Fatigue Oriented Risk Based Inspection and Structural Health Monitoring of FPSOs

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ABSTRACT

This paper provides a brief review of the methodological composition of Risk Based Inspection (RBI) and the application of the methodology for safeguarding hull integrity of offshore floating structures, with fatigue as primary degradation mechanism. The work has a distinct focus on the opportunities RBI has to offer in combination with Structural Health Monitoring. In order to provide a clear picture of the state of the art knowledge, the current practices and regulations are briefly discussed after which the RBI methodology is introduced, the differences in guidelines and applications discussed and an 8-step approach is proposed. Subsequently, the methodology is outlined as an instrument for determining the residual fatigue life and the inspection scope and—schedule and the methodological embedding within an Advisory Hull Monitoring System is discussed and proposed.

KEY WORDS: FPSO; Risk Based Inspection; Structural Health Monitoring; Advisory Hull Monitoring System; Condition Monitoring; Condition Based Maintenance; Fatigue; Offshore Structures.

INTRODUCTION

Floating Production Storage and Offloading units (FPSOs) are being recognized as one of the most economical systems to exploit marginal and (ultra) deep-water area’s (Paik and Tayamballi, 2007). With the increasing of the size, complexity and economic interests of these units, emphasis lies on the optimization of design, building and operations in order to achieve high levels of integrity in terms of Safety, Health and Environmental (SHE) factors, and life-cycle capital (CAPEX) and operational (OPEX) expenditures.

FPSO structures pose some difficulties in contrast to traditional fixed offshore structures and trading tankers, as the units have a large displacement volume and are continuously operated under (benign) site-specific environmental conditions, endure high levels of loading and offloading cycles, are equipped with mooring systems and can experience dynamic impacts from sloshing, green water, wave slamming and shuttle tanker collision and lack the ability to dry-dock. In order to safeguard structural integrity, inspection and fatigue lifetime consumption, calculations are required to detect and predict structural deterioration before a possibly catastrophic, polluting and/or expensive failure can result.

FPSO Regulations and Standards

The current practise of safeguarding structural and functional integrity, consist of local regulations, class society rules, flagging national regulations and recommended industry standards and practises. With respect to the latter, several options exist: hulls are designed and constructed according to marine standards and (topside) installations by offshore industry standards and practices. Unlike the snapshot nature of certification, classification is a continuous process by which the class societies survey an FPSO periodically during its operational life to ensure compliance with the rules. Given their unique independent role internationally, classification societies are also often delegated statutory responsibilities by flag and coastal state authorities to act on behalf of the administration (Parker and Grove, 2001).

The extent of compliance with the above mentioned greatly depends on the geographical location of the vessel and the owner c.q. operators perspective and the requirements posed by the class societies. In addition, the rapidly increasing innovation and inherent complexity of ships and offshore structures are posing challenges. As designs, with certain unique aspects in their configuration, do not necessarily mimic those of their predecessors (Serrate et al, 2007). Furthermore, the application of the most recent engineering codes and class society approval standards (DNV 2004/2005/2010) and the fact fatigue analysis copes with multiple variables with large uncertainties and relatively low safety factors - which are unfortunately defined on fatigue lifetime (Kaminski, 2007) - further complicate this particular application.

Hence, an intricate field of requisites exists. The current trend for goal-setting legislation places asset integrity responsibility, and thus the correct interpretation and execution of the applicable directives, by the operators. In the typical approach to design, safety measures are engineered near the end of the design process, leaving add-on control measures to be the only option available. Control measures added late in the design stage require continual staffing and maintenance throughout the life of the asset, greatly adding to the lifetime costs as well as repetitive training and documentation upkeep (Khan et al, 2004). This asks for thorough assessment of all risks posed on the Safety, Health and Environmental (SHE)-factors and the limitation of downtime.
Baker and Descamps (1999) sketch an illustrative example through a change combination of adverse factors for fatigue. For example: higher than anticipated residual stresses and Stress Concentration Factors; higher stress ranges due to a larger structural response for particular sea states; undetected initial defects in highly stressed parts of a weld; the result of undetected gross defects such as misalignments of the joint or poor welding conditions. Furthermore, the authors state that it would normally be uneconomic to try to make the theoretical Probability of Failure so small that inspection during service is completely unnecessary. A more economic solution is to design for a small probability of fatigue failure during the service life and to minimise the likelihood of undetected excessive crack growth, by planning for periodic structural inspections. Such an approach has the added advantage that any fatigue, fracture or excessive corrosion that occurs as a result of gross design or fabrication errors, and in unexpected locations, has a finite chance of being detected before serious consequences can develop. In addition, the use of more refined analysis methods for loads, load effects and strength - than the often simple and conservative ones used in initial design and the collection and validation of fabrication and structural response - can be used to demonstrate smaller safety margins (Moan, 2005).

With the aforementioned in mind, as well as the fact inspection and maintenance are among the few cost factors which could be actively influenced in the short term, and in combination with the recent regulatory fundamental changes yielding to considerably greater responsibilities for the operator of an asset, the demand for documentation and comprehensibility of measures will increase (Schröder and Kauer, 2004). The fact FPSOs are often owned, managed and operated by different parties further adds the need for transparency in Asset Integrity Management of these complex systems. Hence, an adequate framework for ensuring compliance and the inherent documentation is needed. Especially when assets exceed their planned service life and/or are deployed in other than the initial design conditions.

**Risk Based Inspection**

In order to operationalize residual fatigue life-calculations and performance- and compliance based inspection regimes, the quantification and qualification of risks and the affiliated thresholds is essential. Traditionally, design data, historical records, input from ‘comparable’ assets, expert judgment, Non-Destructive Evaluation/Testing (NDE/NDT), (limited) probabilistic modelling and industry and legal standards are used to determine (initial) regimes. After gaining experience from the initial and subsequent inspections, degradation patterns for probabilistic models can be constructed. These models are able to produce estimations and predictions about asset degradation and structural integrity at a specific time in the future.

