IMPLEMENTING RISK BASED INSPECTION ON OUR F(P)SOs:
FROM A PRACTICAL APPROACH TO THE EDGE OF R&D
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Abstract
Total E&P operates an increasing fleet of floating production units, most being ship-shaped. They range from converted tankers to new built mega-FPSO projects, see reference [1]. In order to keep these units fully operational from the safety, security, environmental, operational, maintenance and quality management viewpoint our Company has developed a tailor made Floating Units Integrity Management System including hull and mooring models, inspection plan, database management and emergency response on a shared web based system.

HAZOP and HAZID are performed during the design in order to minimize the risks. However during the field life of these complex units, damages to the hull structure cannot be excluded. Due to the comprehensive integrity management program in place, the probability of unseen damage is very low but potential consequences may be important if no cure is made. The hull integrity, with very sound design, will not be at risk but the cost of offshore repair with immobilization of part of the storage capacity may be high.

It is important to assess properly the consequences of these low probability events and to rank the structural components by order of criticality. This is achieved through the implementation of Risk Based Inspection techniques (RBI).

Different approaches have been considered, from qualitative to quantitative, including risk assessments for degradation phenomena such as fatigue induced crack propagation particularly in highly repetitive structure. One unit is used as a pilot for an advanced approach in RBI within a joint industry R&D project.

The paper reviews various scenarios of failures and addresses these issues by analysing on a pragmatic point of view what can be reasonably implemented and achieved.

A multi level approach has been implemented for the integrity management of complex hull structures. These facets of the programme are complementary and inter-act with each other to give the best possible inspection programme. They combine structural models, inspections, fatigue and trend analysis. Risk based inspection when properly applied helps ranking the hull structural items by order of criticality and in turn improving the inspection program.

Purpose of the Integrity Program
The aim of Floating Units Integrity Management is to ensure management and continuous follow up of Floating Units from the safety, environmental, operational, maintenance and quality management viewpoints. It includes recommendations on inspection, maintenance and repairs. This calls for:
1. Structural and anchoring modeling and analysis (1st assessment and subsequent annual re-assessments).
2. Inspection plan and inspection manual, completed by RBI implementation (Risk Based Inspection).
3. Yearly reviews of the unit condition and IRM plan when necessary (Inspection, Repair and Maintenance).
4. Data management and storage (including reports).
5. Assistance for Emergency Response.
6. And gives the framework for exceptional analysis.

Panorama of Floating Units covered by the Integrity Management Program
First priority for implementation of the program has been given to the most important assets, i.e. those being operated by our Company and having the function of storage, and/or production, and/or offloading - in short F(P)(S)U. See references [4] to [7]. These Floating Units can be ship-shaped or box-shaped or any other shape such as TLPs, SPARs, SEMIs, etc. They can be in steel or concrete and can handle various types of hydrocarbon products (oil, condensates, gas, liquefied gases...).

The Floating Units Integrity Management program also applies to the anchoring systems and to the offloading buoys, either coastal (associated with onshore storage) or offshore (associated with offshore field development).

The Figure 1 is a world map showing the location of the present and projected Floating Units concerned in priority by the Floating Units Integrity Management program (due to the lack of space the figure does not show all the loading buoys).
Classifications of the Units and Equipment Falling under the Scope of the Program

Classifications of the units
The Company E&P referential stipulates that the Floating Units shall be classed. This concerns namely:
- All the F(P)(S)Us.
- All the permanent anchoring of these units.
- All the transfer systems (side-by-side, tandem) and all the SPMs (Single Point Moorings like offloading buoys…), either coastal or associated with offshore installations.

The classification offers many advantages like third party investigating the condition of the unit and clear criteria on acceptable degradation limits (e.g. coating failure, corrosion, cracks, and wear in the mooring chains). However, although imposing a prescriptive regulatory inspection program, this will not generally be sufficient to guarantee the integrity of the unit on a long life span. This is the main reason why we have developed and implemented a multi levelled approach for the integrity management of complex hull structures. As an example, the RBI implementation, in combination with structural model (location of hot spots), inspection findings and trend analysis, will better help to define where, when and how to inspect.

The equipment falling under the scope of the program
The equipment falling under the scope of the class is logically the same as those falling under the scope of Floating Units Integrity Management program. However the requirements of the program go beyond the class requirements as they encompass the full life of the floating unit, the risks, the constraints dictated by the absence of dry-docking and the cost of in situ repairs and the implementation of an emergency response. They encompass as well Company general specifications and national regulations.

The topsides (process), risers and submerged transfer lines connected to the Floating Units are not part of the scope because they are very project specific and covered separately by other integrity management programs. However they are taken into account in the models as they interact with the floating unit structure and with the mooring. The topside support structures, mooring / station keeping and the loading / offloading systems are part of the scope.

The specificity of the Floating Units concerned
One of the principal challenges encountered was to define and develop a program applicable to our units, which are as different as converted tankers (FSO, FPSO), new-build constructions (FSO, FPU), a concrete unit (FPU), a refrigerated LPG storage unit (FGSO), and a TLP, all in varied environments and in an extensive range of water depths and anchoring patterns.

