rules and standard methods [13] lacks the flexibility to respond to these demands. Risk and reliability based methodologies [7] allow systematic and rational ways for dealing with variations from the “standard” approach. These more advanced methods of maintenance and inspection strategy development follow along an evolutionary continuum that other industries [3-6] are also traveling upon (Figure 1).
the inspection process in an integrated way. This represents a significant improvement over traditional methods where there is little, if any, interaction between the design and in-service phases of the life of the asset. There are several important building blocks necessary to develop a risk-based hull structural inspection scope and frequency as well as provide adequate instruction to the personnel executing the plan. These key aspects can be broken down into the following:

- Information basis (data gathering)
- Structural Analysis
- Qualitative Risk Assessment
- Reliability Analysis
- Aggregating the Results
- Inspection Framework

Figure 2 shows a simple schematic comparing the rule-based and risk-based approach to inspection planning. These two approaches are represented by two paths which lead to the ultimate goal of confirming the hull structure is fit-for-purpose. Note that for the risk-based approach, a major contributor is the foundation of experience from the class rules. This is indicated by the RBI path (solid arrow), which begins with the historical experience of the class society. Additionally, the hatched arrows from the class and industry experience are also incorporated into the RBI plan.

The final stage of the process is the development of forward-looking risk based structural inspection plan for the asset. As with any forward-looking plan, future inspections are subject to the results of ongoing inspections. The key to this part of the RBI is the development of a general rule set for combining the results of the qualitative risk ranking, structural analysis results as well as the degradation and reliability model results. Note that this program is generally specific for the first few years and more generic for future years since new inspection data may alter the outlook for certain areas of the structure and intervals may changed accordingly.
Like industry guidelines or codes, the class rules have been continually revised over the years as more information (such as failures) becomes available. These learnings which are inherent to the rules are invaluable. RBI plans regardless of the complexity and analysis basis generally do not differ grossly from class rules. Instead they tend to parallel class rules drawing upon the rules as a starting point and along the development path with optimizations in the inspection plan where structural analysis, reliability and risk assessment indicate it is justified. The class rules form the well traveled path which over the years has a proven track record for trading vessels and to a lesser extent with offshore facilities.

While the class rules are an integral part of a risk-based inspection plan, how much the risk-based inspection plan differs from the rules is directly related to the foundation of structural analysis and structural reliability developed for the specific asset. This is evident in the comparison of four case studies, described below. RBI plans for structural systems can vary in complexity and structural analysis basis, from the simple qualitative or deterministic approach to the more quantitative or probabilistic route.

RBI Case Studies

ABS has assisted in the implementation of these varying levels of the RBI methodology to several FPSO installations. Four of the applications are presented herein to illustrate the wide range of possible engineering analyses that underlie the flexibility of the ABS RBI methodology.

The case studies provide practical examples of the varying degrees of complexity encountered in such plans as well as the specific information and analysis requirements necessary to feed each of the plan developments.

The four case studies are referred within the paper are as follows:

- Screening assessment – Pre- and Post Survey Scope Assessment
- Structural reliability assessment (I) – Reliability Based Method using SafeHull Analysis
- Structural reliability assessment (II) – Reliability Based Method using Dynamic Load Analysis (DLA) /Spectral Fatigue Analysis (SFA) [2]

The above naming scheme is used to distinguish the differences between the RBI plan development approaches.

Screening Assessment – Pre and Post Survey Scope of Assessment

The Screening Assessment case is a risk-based approach intended to provide guidance on the scope of hull inspections. The method identifies the most critical compartments and structure within a compartment. The approach helps assist surveyors and other personnel involved with developing a compartment inspection scope. It can assist in making choices that are presented in the class rules. For example, the class rules may require a minimum of 3 representative ballast tanks to be inspected and the Screening Assessment case will provide guidance on what 3 ballast tanks have the highest risk. Figure 3 shows the method flow chart.

![Figure 3 Screening Assessment Flow Chart](Image)

The primary basis for the risk based scope comes from the strength and fatigue analysis results from SafeHull. For example, the likelihood of strength failure is calculated deterministically and expressed as the ratio of class renewal thickness over the as-gauged thickness. The consequence is dependent on the location and potential extent or size of the failure. The consequences are based on preset criticality classes for the particular component of interest. For example, if the failure affects the hull girder strength, the level of severity (i.e., the consequence) is high. The three levels are considered in our methodology: Primary, Secondary and Tertiary in parallel to the corresponding type of structure falling into those three categories.