By linking this understanding of degradation propagation with the classification of the inherent risks of this process and the consequences of failure, a more specific assessment and risk ranking can be made as an alternative for standard (prescribed) practices - which could be unsustainable for a specific asset design and/or operational context (over- or under stringent). This practice is referred to as Risk Based Inspection (RBI), which is defined by Xu et al. (2001) as “A rational framework to estimate failure probabilities (likelihood) and consequences for (sub)systems, to design a specific inspection program to assess the condition of structural elements, disclosure of defects/damage and develop information to improve design, construction, operation and maintenance procedures”. The methodology is partially analogue and complementary to methodologies and programs focused on understanding failure modes, such as the Failure Mode and Effect Analysis (FMEA), as well as assessing and addressing these modes and possible outcomes/incidents (such as Process Hazard Analysis, e.g. Hazard and Operability Studies, HAZOP) and therefore improving equipment and process reliability (API580, 2002). In that perspective the methodology can be seen as a more comprehensive successor of Reliability Centered Maintenance as developed for the aviation industry by Nowlan and Heap in 1978. This methodology is primarily focussed on detecting and preventing functional failure through Preventive Maintenance (PM). In essence, the methodologies are very much alike, however the fundamental principle differs as the reliability centered approach strives towards minimal loss of functional integrity of (mostly) dynamic equipment, while Risk Based Inspection deploys directed inspection effort to most critical components/components, which are identified as representative/comparable to other subsystems on that particular asset to control risk, prevent incidents and maintain a specific safety level.

In essence, RBI is a tool which justifies the allocation of resources to those structural components with a higher risk profile, and at the same time potentially relax inspection activities for low-risk components to optimize and target inspection efforts (Ku et al. 2005). Note that this is a life process and the inspection methods and intervals may change during the assets’ operational life. Hence, it is an asset specific alternative to prescriptive rules (Goyet and Rouhan, 2004). One application, which is becoming more widely used within the offshore industry, is RBI for hull structures (Serratella et al, 2007). Besides the abovementioned advantages, potential savings consist of avoidance of failure and inherent safety consequences, avoidance of loss of production and downtime, timely warning for planning, repairs and shutdowns, early detection of process upsets and better investment management due to enhanced understanding of risk and inspection data (Patel, 2005). Another motivation rises from extended asset usage beyond its intended service life (Horn et al, 2009). The latter is not a new principle, as Moan et al. (1993) and others have shown how the allowable cumulative fatigue damage in design can be adjusted when inspection is carried out, i.e. how the fatigue criterion should depend on the inspection plan.

Other methodological advantages are:

I. Higher levels of equipment reliability, thus asset availability
II. Pro-active and auditable safety management
III. Prioritization and focus on high-risk components
IV. Better justified and estimated life cycle costs
V. Better justified and estimated incident costs
VI. Use of the correct inspection resources, skills, methods and frequency
VII. Avoidance of unnecessary, disruptive, inspection and maintenance
VIII. Avoidance of subsequent damage due to inspection or maintenance activities
IX. Better insight in asset lifetime consumption
X. Enhanced probabilistic modelling
XI. Higher levels of asset knowledge to enhance operational planning and logistics.

It is important to recognise that seeking ways to relax inspection practices is not the goal of establishing an RBI program (ABS, 2003). However, the 2003 UKOOA/Lloyds Register report ‘FPSO Inspection Repair & Maintenance Study into Best Practice’ stated concerns in the following quote: “The impression was gathered during the study that Risk-Based maintenance was seen as an opportunity to reduce the amount of maintenance needed and with minimal effort. This is an inherently unsafe assumption.”

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In addition, difficulties in formulating (computationally) traceable approaches for RBI for systems, most procedures hitherto have focused exclusively on individual components (and hot-spots) or have considered system effects in a very simplified manner only (Straub and Faber, 2005). Hence, when applied to the current best-practises of FPSO inspections, one can conclude that RBI has many beneficial properties, but residual risk remains, as the methodology will not (yet) compensate for:

I. Natural disasters, unanticipated effects and deliberate acts
II. Faulty equipment manufacturing and installation
III. Incorrect or ineffective maintenance execution (e.g. Foreign Object Damage)
IV. Fundamental limitations of inspection methods and performance (API580, 2002)
V. Inadequate, inaccurate or missing design, operations and maintenance information
VI. A demand rate or operating context outside the design envelope
VII. Lack of sound engineering and/or operational judgement and human error
VIII. Deviation from the basic principle of risk reduction
IX. System effects; the inter-dependency of parts, failure modes and mutual dependencies.

A very interesting perspective is, that with more thorough insight, proper data acquisition, -management and -analysis provided by SHM-systems, at least the limitations III-IX can be reduced significantly. Paik and Thayamballi (2007) emphasize that formal safety assessment and other risk-based techniques provide a greatly pro-active approach to safety, because such methodologies are used to identify and evaluate risk areas and then implement cost-effective risk-mitigation and containment measures such as basic design changes, monitoring systems, safety equipment, procedural controls and training. Ergo, RBI and SHM can be used for mutual strengthening.

The model of drivers for predictive maintenance (as constructed by Adams (2007) and graphically represented in figure 1) shows these perceived benefits specifically for Structural Health Monitoring as a methodology for pro-actively managing the structural and functional integrity during the useful life of physical assets: reduction of initial risk after fabrication (1), optimization of the system performance (2), extend asset life (3), reduce the logistics burden without introducing risk (4), manage risk as wear accumulates (5), impact design to reduce risk and conservatism, hence more ambitious design (6). These drivers are key in lowering both the CAPEX and OPEX of assets through enhanced asset design and operations.

The conclusion of the Fatigue and Fracture Committee III.2 (Horn et al, ISSC2009) also highlights the latent need to integrate the functionality of condition monitoring activities and Risk Based Inspection: “The re-assessment of fatigue loading is important and fatigue hotspots need to be re-evaluated, in order to ensure a safe operation. The (class) societies today are working in order to peruse guidelines and recommendations, however there are still several uncertain questions that have to be fulfilled, like to judge if an old unit has operated within the design conditions specified. The fast development of monitoring technology opens new possibilities for continuous recording and new platforms today can be monitored in order to ensure that the unit operates within design conditions specified. However, monitoring of platforms will create tremendous information and one main challenge would be how to analyse the data and draw meaningful conclusions.”.