In practice, and possibly less so for the TLP, it was soon realised that these different units have a number of points in common, which represent their specificity and justify the development of a specific system of integrity monitoring:
- They are all compartmented (cargo tanks, seawater ballasts, cofferdams) and governed by extremely strict regulations like the ones on intact stability and stability after flooding of compartments. They have specific circuits for pumping the cargo, the ballast, for water treatment, tank washing and inerting, etc.
- A number of international regulations derived from rules specific to oil tankers apply, or are applied voluntarily: prevention of pollution by ships, safety of life at sea, security for vessels coming to load on the units, flagging in...
some occasions, etc. On the whole, the rules of the classification societies apply.
- The Floating Units are generally built on and subject to the rules applicable to shipyards, though little by little we are managing to have our offshore rules prevail in specific designated areas.
- They are anchored or moored in place with anchoring designed in general for the 100 year met ocean return period. The designs are typically: spread mooring, turret mooring, rigid arm or semi-rigid arm mooring, soft mooring with dual hawser..., with different lines compositions and properties.
- Tank inspection and repair is a time consuming task and, in addition to strict safety rules to be implemented, require careful cargo management to avoid creating inadmissible stress on the structure of the unit. In practice this leads to a sometimes important reduction of the operational storage capacity of the unit.
- Offloading: the offloading is generally done on a separate SPM (Single Point Mooring, most common ones being CALM buoys), in tandem or side-by-side and is part of the Floating Units Integrity Management program.

The Floating Units Integrity Management Program

The goals of our Floating Units Integrity Management program
Because of the major role the units play in field production schemes, what we expect of the program is to obtain information:
- On their condition at all times so that we can keep their class certificates valid (all our Floating Units, the mooring/anchoring systems and the loading buoys are all classed).
- Enabling us to predict any aggravation in deterioration to the structure and its mooring system over the long term, and thereby to minimize the risk of failures that require either production shutdown or significant reductions in their operational storage capacity.
- Evaluating through RBI techniques the risk attached to different failure mode scenarios (risk = probability x consequence of failure) in order to identify critical items and rank them by order of criticality.
- That is grouped and shared across the network (sites, subsidiaries, head office expertise and selected Third Party Assistance companies providing models and expertise).
- Permitting a fast reaction whenever problems or emergency situations arise (a graduated appropriate response).

The Figure 2 gives an overview of the Integrity Management.
Tecnitas, a subsidiary of Bureau Veritas, was selected as one of the Third Party Assistance companies for the deployment of the program and execution of the services (assets monitoring as well as exceptional studies and emergency response service). This guarantees the neutrality of the analyses and studies and likewise the choices recommended. The scope of Tecnitas incorporates the RBI implementation on three recent new-built units now under field production.
Description of the program

A detailed description of the Floating Units Integrity Management program is given in references [2] and [3]. The Figure 3 below is a summary of the main elements of the program.

The program is divided into four complementary, interacting modules:
- Structural (FEA - Finite Element Analysis) and dynamic mooring models.
- IRM (Inspection Repair Maintenance): inspection plan/manual and schedule incorporating class inspection requirements and implementation of RBI (Risk Based Inspection).
- Database (plans, results of models: structural analysis and mooring analysis, inspection reports, status of class certificates with expiry dates, etc.), with information shared in a network system.
- ERS (Emergency Response Service) is a service provided by the Third Party Assistance company for a fast and reliable evaluation of stability after damage and of the structure’s resistance under such conditions. The service is available around the clock 24/7.

Communication and collaboration of asset information is identified as a key factor when considering a successful asset integrity management solution. By opting for a solution that is connected with a database and where information is communicated through a networks system one open up the possibility of sharing and communicating the information to a number of interested parties.

As shown in Figure 4 there may be a number of stake holders that may have an interest in accessing the asset integrity management database, either to view stored data or to contribute to the population of data:
- The Subsidiary in charge of the integrity of the assets.
- The Head Office experts (structure and mooring, hydrodynamics, marine, inspection & maintenance, RBI).
- Selected Third Party Assistance companies providing tools and services.

Deployment and first assessment

- For the units already in service, the so-called first assessment concludes the deployment of the four main tasks listed above. The first assessment of the units comprises a complete analysis of the units (history and documentation, structure and mooring models at “as-is” status, design verification, trend analysis and residual fatigue calculations) and a baseline inspection. It gives an accurate picture of the units, serving as a reference for future re-assessments and as a benchmark for trend analysis. In addition the RBI is carried out for new built important assets.
- For units under construction, an “as-built” structural model and corresponding “as-built” documentation are established and an inspection plan is drawn up before delivery. Soon after installation the above in completed by an “as-installed dynamic mooring model” and by the rest of the program.

Yearly re-assessments

- Each year, the database is updated (with inspection reports, thickness measurements, etc.) as are the structural and mooring models that we run. Trend analyses and fatigue studies are undertaken, incorporating the real history of the Floating Unit (load cases, met ocean data, etc.). The effects and consequences of deteriorations in the structure and mooring are evaluated, and structural details are studied. The inspection plan is updated to factor in the new status of the unit.

Exceptional studies may be commissioned, on longevity for instance, for elder Floating Units.

The first assessment is presented during a mission to the subsidiary. The yearly reassessments are reviewed jointly at meetings including the subsidiary, the head office experts and the Third Party Assistance company. The classification society and the contractor (for units on lease) may also take part.

This periodic process represents the so-called integrity management circle for the Floating Unit and is presented on Figure 5.
Implementation of the RBI on our F(P)SOs

Inspection Plan and Manual
The inspection manual gathers to a single document all the information to perform all the inspections of the hull, offloading buoy, anchorings, etc. It incorporates Company rules, vendors’ Operating & Maintenance manual and class requirements.