The calculated risk of a component is simply the product of the likelihood and the consequence. The risk scores for different compartments and components can then be used to rank or prioritize all structures of all levels.

The benefit of the approach is that it is relatively simple and the risk calculations are automated. It also provides valuable information regarding the vessel’s strength and fatigue characteristics which would not normally be available to a surveyor on a vessel-specific basis. This information coupled with the surveyors experience results in a more focused inspection of the hull structure

Degradation Assessment – Deterministic Approach using Structure Analysis

The Degradation Assessment case is a risk based method intended to determine both the frequency of inspection as well as the scope. The method identifies the most critical compartments and structures within a
compartment using stress and fatigue results generated by ABS SafeHull [2].

The method may take into account corrosion rates that may change over the FPSO’s life time. Corroded structures have reduced strength as a result of the loss of local or global section. The ratio of the forecasted stresses in corroded structures and their allowable limits are used to set the likelihood of a strength related failure on a risk matrix.

The consequences are based on the generic failure severities, using the same process as described in the Screening Assessment case. The risk scores for each component are calculated for the future service years. The risk increases with time as the strength and fatigue ratios increase, which in turn increase the likelihood of a structural failure. The consequence remains the same over time. When specific components within a tank reach the high risk level on the risk matrix, the compartment is to be inspected, thus helping to set the inspection interval. The approach enables an automated formulation of the tank inspection frequencies.

**Figure 4 Degradation Assessment Flow Chart**

Figure 4 shows the flow chart for this method. The information required to develop a Degradation Assessment RBI plan includes:

- Structural Analysis (SafeHull Phase A and B)
- Corrosion Rate Models
- Baseline inspection with comprehensive thickness measurements that provide information on the as-gauged or as-built thickness.

Like the Screening Assessment case, the benefit of this method is that it is semi-automated, and setting the risks tends to be strictly based on the structural analysis results. The fact that the risk results tend to be only based on structural analysis also sets application limits: it cannot go beyond what the engineering tool can do. For example, in many cases hulls and topsides are analyzed separately. Hull structures that support heavier topsides may have a higher probability of failure and therefore drive inspection scopes and frequencies of a hull structure in that particular location. However, this cannot be captured if only hull structures were analyzed in a simplified approach. Generally, the class rules are used to address the scope of structures not explicitly included in assessment process.

**Structural Reliability Assessment – Reliability Based Methods**

These cases represent the more comprehensive approach to RBI plan development [11], [12]. The approach for both the Structural Reliability Assessment (I) and Structural Reliability Assessment (II) cases are generally the same, but there are some significant differences in the structural analysis which result in variations in the reliability analyses used to set inspection frequencies and scopes. The main differentiator between these cases and the cases for the Screening and Degradation Assessments is the use of reliability-based methods to determine when and where the hull structures should be inspected.

**Figure 5 Structural Reliability Assessment Flow Chart**

The objective of the Structural Reliability Assessment in RBI plans is to provide comprehensive forward looking plans that provide not only guidance on scope and frequency but also inspection sequencing and plan updating (i.e., thresholds indicating if changes or specific actions need to take place). The plan development includes not only structural analysis results but also historical data, tank service condition data, condition summary, qualitative risk assessment and information on the all “other” external structures that may affect the hull inspection. Figure 5 shows the flow chart for the two methods.

The process starts with the structural analyses, consisting of both strength and fatigue assessments. The analyses provide global stress and fatigue results in the “as-is” condition as well as results for local models of highly stressed or FPSO specific areas to further refine the assessment. The results of these assessments allow the identification of specific critical areas of the structure that are at high stress levels or are prone to fatigue damage, so that they can then be targeted in the inspection program.
Flexible Approaches to Risk-Based Inspection of FPSOs

The uncertainties of loads and corrosion degradation are taken into consideration using reliability approaches. The degradation models and reliability analysis draw upon the vessel’s past history and baselining inspections, structural analyses and the qualitative risk analysis. The degradation models enable forecasting and time-varying reliability methods to be used in determining acceptable inspection intervals. The results are compared with pre-defined reliability targets to determine the occurrence of structural failure.