A promising example can be found in the 2010 Monitas (Monitoring Advisory System) Joint Industry Project, which has concluded and delivered an automated measurement system and data analysis procedure to monitor the fatigue lifetime consumption of FPSO hulls. The background of the Monitas system is described by Kaminski (2007) and the Monitas methodology and application are discussed in more detail by Aalberts, Van der Cammen and Kaminski (2010), L’Hostis, Van der Cammen, Hageman and Aalberts (2013) and Van der Meulen and Hageman (2013).

**RBI for FPSOs**

Currently, very interesting academic and operational research on the specific application of RBI for FPSOs has been performed, which show the application and enhancement of the methodology. Early front-running publications include Skjong (1985), Madsen (1988, 1991), Kaminski and Krekel. (1995) and Ma (1998), with examples of Probability and Risk-Based approaches and inspection strategy optimization. An interesting perspective is sketched in the paper Risk-Based ‘Optimum’ Inspection for FPSO hulls, in which the authors (Xu et al, 2001) also link Probability-based Inspection Planning with Risk Based Inspection and incorporate both event and Probability of Detection updating using Bayes theorem.

The proceedings published by Lassange, Pang and Vieira (2001) focused on the articulation between traditional prescriptive and risk-based approaches and conclude that the basic principle of a methodology to choose between prescriptive regulations and risk-based regulations was preferable in the nearby future. The authors advocate for three specific areas for further research, namely more precise definition of the specific underlying methodological criteria and stakeholder perception on risk-based approaches (1), a more quantitative approach to rationalize the decision process (2) and investigation of the Risk Acceptance Criteria (RAC) to establish the legitimacy of risk-based regulation and facilitate its implementation (3). These constitutes lie at the basis of this paper, which initiates an illustrated example concerning the detailed inspection and maintenance planning for a welded connection in the hull structure of an FPSO.

According to the aforementioned, the methodology can be depicted as emerging, as both the application as well professional and scientific publications show an increase in the last years. Hence, many publications and working documents exist. However, uniformity and coverage of the knowledge-areas as defined by Lassange et al. (2001) is still under development.

![Figure 1: Potential Impact of SHM – Adams (2007)](image-url)
A literature review by the authors revealed several kinds of RBI-references and guidelines, of which the following are of most interest for FPSO-usage:

<table>
<thead>
<tr>
<th>Reference</th>
<th>Author</th>
<th>Title</th>
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<tbody>
<tr>
<td>HSE-363:2001</td>
<td>UK Health and Safety Executive</td>
<td>Best practice for Risk Based Inspection as a part of plant integrity management</td>
</tr>
<tr>
<td>API-580:2002-09</td>
<td>American Petroleum Institute</td>
<td>Risk Based Inspection. First formal RBI-standard for Pressure Vessel Inspection, extended with process piping, storage tanks, rotating equipment, boilers and heaters, heat exchangers and pressure relief devices.</td>
</tr>
<tr>
<td>SSC-421:2002</td>
<td>Ship Structure Committee</td>
<td>Risk-Informed Inspection of Marine Vessels</td>
</tr>
<tr>
<td>DNV-OSS-300-3:2006-11</td>
<td>Det Norske Veritas</td>
<td>Risk Based Verification of Offshore Structures</td>
</tr>
<tr>
<td>CEN-CWA-15740:2008</td>
<td>European Committee for Standardization</td>
<td>CEN Workshop Agreement: Risk-Based Inspection and Maintenance Procedures for European Industry (RIMAP)</td>
</tr>
<tr>
<td>ISSC-V.6:2009</td>
<td>International Ship and offshore Structures Congress, committee V.6</td>
<td>Condition assessment of aged ships and offshore structures, volume 2</td>
</tr>
<tr>
<td>NORSOK N-006:2009</td>
<td>Standards Norway</td>
<td>Assessment of structural integrity for existing offshore load-bearing structures</td>
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<td>Table 1: Primary RBI References</td>
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In addition, the work by Straub (2004) has provided a starting point for directed research into asset specific applications, including FPSOs. An interesting outline of an Integral Risk-Based Inspection planning approach adapted in the offshore industry for the purpose of managing risks related to the operation of FPSOs is presented by Goyet, Straub and Faber (2002). Subsequent case-studies are presented by Goyet, Rouhan and Faber (2004) through a two-part paper on ‘The industrial implementation of risk based inspection planning, lessons learnt from experience’; the case of FPSOs (1) and steel offshore structures (2). Biasatto and Rouhan (2004) applied the methodology to establish an inspection campaign based on RBI and industry expertise for newly-built and converted FPSOs. Lanquetin, Goyet and Esteve (2007) describe the implementation of a Floating Units Integrity Management program consisting of complementary and interacting modules for structural Finite Element Analysis and dynamic mooring models, Inspection Repair and Maintenance planning and scheduling according to RBI and a shared database and Emergency Response Service for damage evaluation. Goyet et al. (2011) introduced a Probabilistic System Approach including economical optimization of the FPSO service life based on a hierarchical model of the hull, which deploys Bayesian Probabilistic Networks to propagate probabilities from component to system level.

The authors state that their findings have been identified early by major oil companies and by Bureau Veritas which, as Class Society, decided to introduce RBI as an option within the Class regime. This is further underlined by the work of other class society representatives, such as the very clear multi-level and flexible RBI approach for FPSOs as presented by Lee et al. (ABS, 2006).

Although RBI for FPSOs is noticeably adopted by all major stakeholders and refined tools for determining Residual Fatigue Life on hull structures with fatigue as a primary degradation mechanism exists, publications on the detailed procedural combination and application are still very limited. Therefor a more detailed case study is proposed.

**Preparatory case study**

The following section consists of a concise description of the RBI-methodology, specifically directed towards hull integrity with fatigue as a primary degradation parameter. Hence, the other dominant degradation systems; corrosion, coating degradation and operational wear and the Ultimate Limit Strength (ULS) and Accidental Collapse (ALS) are not included in this review. Note that inspections constitute the basis of assessing the current asset state. Due to the inherent characteristics of FPSOs, a larger degree of uncertainty exists as compared to front-running industries applying RBI - such as aviation, onshore process/production industry and the (nuclear) power industry. Primary reasons, besides the ones stated in the introduction, are the sheer size and complexity of the units with integrated functionality, production quality, the demand rate and operational context, asset maturity due to the relative low number of vessels in operation, the differences between the assets, a limited level of experiences and the (lack of) sharing of information. This complexity axiom is also referred to as product maturity (Puik et al, 2013) and phenomenological uncertainty (ABS, 2003). Logically, complexity and uncertainty also translate into challenges from a safety case perspective. In the paper ‘A systematic approach to safety case maintenance’ the authors Kelly and McDermid (2001) emphasize upon the need for on-going safety case management as changing regulatory requirements, additional safety evidence and a changing design will challenge the corresponding case.