This very comprehensive document includes:
- Generalities.
- Risks identification studies performed (HAZID).
- A detailed nomenclature of the elements to be inspected. This nomenclature is referred to in the forms for recording remarks and in the 2-D and 3-D isometrics used to locate the elements to be inspected.
- General inspection plan giving for each zone to be inspected the type of inspection: GVI (General Visual Inspection), CVI (Close Visual Inspection), UTM (Ultrasonic Thickness Measurement), NDT (Non Destructive Test), anodes inspection, inspection of hot spots identified after structural analysis, … The nature of inspection to be carried out and the frequency make reference to the rules to be used.
- Specific inspection plan describing each type of inspection to be done as per above (this is also related to the age of the unit: ≤ 1 year, ≤ 2.5 years, ≤ 5 years, ≤ 10 years, ≤ 15 years, after 15 years)
- Control plan: recording of the inspection and of the defects for further action.
- An annex giving:
  a. The schedule for tanks inspections
  b. The reference documents (Company rules, class rules and other rules)
  c. A general note on the FPSO inspections
  d. The list of inspection equipment available on board
  e. The Company pre-visit inspection: each inspection has to be prepared:
     o Hazid
     o Review of the previous inspection reports
     o Reference documents
     o Visualisation of the tank to be inspected with regard to accesses, …
  f. The 2-D and 3-D isometrics used to locate the elements to be inspected as well as all the necessary structural drawings.

An example of a 3-D isometric contained in the inspection manual is given on Figure 6.

An example of a 3-D isometric describing accesses and permanent facilities for tank inspections is given on Figure 7.
An example of drawings prepared for the inspectors for tank inspection is given on Figure 8.

The inspection plan and manual is, at least at the beginning, a prescriptive document. After some experience gained from the operation of the unit, revisions are planned periodically in order to incorporate:
- Corrosion criteria
- Remarks from users
- Results of RBI analysis.

Implementation of RBI

Once the inspection plan is in hand and operational, the RBI (Risk Based Inspection) tool is implemented. It:
- Incorporates the notion of “acceptable risk” (fatigue levels, risk of loss of the unit or of a component/compartment, degradation of the anti-corrosion system, cost).
- Determines/adjusts the inspection intervals.
- Develops and structures the inspection plan (the structural items, the equipment/systems and mooring are ranked in order of increasing risk).

RBI helps determine what, where, when and how to inspect. The RBI tool is built up with data to become increasingly efficient as experience of defects developing on the mooring systems and structures is gradually gained on the different installations.

The various RBI methods we have considered for our complex units span from practical approach to the edge of R&D. This is further detailed hereafter.

Together with the comprehensive inspection plan and manuals just described above, RBI has been implemented on three major F(P)SOs:

**Girassol F(P)SO in Angola:**

2001 (December): Was marked by the starting of oil production on Girassol field (Angola) from a huge spread moored FPSO with an offloading CALM buoy in 1,400 m water depth. In recognition of all the technical achievements, this field development received the OTC Distinguished Achievement Award in 2003. Main FPSO characteristics: size 300 m x 60 m x 31 m, storage 2,000,000 bbls, deck 180 m x 60 m with (initially, before the ongoing hook-up of Rosa field) 25,000 t topsides, 16 mooring lines (cable 1.8 km dia 120 mm with 650 m chain at bottom to 17 m suction piles and 200 m chain to surface), tandem offloading is possible as a back-up of the CALM buoy. The FPSO and Buoy are connected with two 16” steel transfer lines. The FPSO is designed to handle a production of 250,000 bopd. See Figure 9.

**Unity FSO in Nigeria:**

2003: Installation of the new build FSO Unity moored by an external turret on Amenam field (Nigeria) and an export CALM buoy. The FSO Unity is also equipped with tandem offloading as a back-up. Main characteristics of the FSO: hoses 3x24” and one 6” gas line, mooring with 9 chains each 733m long terminated with a 12 tons anchor, FSO size 298,000 dwt, storage capacity 2,400,000 bbls (300 m x 62 m x 32.2 m), water depth 65 m. The FSO is designed to handle a production of 230,000 bopd. See Figure 10.

**Dalia F(P)SO in Angola:**

2006 (December): Was marked by the starting of oil production on Dalia field (Angola) from the huge FPSO Dalia in 1,400 m water (Angola). Main characteristics FPSO: 300 m...
OTC OTC-18563

x 60 m x 32 m, storage 2,000,000 bbls, 29,400 t topsides, water depth 1,350 m, see Figure 11. The CALM buoy is of a new type called buoy turret loading and has been installed for the first time on Dalia. The FPSO and the buoy are connected by two mid-water export flexibles internal diameter 18.5". The FPSO is designed to handle a production of 240,000 bopd. See Figure 11.

The RBI on FPSO Girassol does not include the topsides structures (the coupled structural model describing the interaction between hull and topsides was not available at delivery and is presently under finalization). Dalia being a more recent FPSO has a RBI including the topsides. The FSO UNITY is a particular case because in parallel to implementation of RBI, this unit was used as a pilot for a R&D project consisting of developing a more realistic fatigue methodology in order to provide a better estimation of the inspection periodicity based on RBI results. This methodology, among other specificities, uses loading-offloading sequences from the logbooks for defining realistic loading cases for fatigue calculations (see further below).