The reliability targets are driven by the potential consequences identified as part of the qualitative risk assessment. The results from the degradation modeling and reliability analysis are inspection intervals for a component or system that will allow that component or system to maintain an acceptable level of reliability. These models and analyses are updateable so that the most recent information is used when determining the current reliability level for both strength and fatigue.

The qualitative risk assessment identifies the potential consequences related to hull structural damage. Generally, the assessment incorporates a structured workshop similar to a hazard identification (HAZID) study where risks associated with the system are systematically identified and assessed. Other less rigorous methods can also be used, but simplifications ultimately result in limitations in the plan (i.e., not all of the key aspects are covered in detail). The risk assessment is used to highlight and account for other factors that may impact hull integrity not necessarily covered by the strength and fatigue analyses or the reliability analysis (such as leak potential from pitting damage, coating breakdown, etc.). The results from this assessment are used to adjust the individual component target reliabilities up or down on a risk basis which in turn influences the required inspection intervals. Furthermore, the input from the operations personnel and risk results generated during the exercise provides a forum to identify key or critical inspection locations as well as understand potential consequences (i.e., impact to operations) related to the structural integrity of the hull.

Because of the quantity of data and various types of input (e.g., reliability indices, outstanding issues, inspection-critical locations, as well as correlations between tanks) a simple formula that calculates the inspection intervals and associated scope is not used. Instead a systematic approach which uses the strength and fatigue reliability as the primary basis (i.e., starting point) for setting the intervals and then draws upon other data such as sampling inspections, critical inspection points, outstanding issues as well as general class requirements to adjust the inspection frequency intervals. The approach couples both the reliability analysis results (i.e., numerical results) with engineering judgment to set inspection interval ranges.

The information required in the development of a Structural Reliability Assessment in RBI plan is significant when compared to the lower level plans. The information includes:

- Vessel Information (vessel historical damage, vessel class fleet historical damage, shipyard construction/conversion inspections and repairs)
- Baseline inspection with comprehensive thickness measurements and connection inspections
- Structural Analysis (SafeHull Phase A and B in the Structural Reliability Assessment (I) case and DLA/SFA for the Structural Reliability Assessment (II))
- Probabilistic Corrosion Rate Models
- Qualitative Risk Assessment (system was broken into tank panels (6 sides of compartment) and risk ranked for fatigue, strength and leak)
- Strength and Fatigue Reliability Analysis Results

Spectrum of engineering analysis

The four case studies vary significantly with regards to developing a foundation for the inspection plan. In all four cases, the class rules are an integral part of a RBI plan. However, how much the risk-based inspection plan differs from the rules is directly related to the foundation of structural analysis and structural reliability developed for the specific asset. This is evident in the comparison of the four case studies.

The Structural Reliability Assessment (II) case represents a risk-based plan that was built upon a first principles approach, incorporating an explicit dynamic load analysis and spectral fatigue analysis of the asset. The analysis utilized the actual as-gauged structure and site environment. This comprehensive foundation of analysis provided the basis for the risk based inspection plan. This level of available analysis provides justification for the variation from the Class rules. This does not necessarily mean that the inspection frequencies and scopes differ more from the class requirements, but rather the basis for the inspections is driven more directly from the structural analysis and structural reliability analysis results.

On the other end of the spectrum, the Screening Assessment has significantly less structural analysis and uses deterministic methods to form the basis for the inspection plan. As a result, the plan has a greater reliance on the class rules.

There is over 150 years of knowledge and experience within the class rules, and in order to justify an alternative from the class guidelines, a significant foundation of structural analysis and structural reliability analysis must be developed. This is illustrated pictorially in Figure 6. The figure shows a qualitative representation of the four case studies and their reliance on the class rules when developing the basis of the risk-based inspection plan. Also shown in Figure 6 is an arrow on the bottom of the figure depicting one of the major advantages of the more comprehensive approach to RBI plan development. With the more comprehensive approach, the inspection plan is able to better account for the site specific variables.

It is important to note that no one plan development approach is necessarily better than another. ABS evaluates the merits of each proposed RBI plan on a
case-by-case basis. Which approach is the best alternative is dependent on the asset particulars, site specific requirements and overall needs of the operator. The case comparisons are intended to provide insight into the level of effort (i.e., analysis) and understanding of the limitations of RBI development approaches.