With inspection as a primary instrument to identify and mitigate system anomalies, RBI can function as a tool to strengthen and update the primary safety case elements for specific functions and structures, as stated by the authors:

- Requirements; the safety objectives that must be addressed to assure safety
- Evidence; information from study, analysis and testing of the system in question
- Argument; showing how the evidence indicates compliance with the requirements
- Context; identifying the basis (e.g. assumptions) of the argument presented.

Hence, the creation of a traditional Deming-cycle (Plan, Do, Check, Act) is inevitable. However, at this moment, the methodological uniformity and consensus on specific details of RBI is not congruent, as the maturity on specific applications of the methodology differs. The literature study showed some key findings to take into consideration:

- Functional decomposition and screening is often not depicted as a separate step. In the authors view, this should be the case to prevent bias before assessing the consequence and probability of failure.
In a number of applications and guidelines, the consequence of failure is assessed before the probability. From an engineering and HSE-perspective it would make more sense to commence with the assessment of the probability of failure right after the functional asset decomposition and then assess the consequences. By determining the consequences first, the determination of the probability can become biased. In addition, why focus on the consequences if the probability is not realistic? This is analogue to the Failure Mode and Effect Analysis as used in the RCM-methodology.

In this approach, system feedback and model updating are separated. As adjusting the inspection frequency due to the detection of e.g. structural fatigue cracks is different than updating the design(tool) of e.g. fatigue sensitive joints with the information gained.

With the aforementioned in mind, a uniform 8-step RBI-approach is proposed for this case study:

1. Determination of the Asset Integrity Policy
2. Functional decomposition and asset screening
3. Assessment of the Probability of a Failure event (PoF)
4. Assessment of the Consequences of the Failure event (CoF)
5. The relative ranking
6. Determination of the inspection programme
7. Implementation, data evaluation and system feedback
8. Conditional Updating of the model.

To provide a clear image, the methodological steps are subsequently outlined hereafter and specific focus-points for the case application are incorporated. Note that this is not an exhaustive overview, but a synopsis for this specific preliminary case. Please refer to the references stated in table 1 for a complete overview.

**RBI step 1: Determination of the Asset Integrity Policy**

With regard to the interpretation of a specific risk, structured determination of the acceptance criteria definitions is key and the following hierarchy is to be considered:

i. (Local) Legal Requirements
ii. The company requirements, which are directly derived from the philosophy
iii. Selection, scope and application of the methodology for a compliant inspection programme
iv. The inspection programme
v. The operational translation.

In general, the Risk Acceptance Criteria consist of the risk towards:

- Personnel health and safety
- Environmental damage
- Economical perspectives

As stated, risk is defined as the product of the frequency for which an event is anticipated to occur and the consequence of the event’s outcome (ABS, 2003). Hence, frequency multiplied by consequence. Note that it is important to realize that compliance with existing prescriptive codes, standards and guidelines may not be sufficient to design, construct, and safely operate production systems. Rather these guidelines must be appropriately interpreted and supplemented for the particular structure, facility and circumstances involved; also, currently available advanced engineering practices, which are based on concepts such as risk or formal safety assessments must be used concurrently as necessary (Lassagne et al, 2001).

The guidelines itself often do not quantify risk as units of loss of HSE or economical measures, nor present these qualitatively. Further in the paper, an industrial example of such quantification is given. Although the use of risk matrices is uprising in several guidelines, such as the OHSAS18002, PAS55 and AIRMIC, ALARM and IRM:2002. Care must be taken that the graphical representation can distort ones image, as the underlying weighting factors are essential. Hence, management systems should be tailor-made as the standard requirements can be objectively audited. However, absolute requirements for HSE-performance beyond the commitments and the level of detail and complexity are a utopia, as the extent of documentation and devoted resources are very dependant of the organizations nature in size, structure, complexity, activities and philosophy (OHSAS18001).

Hence, two organizations carrying out similar operations but having different HSE programme’s can both conform to the requirements, or vice versa. In this perspective RBI is a useful tool, which underwrites and facilitates this perspective and the trend towards Safety Case Management.

**RBI step 2: Functional Decomposition and Asset Screening**

The second step of the methodology provides insight in which specific details are of importance for inspection and arrange for a logical grouping and hierarchy of (sub)systems, functions and interrelations - preferably with a clear reference to the asset tag number system. As complex systems often comprise of several (interrelated) functions. This is also referred to as ‘Grouping and Baselining’ (ABS, 2003) and ‘System Definition’ (HSE, 2002 and Koppen, 1998). In essence, a high-level risk assessment of manageable size groupings (or ‘inspectable units’, such as storage- and ballast tanks, hull sections etc.). Note that this is a practise comparable to the FMEA, but with less detail.

The use of risk matrices to visualize the outcome of the risk screening, enhances the insight through graphical representation of the Failure Probability and Consequences assessment, and offers the opportunity to categorize asset components. In the case of high consequence and/or high probability of failure, more detailed assessment and a preliminary Root Cause Analysis need to be constructed. If the levels of risk are determined unacceptable, the level may be reduced by either lowering the probability or reducing the inherent consequences of failure.

All references and guidelines stress that this requires a trained and experienced multi-disciplinary RBI-team and proper insight in primary structural and operational references, such as design and operational data, construction reports and inspection outcomes, (initial) inspection and survey reports, maintenance and modification (Management of Change) records and incident and event reports (e.g. damage). In general maintenance practices, this asset knowledge acquisition procedure is often seen as one of the most difficult cases in building an expert system due to the consulting of domain experts and translation of an agreed opinion and that from other published works and equipment fault history (Wang, 2003). This step provides the first possibility to assess the Fitness For Service (FFS). Reference guidelines (such as the BS7910 and the API579) and (additional) inspections can be used to determine whether the inspectable units conform to the minimal standards.