Fundamentals aspects of RBI

The RBI methodology is well described in some papers recently published; see references [9], [10], [11]. Inspection planning based on the RBI approach is a rational and cost efficient decision framework for determining:
- Where to inspect
- What to inspect
- How to inspect
- When to inspect

and at the same time ensuring and documenting those requirements with respect to the safety of personnel and environment are fulfilled. Furthermore the RBI approach readily provides guidance on risk reducing measures to be taken depending on the inspection results. The domain of the inspection planning is illustrated in Figure 12 below:

Risk Based Inspection Methodology

General

Reliability and Risk Based Inspection planning for offshore facilities have been an issue of high interest for the offshore engineering profession over the last two decades. Structural reliability methods have played an important role in these developments. Now, basic theoretical framework for RBI and its methodologies including Risk Acceptance Criteria, Risk Screening, Detailed RBI procedures, Inspection Scheduling and Updating may be considered as fully relevant and operational. Consequently, RBI methodologies are increasingly applied by operators and the Company with the objective to establish optimal inspection planning for offshore facilities.

FPSO’s are complex installations in the sense that they include all the different functions of the traditional offshore industry: production, treatment, storage and offloading.

The fact that the production and the treatment of oil and gas takes place on the Floating Unit itself – as on classical oil platforms - leads to particular risks for the system associated with these activities: risk of explosion, risk of incidents and risk of structural damages due to accidental events in the process systems. The risk analysis applied on a FPSO therefore has to account for all sub-systems of the installations:
- Hull structures, topside structures and flare tower
- Process system
- Ship service systems
- Risers
- Turret / mooring structure
- Complementary systems and structures
- Offloading system and offloading buoys.

Classification societies and operators have developed RBI methodologies for the main sub-systems listed above including the process system, the topsides structures (supporting all process equipments) and the hull part. At the time being, RBI applied to topsides structures is not included in the Floating Units Integrity Management program for the Girassol FPSO where RBI was first applied, see reference [8]. However it is included in the recent FPSO Dalia. A paper specially devoted to the RBI for topsides structures is presented in this conference (paper OTC 18912, see reference [17]), gives an approach for RBI applied to topsides structures and shows how this approach was applied to the new built FPSO Dalia.
The inspection planning and maintenance problem is complex not only due to the large number of parameters involved in the RBI problem (as shown on Figure 12) but also due to:
- The complexity of the units
- The enormous amount of components needed to be considered
- The theoretical framework used for the risk analysis.

These three kinds of complexity are solved:
1) Using an “unified approach”,
2) Using for each system/sub-system a stepwise approach,
3) Using the decision theory as the basis for the risk analysis.

The RBI approach is a unified approach
For an offshore operator responsible for the safe operation of an entire installation it is important that the overall facility specific requirements to the risk to personnel, environment and economy can be verified and documented to the relevant authorities. A prerequisite to this is that the risks for all types of equipment and systems are assessed on a compatible and consistent basis. This implies that the fundamental modeling of failure modes, treatment of uncertainties and applied methodology for the quantification of risks should be uniform in this respect. The basis for defining a unified approach can be found in references [10], [12].

The RBI approach is a stepwise approach
Offshore hydrocarbons production facilities are complex within the context of RBI not least due to the large diversity of equipment they consist of, but also due to the enormous amount of different components that needs to be considered. It is therefore a requirement that the working process when conducting RBI analysis for such facilities is very structured and targeted in view of the objective: assessing and controlling risk. Consequently, the RBI approach as developed by Bureau Veritas is a stepwise approach as shown on Figure 13:

The main steps of the RBI approach are the following ones:
- Collection of information
- Risk Acceptance Criteria
- Risk screening
- Detailed RBI
- Scheduling
- Inspection
- Updating according to inspection results.

Risk Acceptance Criteria:
A RBI project is initiated by identifying the overall target to be achieved by the inspection plans, namely the acceptance criteria. The acceptance criteria form the basis on which the decisions are made for future inspection and maintenance activities. Given the overall risk acceptance criteria for the installation as a whole, the acceptance criteria are derived for the various components in the installation. It is checked which of the three different acceptance criteria - risk to personnel, risk to environment and economical risk - gives the strongest requirement to the acceptable annual failure probability and this is selected as basis for the determination of the inspection plan.

Collection of information:
One of the first tasks in any RBI project is to collect all available information concerning the systems and components to be considered. It is assumed that for structural systems the available information includes: design resume, construction and installation resume, baseline inspections, operations and maintenance history.

Risk screening:
Risk screening is performed on the basis of the established information. The overall purpose of risk screening is to establish an overview of the facility, its systems and components with regard to their contribution to the risks and prevailing degradation mechanisms. This is carried out in accordance with the acceptance criteria. Risk screening then facilitates an identification of those systems and components which need no further detailed RBI assessment and allocates them for either regular corrective maintenance activities or monitoring depending on the characteristics of the degradation process and the consequences of failure.

This risk screening process cuts down the number of components for further consideration. The considered facility is divided into subsystems and components. For each of these the consequences of failure together with the probability of failure are assessed qualitatively or semi-quantitatively depending on the information available. Selection of those components which need more detailed assessment is based on these probabilities of failure and these consequences of failure.

For structural systems, normally fatigue and corrosion are the relevant issues. Details with a fatigue life higher than 10 times the design service life do not, in general, require detailed RBI analysis. Areas, with potentially critical structural details but where no information is available regarding design fatigue lives, are identified for further fatigue analysis during the detailed RBI.

Figure 13: RBI approach is a stepwise approach
Detailed RBI:
Detailed RBI is explained in the section devoted to Decision Theory. Detailed RBI is based on quantitative models for degradation mechanisms and has been mainly developed for the fatigue degradation phenomena. Crack propagation models used refer generally to the Paris’s law. Similar effort is on going for developing quantitative models for corrosion.