**Figure 6 Relationship of Class Rules to RBI in the Development of the Four Case Studies**

**RBI Software Program Development**

As part of the development process, ABS has initiated the process of applying the methodology to a software program. This is an ongoing process, and the initial aspects of the software program are presented below for illustration. The presentation of the software is used not only to illustrate the features of the tool but also to highlight some of the challenges in application.

**Architecture of Software System**

The software system is designed to fit in with the flexible approaches to risk-based inspection described above. In order to take the advantage of the flexibility, currently a multi-level methodology is implemented into the software system. In this software system, a user can perform three levels of assessment - screening, degradation, and structural reliability assessments (Figure 7).

The screening assessment is performed to identify the most critical areas. A semi-quantitative assessment is performed using a risk matrix. The assessment results in parts of structure ranked in terms of “criticality”. The “criticality” corresponds to “risk” which is a measure of the likelihood of failure and the consequences of that failure. Two sets of analyses are performed: corrosion wastage and fatigue failure analyses. The first set of analyses is concerned with the usual structural limit states (yield and buckling strength) taking account of corrosion wastage. The second set of analyses is concerned with estimating the remaining fatigue life taken account of damage ratio of ship’s experienced years. The results of the analyses outlined above are then used to perform risk assessments.

**Data Flow of Software Program**

Figure 8 shows the data flow of screening and degradation assessments in the RBI software program. For both assessments, the RBI plan is developed within the traditional survey regime which is subject to the usual statutory and regulatory requirement. Inputs to the RBI program are results from design and analysis studies such as Classification Society Rule calculations, SafeHull, DLA, and SFA. For degradation assessment, time-varying degradation effects will be taken into account and hence associated inputs, such as corrosion rates, will be required.

Two types of output are envisaged. For screening and degradation assessments, the output from the RBI program is a risk score of the components and will be used to select which of a set of structural assemblies or components should be inspected. For degradation assessment, the output from RBI program comprises the time at which the structure will degrade to an unacceptable level.

**Figure 8 Data Flow Chart of RBI Software Program**
Risk Score Calculation

A risk matrix, shown in Table 1 was devised where the risk level is represented on a numerical scale from one to ten. “Likelihood” is characterized as “high”, “medium” and “low” and “consequence” is characterized as “catastrophic”, “critical”, “significant” and “minor”. The risk score is determined by estimating likelihood and consequence.

Table 1 Example Risk Score Matrix

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>high</th>
<th>medium</th>
<th>low</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Consequence</td>
<td>minor</td>
<td>significant</td>
<td>critical</td>
</tr>
</tbody>
</table>

At the fundamental level, likelihood is expressed as a lifetime or annual probability of failure. However, the probability of failure is rarely explicitly calculated. This is because the calculation is computationally intensive and the estimate, in any case, is “notional” rather than “actual”. In general a surrogate representing the probability of failure is used in practice.

In this regard a reasonable assertion is that on average the ratio of predicted peak stress and the allowable stress (usually some proportion of the material’s yield stress) will be related to probability of failure. Similar ratios can be formed for other failure modes: for buckling failure, the ratio would be the predicted peak stress and critical buckling stress, and for fatigue failure the ratio would the design life of the vessel and predicted fatigue life for the component concerned. For present purposes these ratios are referred to as “design ratios”. A design ratio above unity indicates failure. The simplest expression of “likelihood” is by using a matrix in which the “likelihood” is characterized as “high”, “medium”, and “low” in terms of design ratio. For example, the likelihood of plate yielding failure is “high”, if the design ratio of plate yielding strength is greater than 0.85. If the design ratio is in the range of 0.7-0.85, the likelihood of plate yielding failure is “medium”. If the design ratio plate yielding strength is less than 0.7, the likelihood of plate yielding failure is “low”. The precise numerical range is the subject of current investigation and calibration.

In marine structures risk assessments consequence is normally considered in three categories: 1) personnel, 2) environment, and 3) asset. The personnel consequence is related to human injury and fatality. The environment consequence is related to oil leakage leading to environmental pollution. The asset consequence is related to costs associated with a structural failure.