For more details including facilitating the interpersonal process of team composition, see the references from table 1. During this process the RBI-team needs to evaluate whether the screening process has provided enough data to base the assessment of the Probability- and the Consequence of Failure on. If necessary, additional detailed inspections and calculations are made. In general RBI practitioners define several levels of actions: from general visual to local NDT inspections, and from simplified fatigue calculations to Finite Element modelling in...
combination with full Spectral or Time Domain Fatigue Calculations,
which can involve full stochastic analysis. Normal practise regarding
hull fatigue deploy a global FE-model in combination with local
detailed (sub)models. The outcome of this phase consists of a list of
asset details for assessment in the next steps.

**RBI step 3: Assessment of the Probability of Failure**
In order to be able to control the vessel’s risk over its service life, the
probability of failure scenarios must be assessed on detail level and for
the whole structure. Failure probabilities may be estimated by
qualitative assessment, from experience data or by quantitative
calculations using more or less refined physical and probabilistic
models (DNV, 2010). The required level of detail depends on the
criticality of the item and the Limit State Function for the specific
deterioration and failure modes, in this case of the hull structure the
Fatigue Limit State (FLS). Note that in risk assessments, failures are
often depicted as the initiating events. In RBI, normally the initiating
event is some form of structural failure due to progressive damage
(ABS, 2003), hence in this case high cycle fatigue.

As stated, one of the primary RBI-limitations for FPSO application is
the availability of reliable data. At this moment, RBI input and
judgement are based on historical data, ‘comparable’ assets, generic
databases such (e.g. OREDA), expert judgement, NDf and limited
probabilistic modelling. Note that Probability of Failure will increase
over time due to time-dependent degradation and the likelihood of
failures may be altered through inspections, repair and structural
modifications as these enhance asset insight and information on
structural integrity. With reference to fatigue cracking, the probability
of failure due to fatigue is determined by a function of the calculated
fatigue life. This determination is often a simplification of a very
complex phenomena - as there are many things to take into account -
such as the degradation mechanisms and mutual influence (such as
fatigue and corrosion), low- and high cycle fatigue, local geometry,
geometrical imperfection and overall workmanship (e.g. fillet welds),
microon and loading conditions and the inherent model uncertainties.
The calculated fatigue life is a measure of probability of the above,
state with Coefficients of Variation. Logically, the details with the
shortest fatigue life are to be considered first and dominant in the
inspection regime. Details of similar engineering characteristics and
subjected to comparable variation can be used as a reference for
comparable details. In order to successfully apply RBI for hull
structures, at least the two below mentioned probabilities need to be
defined and calculated in this step:

1. **Probability of Failure for a specific service life**
The determination of the fatigue Probability of Failure for
fatigue/critical crack size is defined in the following 8 steps and in
general defined for 20 years of service time and fatigue life:

   1. Select the specific hot-spot / fatigue detail
   2. Define the appropriate S-N curve
   3. Define the appropriate Crack Growth model
   4. Define the uncertainty models for both the S-N and FM-
based analysis
   5. Define the calibration parameters in the FM model
   6. Define the calibration criterion, which compares the failure
      probability obtained by the S-N model and the Crack Growth
      model
   7. Calibrate the FM model
   8. Update the estimated Fatigue Reliability Index and stochastic
      model with the fatigue crack inspection results.

The probability of failure using the S-N approach is calculated using
the following (natural) logarithmic failure function:

\[ \ln \left[ \frac{v T}{C_{SN}} q^{m_{SN}} \Gamma \left( 1 + \frac{m_{SN}}{h} \right) \right] - \ln(\eta) \leq 0 \]  

where: \( v \) is the average zero-crossing frequency of stress cycles; \( T \) is
the time in seconds and the moment when the probability of failure is
being calculated; \( C_{SN} \) and \( m_{SN} \) are the S-N fatigue parameters (i.e. the
intercept parameter and the inverse slope parameter, respectively) of
considered joint; \( q \) is the scale parameter and \( h \) is the shape parameter
of the Weibull distribution of far field stress ranges; \( \eta \) is the fatigue
damage limit associated with the linear accumulation hypothesis
proposed by Miner (in general, it is assumed that \( \eta = 1 \); however, \( \eta 
 itself is also a stochastic variable).

Note that equation 1 represents a single slope S-N curve. The
derivations hereafter can be easily extended to the two-slope S-N curve.
However, in this paper it is not done because the equations are
becoming more complex, whereas the calibration methodology remains
the same.

The probability of failure using the FM-approach is calculated using
the following failure function:

\[ \ln \left[ \int_{a_0}^{a_c} \frac{da}{(A Y_g(\alpha) \sqrt{\pi a})^{m_{FM}}} \right] - \ln \left[ C_{FM} T q^{m_{FM}} \Gamma \left( 1 + \frac{m_{FM}}{h} \right) \right] \leq 0 \]

where: \( a_0 \) is the initial crack size and \( a_c \) is the critical crack size; \( Y_g(\alpha) \)
is the geometrical function of considered detail with uncertainty
expressed by parameter \( A \); and \( C_{FM} \) and \( m_{FM} \) are the crack growth
parameters of considered (welded) material.

In general the fatigue life calculations are based on membrane stress,
showing an exponential crack growth, which may result in conservative
estimates (Paik and Thayamballi, 2007). Also, when performing
probabilistic analysis, significant differences in calculated results can
occur due to differences in applied models and/or distributions used for
the input variables (NORSOK N-006). Hence, the stated steps should
be performed under these specific considerations. In general a Weibull-
distribution with shape parameter (0.95) is deployed for the long-term
hot spot stress distribution, such that the calculated fatigue life is the
same as obtained in the fatigue analysis. The appropriate Crack Growth
Model can be selected according to BS7970. DNV CN30.2 or
equivalent guidelines. The next table gives a possible stochastic model,
which can be used for the FM calibration (step 4 in this process).