Scheduling:
Having identified the cost optimal inspection plans for all considered components of the facility, these inspection plans are co-coordinated and organized in order to achieve an overall optimal inspection schedule under consideration of the:
- Availability and capacity of the inspection contractor
- Impact of inspections on the operation of the facility
- Logistics
- The rule based specifications for inspection plans as given by the relevant classification society.

Finally, the inspection planning may be rearranged in order to account for the impact of information obtained from inspection of one component on the risk of others.

Inspection:
Based on inspection manual and/or handbooks, inspections are performed.

Updating according to inspection results:
Based on inspection results, inspection plans are updated in case of defect finding.

The RBI approach is based on the Decision Theory
The inspection and maintenance planning process – as applied to the most critical components selected for detailed RBI analysis - is formulated as a problem where the overall service life costs are minimized. The pre-posterior analysis from classical decision theory provides a consistent and systematic framework for its solution. A short summary is given here, closely following Faber et al., see reference [10].

The inspection decision problem may be represented as shown in Figure 14. With reference to Figure 14, the parameters defining the inspection plan may be collected in $e=(△t, l, r)^T$ where $△t=(△t_1, .., △t_N)^T$ are the intervals between the times of N inspections $t=(t_1, .., t_N)^T$, $l=(l(t_1), .., l(t_N))^T$ are the locations to inspect at the inspection times $t_i$. Finally $r=(r_1, .., r_N)^T$ defines the reliability (quality) of the planned inspections.

The inspection results are uncertain due to the fact that they depend not only on the uncertain performance of the inspection itself but also on the uncertain state of degradation. The uncertain inspection results (Figure 14) are modeled by the random vector $S=(S(t_1), .., S(t_N))^T$ in which the individual components refer to the results obtained from the inspections at the different locations $l(t_i)$. $d(s)$ is a decision rule defining the repair action to take depending on the inspection results. Finally $υ$ is the realization of the uncertainties $θ$ influencing the state of the system.

The utility associated with the inspection plan and the repair decision rule is denoted $u(e,s,d(s),υ)$ and the optimal inspection may be determined as the plan that maximizes the expected utility $u$. Usually the utility function may be readily associated with the service life costs and the optimization problem can be reformulated as a cost minimization problem.

![Figure 14: decision tree as a basis for inspection planning](image1)

Practical applications of this theoretical framework, in particular simplified and generic approaches, may be found in reference [9]. The quantitative detailed RBI is also illustrated on Figures 15 to 18 below.

![Figure 15: decision tree associated to a specific inspection plan](image2)

![Figure 16: Optimal inspection plan under reliability constraint](image3)
the annual probability of component fatigue failure. Inspection
new optimization parameter which is the threshold value of
inspection itself. This is illustrated on Figure 16.

This simplified approach is illustrated on Figures 17 and
18. Figure 18 gives a “model example”: the optimal value for
the annual probability of fatigue failure is $10^{-3}$ and the
corresponding times for inspection are 4, 7, 11 and 15.

RBI State-of-the-art and further developments
- The Bureau Veritas RBI methodology and the Bureau
Veritas RBI approach statement as described above are
fully operational and constitute the BV RBI Services
Offer which may be used in isolation or fully integrated in
the Floating Units Integrity Management program
described in the previous sections.
- In parallel, a RBI R&D effort is also running with the
objective to improve continuously the BV RBI Services
Offer and to answer to new challenges in terms of
inspection and maintenance of offshore installations. This
R&D effort is done in partnership with the Company.

The two next sections give general information about RBI
as applied to FPSO Girassol and FPSO Dalia (state-of-the art)
and to FSO Unity (on going R&D effort).

RBI as applied to Girassol and Dalia units

**Fatigue analysis for RBI**
The RBI procedure requires fatigue calculations among which
Fatigue Design Factors (the “FDF’s”) are the most important
output. The FDF of a specific component is the ratio between
its fatigue life and the service life. For example, if the fatigue
life is twice the service life, then the FDF is equal to 2.

Review of hull fatigue computations for FPSO Girassol
concludes that fatigue lives on site are high. The conclusions
came from RBI fatigue computations where conservatisms
were removed as far as possible and on site loadings were
used instead of North Atlantic waves. These computations
led to a more refined fatigue knowledge and showed that
fatigue life in all tanks under investigations is high (see Table
1 which indicates that all FDF values are higher than 5). Thus,
structural details inside these tanks were not selected for
further detailed quantitative RBI computations. Qualitative
risk based inspection were performed instead. From the
fatigue point of view, the most critical area is located on the
deck, at the main support frame of the integrated deck.

Fatigue computations for RBI were performed as follows:
Preliminary fatigue calculations using MARS software (midship section) for identifying the most critical areas.

Refined fatigue calculations using VERISTAR based on fine and very fine meshes models.

Results are given on Figures 19 and 20 and Table 1.

**Figure 19: MARS software (Girassol midship section)**

<table>
<thead>
<tr>
<th>Nº</th>
<th>Frame</th>
<th>Location of details</th>
<th>On site fatigue life</th>
<th>FDF</th>
</tr>
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<tr>
<td>1</td>
<td>Fr62</td>
<td>Toe of backing bracket, stricker 1</td>
<td>&gt;1000</td>
<td>&gt;5</td>
</tr>
<tr>
<td>2</td>
<td>Fr63</td>
<td>Bottom longitudinal 17</td>
<td>870</td>
<td>&gt;5</td>
</tr>
<tr>
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<td>Fr64</td>
<td>Bottom longitudinal 17</td>
<td>345</td>
<td>&gt;5</td>
</tr>
<tr>
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<td>Fr65</td>
<td>Bottom longitudinal 17</td>
<td>310</td>
<td>&gt;5</td>
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<tr>
<td>5</td>
<td>Fr66</td>
<td>Side shell longitudinal L59</td>
<td>175</td>
<td>&gt;5</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>Side shell longitudinal L60</td>
<td>230</td>
<td>&gt;5</td>
</tr>
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<td>7</td>
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<td>585</td>
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**Table 1: Fine mesh fatigue analysis results using Veristar Software**

**Figure 20: side shell longitudinal and transverse web**

Similar results were obtained in RBI fatigue calculations performed on the FPSO Dalia and again no quantitative detailed RBI was undertaken as explained above.