Table 2 Sample Consequence Table for Ship Structures in Four Categories

<table>
<thead>
<tr>
<th>Tertiary Level</th>
<th>Structures</th>
<th>Specific Location</th>
<th>Personnel (P)</th>
<th>Environment (E)</th>
<th>Asset (A)</th>
<th>Total (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deck</td>
<td>Plating</td>
<td>(significant)</td>
<td>Non-severe injury, possible lost time</td>
<td>(significant)</td>
<td>Significant leakage of polluted water/fuel oil into ocean</td>
<td>(critical)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stiffener</td>
<td>(minor)</td>
<td>(minor)</td>
<td>(critical)</td>
<td>Immediate repair</td>
<td>(minor)</td>
</tr>
</tbody>
</table>

Risk Score Aggregation

It order to reduce the scope of the analysis to reasonable proportions the practice is to divide the structure into components rather than treat each and every structural detail. In the RBI software program, the deck and bottom are treated as single components in each tank; side shell and longitudinal bulkhead structures are subdivided in three regions (upper, middle, and lower). For each region, risk assessments are performed to identify parts of the structure where the focus of inspections should be. The risk score calculation of region is performed using the results of strength and fatigue analysis for plates and stiffeners.

The overall risk of region is 90 percentile of risk score of analysis results.

A crude measure of consequence is the proportion of the entire structure that participates in the failure. Generally, a small, localized failure will have a smaller consequence than if a large stiffened panel failed. (Of course the possibility of progressive failure must be guarded against). Applying this kind of thinking to a generic tanker/ship-shaped FPSO structure it appears reasonable to consider structure in three broad categories (as is often done in ship design). Three levels (primary, secondary, and tertiary) of structure component are identified. The primary level of structure includes the hull girder. The secondary level of structure is composed primarily of large stiffened panels. The tertiary level includes plates, stiffeners, and small stiffened panels. A sample consequence of tertiary level of deck structure is shown for four consequence categories in Table 2. From this sample consequence, each of the categories (personnel, environment, asset, and total) has, in general, different levels of severity by structure type (plate and stiffener).

The risk score aggregation of structure component in a tank is summarized and shown in Figure 9 by a fault tree. This tree illustrates the process used in aggregating risk score from individual regions to yield a component level of risk and similarly from components to tank risk scores. This method used to aggregate risk is one of key challenges in combining the results in a form that is useable by those preparing an inspection plan.
Prototype Results of RBI Software Program

Prototype results are shown for both screening and degradation assessments in RBI software program. The subject vessel is a converted FPSO.

In the screening assessment of the RBI software program, the risk score of structure component in a tank is summarized and shown in Figure 10. In wing cargo tank, the structure components include bottom, bilge, side shell, deck, longitudinal bulkhead and hull girder. The aggregate risk score of wing tank reaches critical level. This is induced by side shell component which is identified as critical, requiring immediate inspection or repair. In centre cargo tank, the structure components include bottom, longitudinal bulkhead, deck, and hull girder. The aggregate risk score of centre tank reaches marginal level. This center tank needs to be close monitoring and tracing to avoid the sudden deteriorate condition.

As noted, the advantage of the degradation assessment over the screening assessment is the explicit consideration of degradation of the structure with time. The risk score of tanks is summarized and shown in Figure 11 with the reduction in structural capacity due to corrosion. In the center cargo tank, the risk score doesn’t reach critical level until years 20. The suggested inspection interval of center tank would be about years 20. In the wing cargo tank, the risk score reaches critical level at year 0. The wing tank needs immediately detailed inspection or repair.

Figure 9 Fault Tree of Structures

Figure 10 Aggregate Risk Scores of Two Cargo Tanks
Conclusions

With the maturing FPSO fleet, how to more rationally and efficiently manage the life-cycle integrity of an FPSO is attracting more and more attention.

ABS has developed a multi-level risk-based inspection methodology that is rationally based and flexible to meet the diverse needs of each individual FPSO. The developed risk-based inspection methodology has been successfully applied in inspection planning for some FPSO installations. A wide range of engineering analyses was involved, depending on the needs of individual projects and clients request. Case studies were presented illustrating the spectrum of engineering analysis complexity and flexibility of the RBI methodology. Currently, the RBI software program is continuing its development that will ultimately automate the multi-level RBI methodology to a reasonable level.

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