Basically, steps 5 and 6 of the procedure should consist of calibrating
the FM stochastic model in such a way that the differences between
the probabilities of failure expressed by safety indexes calculated based
on the S-N and FM approaches are minimal over the considered service
time, e.g. lifetime. Usually, the least-squares fitting is applied for this
purpose. A different approach is to minimize the difference between
the probabilities of failure expressed by safety indexes calculated based
on the S-N and FM approaches at the end of considered lifetime. The
authors have concluded that, at this moment, no specific generally
accepted calibration procedures are available.
### Variables and their distributions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Distribution</th>
<th>Mean</th>
<th>Dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S-N )- resistance material properties, e.g. for D class detail</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \log(c^{SN}) )</td>
<td>Stress in MPa</td>
<td>Normal</td>
<td>12.6</td>
<td>s.d. = 0.2</td>
</tr>
<tr>
<td>( m^{SN} )</td>
<td>-</td>
<td>Fixed</td>
<td>3.0</td>
<td>-</td>
</tr>
</tbody>
</table>

### Fatigue limit based on linear accumulation model

| \( \eta \) | - | Log-normal | 1.60 | s.d. = 0.3 |

### FM – resistance material and detail properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Distribution</th>
<th>Value</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_g )</td>
<td>mm</td>
<td>Exponential</td>
<td>0.11</td>
<td>s.d. = 0.1</td>
</tr>
<tr>
<td>( a_c )</td>
<td>mm</td>
<td>Fixed</td>
<td>20.0</td>
<td>-</td>
</tr>
<tr>
<td>( A )</td>
<td>-</td>
<td>Log-normal</td>
<td>1.00</td>
<td>s.d. = 0.1</td>
</tr>
<tr>
<td>( \ln(c^{FM}) )</td>
<td>Stress in MPa, Crack in mm</td>
<td>Normal</td>
<td>-31.0</td>
<td>s.d. = 0.77</td>
</tr>
<tr>
<td>( m^{FM} )</td>
<td>-</td>
<td>Fixed</td>
<td>3.00</td>
<td>-</td>
</tr>
</tbody>
</table>

### Stress range loading

| \( \ln(q) \) | Stress in MPa | Normal | 16.5 | c.o.v. = 8% |
| \( h \) | - | Fixed | 0.95 | - |
| \( \nu \) | Hz | Fixed | 0.13 | - |
| \( T \) | s | Fixed | 20 years | - |

### Calibration parameter comments

- **Stress range loading, \( \ln(q) \)**
  - Applied by ABS and BV in combination with material properties
  - Argued that reflects sequence and non-constant amplitude loading effects
  - Use of mean and/or standard deviation as calibration parameters
  - The authors are of the opinion that loading parameters should not be used as calibration parameters, because they are independent of the selected fatigue approach.

- **Geometrical function, \( A \)**
  - Applied by DNV
  - Use of mean and standard deviation as calibration parameters
  - Use as deterministic parameter (i.e. Fixed distribution type in table 2).

- **Crack property, \( a_0 \)**
  - Applied by Ayala-Uraga and Moan, 2007; in combination with the crack aspect ratio (in this paper the crack aspect ratio has been disregarded)
  - Use of mean as calibration parameter.

- **Material property, \( \ln(c^{FM}) \)**
  - Applied by Straub, 2004; in combination with the stress intensity threshold factor (in this paper this factor has been disregarded)
  - Use of mean as calibration parameter.

### Table 3: Overview of used calibration parameters

The method of Ayala-Uraga and Moan (2007) uses BS7919 Fracture Mechanics data to perform the probabilistic calibration to the S-N curve. The authors disregard the crack initiation time and use mean values of the initial crack size (0.2 mm for an F-joint and 0.15 mm for a C-joint) and concluded that the calibration of bilinear Fracture Mechanics was more challenging and requires calibration tuning based upon two or three parameters. Straub (2004) indicates that several recent studies indicate a 0.1 mm initial crack size for Linear Elastic Fracture Mechanics.

The level of the probability of failure is determined with the use of probabilistic analysis software (e.g. DNV Sesam Probability). Note that due to the nature of the fatigue phenomena minor changes in basic assumptions can have significant influence on the calculated fatigue lives. Thus the calculated fatigue lives are highly dependent on a reliable assessment of the input parameters used in a deterministic approach (NORSOK N-006). The effect of inspection on reliability, i.e. reliability updating, for the bilinear FM-model needs to carried out by means of Monte Carlo simulation, as the first and second order reliability analysis (FORM/SORM) approaches are found to be non-conservative. At this moment, the procedure often consists of the application of FORM/SORM analysis, after which the Monte Carlo method is used to validate the results.

### I. The Probability of Detection

Logically, the Probability of Detection (PoD) of degraded parts depends on the inspection method deployed. In general, the probability of Non Destructive Testing is defined with PoD-curves, which effectively are functions of the defect size:

\[
P(a) = 1 - \frac{1}{1 + (\frac{a}{c^b})}
\]

where \( c = 0.161 \) and \( b = 1.01 \) for Eddy Current testing and \( c = 0.410 \) and \( b = 0.642 \) for Ultrasonic testing. The \( c \) and \( b \) parameters can be determined by fitting a PoD-Curve to the results as recorded in the HSE Offshore Technology Report 2000/018 – POD/POS curves for non-destructive examination (HSE, 2002) and the ICON database (Inter-Calibration of Offshore Non-destructive testing, 1996) or other references and experiences gained. The work by Demsetz and Cabrera (1999) for the SSC-408 - Detection probability assessment for visual inspection of ships - shows the factors and limitations of human inspection and the PoD.

The resulting amount of required in-service inspection is also dependent on how this calibration is performed. Due to uncertainties in the input parameters, probabilistic analyses are found to be attractive for assessment of the reliability of fatigue failures of structures. Here, a distribution of each of the input parameters can be used as input data to the analysis (NORSOK N-006). Note that the target reliability of functional (fatigue) failure for specific functions, hence locations, depends on the mode, nature and distribution of the failure phenomena and available data, the method of analysis and the inherent methodological uncertainties and the structural position and accessibility for in-service inspection. The target reliability is a nominal measure of the acceptable reliability of the structure for a considered failure mode (ABS, 2003).