This kind of results is Girassol and Dalia specific. It is expected that similar results will be observed on new-built FPSOs or recent-built FPSOs where high provisions were included at the design phase. But, the conclusions are different for other type of units as for example conversions. In that case, lower fatigue lives are generally expected and quantitative detailed RBI is required for defining inspection plans.

It has to keep in mind that RBI approach for fatigue is not identical to design approach. In design calculations only the assumed most critical elements are checked for fatigue. In RBI, fatigue calculations are extended to a significant set of representative components of the hull. This is due to the fact inspection planning using RBI requires fatigue lives of a significant set of components for defining the periodicity of inspection of each component.

Although not required, some components of Girassol and Dalia were analyzed in detailed RBI for demonstration.

**Qualitative RBI**

Qualitative RBI as applied on Girassol and Dalia FPSOs was led via three specific meetings between Bureau Veritas and the Company.

- The first meeting was a corrosion meeting where all aspects dealing with corrosion were reviewed by the operator and the classification society:
  - Factors influencing corrosion degradation.
  - Expected corrosion rates in the various areas of the units.
  - Type of painting and expected painting lifetime.
  - Other corrosion protection systems as sacrificial anodes.
The second meeting was a consequence meeting where all consequences of failures (fatigue, corrosion) in terms of operability and availability of the units were investigated. The third meeting was a consequence meeting where all consequences of failures (fatigue, corrosion) in terms of risk of fire or explosion were investigated.

The Figures 21 to 23 give an illustration of the process.

The effective lifetime of a protective coating system depends on a significant number of factors:

1. The substrate
2. The environment
3. Surface preparation
4. The quality of the paint
5. The choice of generic types of paint, and their combination into a coating system
6. Application. Not only the workmanship and the equipment, but also the micro-climatic conditions during application and while paint dries and/or cures
7. The overall thickness of the coating system

Figure 21 Factors influencing the effective lifetime of a protective coating

Figure 22: Scenarios used in the Girassol consequence analysis study (1/2)

Figure 23: Scenarios used in the Girassol consequence analysis study (2/2)

Scenarios on Figures 22 and 23 are the following ones:

1. Through crack in outboard longitudinal bulkhead: Oil and water ballast tanks are in communication.
2. Through crack in centre line elevation: oil tanks in communication.
3. Through crack in upper deck plating: air at deck level and oil tank in communication.
4. Through crack in transverse bulkhead in way of two water ballast tanks: two water ballast tanks are in communication.
5. Through crack in side shell (water ballast tank) above splash zone.
6. Through crack in side shell (water ballast tank) underwater.
7. Through crack in bottom in oil tanks.
8. Through crack in oil tight bulkhead: two oil tanks from different holds in communications.

These scenarios were used as a background for conducting the two consequences meetings. Particular attention was devoted to repair procedures and their consequence on operations, with the objective to avoid significant interruption due to structural failures. One of the advantages of RBI is clearly to focus maintenance of structural integrity to most risky points.

Results of qualitative RBI were merged with the inspection manual previously mentioned for defining the “final” inspection plan and manual. As a consequence, the “final” inspection plan incorporates:

- Company rules,
- Vendors’ Operating & Maintenance manual,
- Usual class requirements,
- and RBI requirements.

RBI development on Amenam unit

R&D effort was conducted on the FSO Amenam with the objective of developing a more realistic fatigue methodology in order to provide a better estimation of the inspection periodicity based on RBI results. This R&D effort was undertaken in the framework of the French CEPM project “Optimization of the inspection program of FPSOs” (CEPM = Commission d’Etudes Petrolieres Marines):

- Fatigue due to static loads variation induced by the loading/unloading of the FPSO (which is generally not studied in the standard procedure) has been combined to the “standard” fatigue due to dynamic wave loads (see Figure 24). It is to be noticed that fatigue due to static loads variation may be significantly greater than fatigue due to wave loads for FPSOs located in sheltered/tropical waters.

- Logbooks from the unit were used and a representative set (more than three months) of loading and offloading sequences were analyzed in detail. “Rainflow counting method” was applied to static loads variation and 8 fatigue loading cases were established, significantly different from the ones used for the design. These 8
loading cases represent the actual loading-offloading sequences, which correspond to the operational conditions. This procedure is probably more rigorous but can be implemented only once the unit is in regular operations (perhaps 6 months or 1 year after the first oil time).

- Based on the 8 previously determined fatigue loading cases, fatigue calculations were performed using fine and very fine meshes models as shown on Figure 25. Fatigue calculations were performed on a set of 6 details judged critical by the fatigue team of the Classification Society.

- Fatigue damage accumulation using “Rainflow counting method” was performed by combining the fatigue damage due to loading-offloading sequences and the fatigue damage due to wave cycles.

Figure 24: Stress ranges due to wave cycles and stress ranges due to loading-offloading sequences.

Figure 25: Coarse, fine and very fine meshes for fatigue calculations.

Risk Based Inspection and Classification
Classification Societies have rules for obtaining and maintaining the class notations. But the necessary requirements for maintaining a certain class and the condition control requirements applied to traditional marine transport systems cannot be applied directly to facilities such as FPSO’s. This is due to the lack of dry-docking facilities for inspection, verification and repair - FPSO have to be inspected and maintained while in operations - , as well as the operational constraints (loading and offloading cycles). Also, FPSO’s are relatively new concepts for which there is no tradition and limited experience. Thus, the application of traditional rules for classification of trading ships cannot be directly extrapolated to FPSO’s. For these reasons, there was a great pressure from offshore operators, including the Company, for new rules for design and also new rules - based on optimization procedures derived from specific risk assessments - for inspection and repairs to be developed and applied to FPSO’s.

Facing this demand from industry, BV as Classification Society:
- Established Rules for the classification of offshore units, see reference [16],
- Implemented Risk Based Inspection (RBI) methodologies and also full RBI services including technical offers with RBI teams as supports.

Rules for the classification of offshore units mention (see reference [16], section 2.6.1 of the rule): “As an alternative to the full application of the present prescriptive rules, a hazard analysis approach may be used to justify deviations or modifications from rules requirements”. As a consequence, Bureau Veritas supports the general trend from prescriptive rules to risk based rules. This may lead to increased inspection scope when risk levels are found higher than in the class rules or might be lower than the rules requires for low risk components.

At the time being, inspection requirements recommended by BV are either the prescriptive requirements from the rules or a set of requirements including both prescriptive requirements from the rules and risk based requirements from RBI. In the future it is expected that full RBI regime will be established as alternative of the regime based on the usual prescriptive rules.

Lessons learnt from experience
Lessons learnt from experience deal with submission & quotation, execution and organization.

Submission and Quotation
Additional fatigue calculations are generally required
The initial idea, see reference [12], was to use fatigue calculations performed at the design stage (new-built) or at the conversion stage. Experience gained by the author’s show that very often new fatigue calculations have to be performed. It was the case of the two FPSOs studied in this paper. It was also the case of all units recently analyzed in RBI by the authors (see for example reference [13]). This is due to three main reasons:

- In some cases available fatigue calculations are not sufficiently documented. It is therefore difficult to achieve the two first steps of detailed RBI procedure (stress calibration, fracture mechanics model). Stress calibration, for example, cannot be done if no information dealing
with SN Curves is available (type of SN Curve and/or stochastic description of the two parameters m and K).

- Design and RBI philosophies for fatigue calculations are not the same. At the design stage, FLS (Fatigue Limit State) checking deals with only the most critical components. If the usual fatigue criterion is satisfied for the most critical components, then the other ones – less critical – will be satisfying the fatigue criterion. In RBI analysis, FDF values for all details selected for the cost optimization procedure (the so called “detailed RBI”) are required for establishing inspection plans. Even if fatigue calculations for RBI are limited to a representative subset of components, the number of components in this subset will be larger than the size of the subset of details analyzed for fatigue at the design stage.

- Assumptions done for fatigue calculations at the design stage may be invalid when RBI analysis is undertaken. In the case of FPSOs, for example, assumptions dealing with draughts in initial fatigue calculations did not correspond to the operational draughts finally determined by the loading/offloading procedures.

RBI database has to be discussed during the submission/quotation phase
RBI databases will usually contain all information dealing with inspection planning of the unit. That includes:
- Detailed RBI inspection plans and manuals.
- Final inspection plans and manual after scheduling.
- Inspection results and mitigation actions in case of detection of defects.
- Updating of inspection plans in case of detection only or in case of detection followed by some repair/mitigation action.

Inspection plan and manuals - as described further above in the paper –, handbooks and RBI databases are the operational deliverables of any RBI study.

Execution

Collection of basic information, tag lists, equipment lists, is an important and difficult task and therefore should not be underestimated.

Collection of information and risk screening where basic information is also collected are important tasks, usually – until now – underestimated (see also reference [14]). The objective of these two tasks is to reach a comprehensive understanding of the unit with the objective to select appropriately the set of components to be analyzed further in detailed RBI and to assemble all input data required for detailed RBI. Difficulty comes from the fact that information is usually available in various teams located at the owner (the Company), the shipyard, the consultant or the engineering companies. Centralized document control/management is consequently a must.

Detailed RBI has to be kept flexible and opened to adaptations/modifications if required
Detailed RBI should be able to be run in various configurations:
- Constant threshold plans where inspection times are determined as a function of the maximum annual probability of component fatigue failure, which is kept constant over the service life.
- Variable threshold plans in the case of two periods with different policies in terms of Risk Acceptance Criteria (policy of a first Classification Society when the unit acts as a tanker, policy of a second Classification Society when the unit acts as an FPSO).
- Equidistant plans where inspection frequency is kept constant over the service life.
- Several periods of time where damage rates are specific, including inspection feedback if available (FPSO/FSO in case of conversion)
- Optimization of modifications/reinforcements during the conversion using a comparison between RBI plans established either with modifications/reinforcements or without modifications/reinforcements.

Scheduling aspects have to be investigated and developed in the future:

Modifications of inspection times:
In that case, it should be checked that Risk Acceptance Criteria are always fulfilled. It will be the case if inspection is anticipated. It could also be the case for postponing if the optimal value for the annual probability of fatigue failure is lower than the component Risk Acceptance Criteria. But we have to keep in mind anticipation or postponing modifies the initial RBI planning. This question of anticipation/postponing, which may also be a demand from the operator, is a part of research needs for the coming period.