### RBI Step 4: Assessment of the Consequences of the Failure event

Logically, consequences might have significant impact on HSE- and both economic aspects of which production downtime, production loss, asset (integrity) loss and corporate image are the dominant factors. These include the costs of damage, repair, mitigation and (additional) inspection activities. Special attention must be paid to consequences with additional adverse effects to other system parts and functionality. In addition, note that consequences derived from fatigue factors, hence strength, may implicitly hold substantial impact other than solitary detail fatigue and that the consequence for this specific degradation and failure mode will be fixed during the asset service life – unless significant changes are made in the demand rate or operating context. However, note that detail interrelations and multi-detail crack propagation effects – to areas of other categories and different inspection regimes and/or accessibility – should be considered.
As an example, the following tables depict five classes for the probability of occurrence and the consequences of an incident. The risk is assessed for three categories, with five gradations of consequence severance. The latter is expressed in terms of replacement costs while environmental damage is expressed in terms of oil pollution in barrels (bbl). The severity of consequence in terms of personnel is divided into a number of people exposed onsite and people exposed externally. The number between closed brackets […] denotes the number of fatalities corresponding to the defined consequence level. More examples can be found in relevant guidelines, such as ISO17776:2000 (Offshore production installations - Guidelines on tools and techniques for hazard identification and risk assessment) and the references in table 1.

<table>
<thead>
<tr>
<th>Frequency category</th>
<th>Frequency range</th>
<th>Corresponding severity level</th>
<th>Severity of consequence in Million €</th>
<th>Consequence Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Likely</td>
<td>$&gt;10^{-2}$</td>
<td>Moderate</td>
<td>0.2</td>
<td>Environment range (1,000 bbl)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Personnel onsite range [# of people]</td>
</tr>
<tr>
<td>Unlikely</td>
<td>$10^{-2} - 10^{-3}$</td>
<td>Serious</td>
<td>0.2 - 2</td>
<td>Personnel external range [# of people]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.01 - 1</td>
<td>Personnel range additional criteria [# of people]</td>
</tr>
<tr>
<td>Very unlikely</td>
<td>$10^{-3} - 10^{-4}$</td>
<td>Major</td>
<td>2 - 10</td>
<td></td>
</tr>
<tr>
<td>Extremely unlikely</td>
<td>$10^{-4} - 10^{-5}$</td>
<td>Catastrophic</td>
<td>10 - 100</td>
<td>100-499 [1]</td>
</tr>
<tr>
<td>Remote</td>
<td>$&lt;10^{-5}$</td>
<td>Disastrous</td>
<td>&gt;100</td>
<td>&gt;200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;999 [&gt;2]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;999 [&gt;5]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;1,000</td>
</tr>
</tbody>
</table>

Table 4: Example of Risk Assessment Criteria

The reduction of the consequences is usually performed through mitigation measures and the acceptance criteria derived from the cost and effectiveness of these measures or by design considerations. Hence for fatigue, using a specific Design Fatigue Factor on Lifetime (DFF/DFFL) for fatigue sensitive details. Considerations for this definition are:

- The ability to inspect and repair, e.g. accessibility
- The ability to detect defects, e.g. the possibility/ability for successful Non Destructive Testing
- Detail characteristics, e.g. structural interrelations
- Crack growth characteristics; propagation speed and path
- The outcomes of failure, e.g. risk of explosion, environmental damage and/or product deterioration.

Norsok standard N-006 (2009) states that an acceptance criterion for a connection with a large consequence of failure can be derived from a rule-of-thumb that a DFF of 10 is required in case that there is no access for in-service inspection, inspection is not possible or in the case if leak-before-failure cannot be proven (Andreassen and Valsgård, 2002). Due to the complex structure and the large number of potential crack sites with difficult access, Ayala-Uraga and Moan (2007) suggest an overall larger DFF of 2 to 3. This value can similarly be used as basis for establishing target reliability level for such connections. Naturally, the specific Design Fatigue Factors can be found in the Class Society references, e.g. DNV-OS-C101-2:2011.

**RBI Step 5: The relative Ranking of the Risk**

RBI practitioners should realise that the acceptance criteria itself are high-level oriented on the total asset. In case of the application for specific asset parts (e.g. topside installations, and in this case the hull structure), the acceptance criteria must be made on the same base level for that specific function. Hence, from the Asset Integrity Policy (RBI step 1) a limit-state formulation and acceptance criteria – hence, target reliability level should be made for the identified specific (groups of) parts, joints, sections etc. By deploying the risk as prioritization parameter, the goal of RBI – a better-justified inspection resource allocation is achieved. An important side-note is to use conservative likelihood and consequence values as not all scenarios related to a risk can exhaustively be described. This especially the case during the start, as the data will be limited.

Logically, the relative positioning within the matrix will shift during asset operation, life time consumption, modification and (re)assessments and changes in legal- or stakeholder requirements. Keeping the methodology, the constitutes and outcomes of the analysis up-to-date is challenging, but inevitable to prevent a ‘paper reality’, which doesn’t represent the real-life situation sufficiently.

**RBI Step 6: Determination of the Inspection Programme**

The inspection programme should be constructed according to the Asset Integrity Policy (step 1), manufacturer specifications and formal rules and guidelines as stated under the heading ‘FPSO Regulations and Standards’ and the determined inherent risk. Naturally, inspection execution has to be covered in a preparatory hazard identification (HazId).

The focussed aim of RBI directs effort to the critical locations and defects and more adverse effects of unanticipated degradation, which might compromise the integrity of operations, the asset and the inherent HSE-aspects. In line with the aforementioned, the inspection plan is a life document and initially based on a (conservative) baseline. The forecasting will be adjusted/updated in time with the collection of inspection- and operational data.

The inspection plan should clearly state the components, inspection type/method and nature, focus points and frequency, risk classification, frequency and scope of the inspection and the inherent Probability of Detection and should state a consistent procedure for logging and referring to the data acquisition- and storage, findings, guidelines and the system feedback/updating procedure.

The inspection itself should focus on the detection, sizing of the defect and determination of the propagation rate and the consequences of time-dependent degradation as well as incident-dependent structural damage induced by fabrication, installation or operations (e.g. weld defects, towing- or collision, demand rate induced damage such as loading, but also adverse events such as off-specification product storage).
Experience with the selection of measured variables, location of the measuring points, indication variables and their timely process procedures are important factors and often define a complex context (Schröder and Kauer, 2004). Research performed by Jones (1995) indicated that 60% of fatigue and corrosion damage is detected during routine inspections and 40% accidentally or during non-routine practices. In addition, Paik and Thayamballi (2007) indicate that a major source of NDE data scatter is attributed to operator skill and practical difficulties rather than measuring equipment. So the programme has to be able to deal with these shortcomings through additional measures/monitoring, equipment or refined models.