Determination of inspection campaigns:
When we are facing to two or more different sub-structural parts of the unit, determination of inspection campaigns may be difficult to achieve. In general, each sub-structural part – each cargo or ballast tank - has to be considered as a specific entity. Problems linked to the determination of optimal inspection campaigns deal with:
- Technical constraints for performing inspection,
- Availability of inspection teams,
- F(P)SOS availability in terms of production rate and loss of production,
- Usual inspection procedures in terms of gas freeing, ventilation, cleaning,
- Loading and offloading procedures.

System effects:
The so-called system effects in inspection planning are due to the fact that some of the uncertainties (probabilities) as well as the consequences are not independent from one hot spot to another (e.g. detection of a defect at one hot spot increases the probability of finding a defect at a similar location). Although these observations in general are well recognized, they have rarely been taken into account in quantitative RBI analysis. Some interesting considerations about system characteristics may be found in reference [15]. One of the most important characteristic may be expressed as follows: Information obtained at inspections and from observed failures, due to
correlation effects in the models of the degradation process, contain information about the condition of non-inspected hot spots. The previously mentioned problem addresses one of the most important but also the most challenging system characteristic to include in the inspection and maintenance planning framework. This problem is a part of research needs in the coming period.

Organization

There must be a continuous and good communication between the experts of the Company and the experts of the consultant

The cooperation between the client and the Company (the “owner”) is illustrated in Figure 26.

![RBI workflow diagram]

Figure 26: RBI workflow

Open minded attitude to appreciate and solve new problems during the project is required.

This open-minded attitude has already emphasized when fatigue calculations, detailed RBI and scheduling were examined. Due to the fact that:
- each unit is specific;
- objective and constraints may be very different from one unit to another and may also vary in time.

RBI specialists will in general facing new problems. Therefore, an open minded attitude is required for solving these problems.

Conclusions

The Floating Units Integrity Management program that has been described is a complete, methodical program specific to our Company, which can adapt to a wide variety of designs and operating conditions.

The paper has highlighted the need of having complementary approaches and sources of information to continuously assess the hull condition, degradation modes and trends for such complex hull structures permanently subject to direct action of waves and changing loading patterns.

The models, inspection programs, data management and trend analyses system are, together with the Emergency Response System, the corner pieces set in place for periodically assessing the condition of the Floating Units and enabling us to take action at any moment in time.

Although sound designs and continuous monitoring of the units are implemented, various degradation modes including corrosion, cracks and fatigue still may occur during the life span of the unit with ranges of consequences to be assessed through risk analysis techniques.

To address these low probability events associated with potentially high consequences; RBI is implemented allowing identifying the most critical structural components and ranking them by order of criticality. The RBI allows adapting an initially prescriptive inspection plan in view of the objective “assessing and controlling risk”. It does not mean automatically less inspection but it allows, together with the structural hull analysis highlighting hotspots and together with the previous inspection results and trend analysis, a better definition on what, where, when and how to inspect in order to assess that the acceptance criteria are fulfilled throughout the service life of the units. The RBI ensures that the risk remains as low as reasonably practicable.

For complex structural units like FPSO hulls with relatively low statistics on failure probabilities, different approaches have been considered for the RBI, from qualitative to quantitative. There is no conflict between these two types of approaches and both – qualitative and quantitative – are usually used together in RBI studies. Quantitative methods are recommended for the most critical components – if any – because modeling of degradation using quantitative degradation models (crack growth propagation models for example) allows defining optimally inspection times and updating the inspection plans using inspection results (crack length or crack depth). Finally R&D effort is required for improving the existing inspection procedures for example taking into account the registered loading-offloading sequences from the logbooks as it was done for the FSO Amenam.

Acknowledgements

TOTAL Subsidiaries must be acknowledged for their contributions; the names of the Floating Units they operate, which are more specifically concerned with the implementation of the RBI, have been included in the paper and illustrations.
Figures

Figure 1: Location of the units concerned by the integrity management program
Figure 2: Integrity Management overview
Figure 3: The four main tasks of the program
Figure 4: Web-based shared database
Figure 5: The integrity management circle
Figure 6: Example of 3-D isometric for a tank inspection
Figure 7: Example of 3-D isometric for tank access and permanent facilities in place for inspection
Figure 8: NKP (concrete) FPU Gas – Congo
Figure 9: Example of drawings prepared for the inspectors for tank inspection
Figure 10: Girassol FPSO (Angola 2001)
Figure 11: New built FPSO Dalia with topsides installation completed 11 June 2005 for Dalia field (Angola)
Figure 12: Risk Based Inspection domain
Figure 13: RBI – Constant threshold approach
Figure 14: Decision tree as a basis for inspection planning
Figure 15: Decision tree associated to a specific inspection plan
Figure 16: Optimal inspection plan under reliability constraint
Figure 17: RBI – Constant threshold approach
Figure 18: An example of the constant threshold approach
Figure 19: MARS software (Girassol midship section)
Figure 20: Side shell longitudinal and transverse web
Figure 21: Factors influencing the effective lifetime of a protective coating
Figure 22: Scenarios used in the Girassol consequence analysis study (1)
Figure 23: Scenarios used in the Girassol consequence analysis study (2)
Figure 24: Stress ranges due to wave cycles and stress ranges due to loading-offloading sequences
Figure 25: Coarse, fine and very fine meshes for fatigue calculations
Figure 26: RBI workflow

Table 1: Fine mesh fatigue analysis results using Veristar software

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