Hence, it is essential to acknowledge that the reliability of the inspection itself greatly depends on the accuracy of the inspections and the outcomes of the measurements, which also is a trade-off between the level of detail required and the costs. The results can be divided as followed:

- Probability of Non-Detection (False negative, type I error)
- Probability of False Indication (False positive, type II error)
- Probability of Incorrect Sizing

Which are influenced by:

- The engineering/design factors
- Condition/maintenance factors
- Inspector (experience, training, motivation, mood)
- Physical environment (weather, location)
- Procedural factors (assess, crew support, time table)
- Technological shortcomings (e.g. resolution).

Logically, time-dependant degradation can be monitored and further controlled with periodical inspections. The RBI methodology is relevant for all degradation mechanisms such as fatigue, corrosion and wear. However, RBI seems best suited for fatigue degradation since more well established numerical models for crack growth have been developed (DNV, 2010).

RBI Step 7: Implementation, data evaluation and system feedback

In line with step 6, it is important to acknowledge the fact that during implementation and operation the data itself needs to be critically reviewed to relate- and account for the inherent uncertainties, of which the subjoined are most critical:

I. Physical Model Uncertainty: In essence, models are designed as representations of an ‘as-is’ or ‘should-be’ real-life situation. Hence, an approximation, representation, or idealization of selected aspects of the structure, behaviour, operation or other characteristics of a real-world process, concept, or system (IEEE 610.12), i.e. an abstraction. Ergo, there is always an element of estimation and generalization present due to natural variability, inexactness and assumptions made during this process.

II. Probabilistic Model Uncertainty: In line with the physical model uncertainty on which the probabilistic models are based (hence, the change of Error Propagation also exists). Probabilistic Models possess inherent stochastic properties due to assumptions, generalizations and System Effects – the possible influence, hence collaboration among elements due to load- and degradation sharing and interconnected (partial) failure modes.


IV. Statistical Uncertainty: Is introduced due to the use of limited/sample (subset) data to represent and reflect on a wider population. Hence, statistical uncertainty is often a deliberate choice to limit sampling and computational efforts.

The uncertainties stated above should be fed-back into the analysis and the inherent determination of the current risk level, inspection and mitigation activities. Model Based System Engineering (MBSE), which is defined as “A formalized application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases.” (The International Counsel on Systems Engineering, 2007) provides an interesting framework to deal with the increasing complexity in both the modelling as well as to store and analyse the findings and assumptions to improve overall accuracy and provide for the required documentation – which should show an overall understanding of the risk including these assumptions and uncertainties

RBI Step 8: Conditional Updating of the RBI model

It is important to note that there is a fundamental difference between updating of the asset (section) reliability and the model reliability – of which the challenges are stated above. Conditional RBI uses the concept of ‘probabilistic conditional Bayesian updating’ to account for the different outcomes of the inspections, the detection level, the applied equipment and the uncertainties associated with the sizing of the inspection outcome (DNV, 2000) to update the estimated reliability. Logically, as inspection results enhance our knowledge of the structure, these results should be utilized to increase the accuracy of the predictions and reduce the uncertainty. Hence, the initial models can be updated and calibrated with the operational experience.

Interesting publications include the work of Garbatov and Soares (2002), in which the authors propose a methodology to assess the structural reliability of marine structures subjected to the corrosion and fatigue degradation. The authors link the degradation process with the effect of maintenance and inspection and conclude that accurate information about loading conditions, deterioration processes the variation of material parameters as a function of temperature and stress field patterns as well as appropriate test methods for their quantification and inspection methodology should be given. Hence, a clear case for real-time monitoring is made when deploying conditional RBI. In addition, the work by Li et al. (2003) proposes a Bayesian updating method for Probability of Detection of corrosion inspections. Kallen and Noortwijk (2005) have elucidated upon an adaptive Bayesian decision model to determine these optimal inspection plans under uncertainty in deterioration and imperfect inspection. The presentation of Goyet (2010) on Risk Analysis of complex systems with the use Bayesian Networks shows the application of hierarchical Bayesian Modelling for FPSOs.

In addition, Sørensen (2011) introduced a risk-based life-cycle approach for optimal planning of inspections, operation and maintenance based on pre-posterior Bayesian decision theory for deterioration mechanisms such as fatigue, corrosion, wear and erosion under inspection and/or monitoring. The recent publication by Farias and Netto (2012) consists of two case studies on FPSO corrosion damage and shows the application of Bayesian updating, coupled with a nonlinear corrosion evolution model to enable a comparison between actual (measurements) and inferred data. The authors conclude that this comparison is appropriate and the estimates consistent, and state that the Bayesian approach provides a valuable tool for optimizing inspection periodicity.
CONCLUSIONS

The analysis shows that, as an emerging methodology, Risk Based Inspection will claim an inevitable role in determining inspection intervals and cost optimization cases with respect to fatigue degradation for FPSO hulls. Methodological difficulties still lie in the collection of accurate data and the determination of the total accumulated fatigue damage for specific locations. This paper has provided a clear overview of the methodology, references, constitutes and stochastic properties of the S-N and FM models to provide for model calibration and Residual Fatigue Life determination and a preparatory test case.

RBI is likely to dictate future practices on safeguarding structural and functional integrity for FPSOs due to their inherent complex nature and low product maturity. From that perspective, illustrative new situations emerge. In the majority of cases, the shipyards are becoming more aware of the structural hot-spots and take adequate measures to ensure sufficient lifetime. For example, through structural redesign, strengthening, additional enhancement such as coatings, ultrasonic peening, burr grinding and increased quality control. Hence, the design and construction will be optimised for the known problematic details. This implies a shift from the traditional focus points during inspection, towards other, hence new, problematic areas – which asks for adapted approaches to assure structural integrity and regulative and policy compliance.

It is evident that the use of RBI, preferably in combination with an Advisory Hull Monitoring System, will help to deal with the methodological difficulties and the shift in focus areas and (safety case) regulations. The assumption is that, due to the application of AHMS data, the knowledge-basis and RBI-methodology maturity will be greatly enhanced through accurate real-life measured and calculated structural stress and damage to determine the Residual Fatigue Life at a specific point in time for a specific risk level. Ergo, contribute to the fundament on which the methodology was designed for.

REFERENCES


