RISK BASED INSPECTION ON F(P)SOs’ HULLS: CASE STUDIES ON NEW BUILT UNITS

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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 complex units fully operational from the safety, security, environmental, operational, maintenance and quality management view points, our Company has developed and implemented a multi level approach for the integrity management of complex hull structures. This approach combines structural and mooring models, inspections, fatigue and trend analysis. A database shared through a networking system and an Emergency Response Service have been implemented as well.

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 or all of the storage capacity may be high.

It is therefore 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). When properly applied RBI helps improving the inspection program of existing units and the design of future new built units.

Different approaches have been considered, from qualitative to quantitative, including risk assessments for degradation phenomena such as fatigue induced crack propagation and corrosion. The paper reviews cases studies where RBI has been recently implemented for the hull part of new built FPSOs.

AIM 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, LPG, LNG...).

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

The Fig. 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 / offloading buoys).

CLASSIFICATION OF THE UNITS AND EQUIPMENT FALLING UNDER THE SCOPE OF THE PROGRAM

Classification 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 system.
The topsides (process), risers and submerged transfer lines connected to the Floating Units are not part of the scope because they are covered separately by other integrity management programs. However they are taken into account in the model 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 units 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 hawsers…, 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), 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 (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, affiliates, 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 Fig. 2 gives an overview of the Integrity Management.

![Integrity Management overview](image)

Tecnitas, a subsidiary of Bureau Veritas, was selected for the two new built units used later in the paper to illustrate case studies on RBI implementation. Tecnitas contributes to the content and deployment of the program and to the monitoring of the units in order to guarantee the neutrality of the analyses and studies and likewise the choices recommended.

**Description of the program**

A detailed description of the Floating Units Integrity Management program is given in references [2] and [3].

The Fig. 3 below is a summary of the main elements of the program.

![The four main tasks in the program](image)
The program is divided into four complementary, interacting modules:
- Structural (FEA - Finite Element Analysis) and dynamic mooring models.
- IRM (Inspection Repair Maintenance): inspection plans / manuals and schedule, status of class certificates with expiry dates, and implementation of RBI (Risk Based Inspection). See references [9], [10].
- Database (plans, results of models, inspection reports, class status, etc.), with information shared in a network system.
- ERS (Emergency Response Service).

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 network system, one open up the possibility of sharing and communicating the information to a number of interested parties. As shown in Fig. 4 there may be a number of stakeholders 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).
- Third selected Third Party Assistance companies providing tools and services.

**DATA MANAGEMENT ON THE WEB-BASED SYSTEM**  (VeriSTAR AIMS / DNV FLCM)

- Secured web Application
- Controlled access using passwords
- Users:
  - Subsidiary / Offshore Site
  - Head Office Experts
  - Third Party Assistance company
- Floating Unit Integrity Management:
  - Data Base
  - Inspection plan
  - List of maintenance operations
  - List of comments
- Class activity follow-up
  - Upcoming inspections
  - Certificates
  - Class reports
- Class activity follow-up
  - Upcoming inspections
  - Certificates
  - Class reports

**Figure 4: Collaboration of information scenarios**

**How the program works**
The program is run as follows:

**Deployment and first assessment**
- For the units already in service, besides deployment of the four main tasks listed above, a “first assessment” is made, comprising a complete analysis (history, 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 condition of the unit, serving as a reference for future re-assessments and for trend analyses. Additionally 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.
Yearly re-assessments
- Each year, the database is updated (with inspection reports, thickness measurements, class status, 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, encountered met ocean conditions, 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 in Fig. 5.

![Figure 5: The integrity management circle](image)

The above part of 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.
Various degradation modes including corrosion, cracks and fatigue may occur during the life span of the unit and analysis of risk is an integral part of the monitoring elements in place like structural models, inspection plan and trend analysis. This is described now in the second part of present paper.

APPLICATION OF RBI- BUREAU VERITAS APPROCHES TO RBI
BV (Bureau Veritas) has developed for years RBI methodologies for structures. This includes up to now jacket structures, topside structures and hull structures.

Range of applicability of RBI
Basically, Risk Based Inspection planning aims at defining optimal inspections and repairs (tools, content / extend, frequencies, etc.) based on risk analysis. In such analyses, one may consider three main regions for risk levels: negligible, ALARP (As Low As Reasonably Practicable) and intolerable. For structural component with intolerable risk level, design is to be reviewed and corrective action taken. It is meant here that inspections will not solve the problem or eventually at high expenses for those structural items which intolerable risk level. For ALARP risk level structural components, RBI fully applies, i.e. the risk level of the component is reduced As Low As Reasonably Practicable through inspection / repair effort. For structural component with negligible risk level, GVI (General Visual Inspection) during planned inspections or regular overall survey might be sufficient. In that case, regulatory regime applies and might be relaxed to some extend.
Several approaches for evaluation the optimal inspection plan may be used, depending on the risk analysis approach used. Two main approaches are used in RBI analyses:

**Quantitative approach**
The quantitative approach is used when the relevant degradation mechanism can be assessed by physical models, i.e. for fatigue and crack propagation, to a less degree corrosion. These physical models have their own limits that is for crack propagation for example, high or low crack propagation rates need for other models. The use of probabilistic models of degradation phenomena is of great benefit: the probabilities are computed with a reduced level of uncertainty compared to qualitative approach, and Bayesian updating taking into account inspection quality is also part of the probability evaluation. Example of experience in quantitative approaches is presented reference [11].

**Qualitative approach**
This approach is well suited for components where damage is not directly quantifiable or when boundaries of quantitative models are reached. Then, probabilities and consequences are assessed by expert judgement through several meetings, using HAZID and HAZOP sessions. The risk level of failure is then established and structural components are ranked according to it.

These both approaches have often to be mixed together to provide the overall inspection plan of the unit, as presented on Fig. 6, see also reference [12].

![Figure 6: RBI merging quantitative and qualitative approaches for fatigue](image)

**Combination with Class requirements**
Classification societies have their own rules for classification, and in-service survey of units is part of it. The rules are based on the past experience of the society, IMO and IACS requirements, etc. Consequently, rules have a prescriptive regime, which is usually enough for ships. For F(P)SOs, feedback is important but limited to a short period in time, see reference [8]. Thus offshore rules developed by classification societies tend now to highlight the specificities of offshore units. Compared to those usual ships, F(P)SO units do not go dry dock periodically for inspection and repairs, and thus must be inspected and maintained while in operations. Another strong point is that the interruption of operations on these units or reducing the operational storage capacity for tank repairs has a high economical impact. Thus avoiding unnecessary interruption due to structural failures is a key point from the optimal maintenance point of view. This is an advantage of the RBI over usual rules to adapt to the unit: the objective of RBI is to focus maintenance of integrity to most risky points.
The Offshore rules from Bureau Veritas leaves the opportunity for Risk Based Inspection applied to F(P)SOs to justify deviations or modifications from Rule requirements. 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.

**CASE STUDIES**

In this section, two case studies are presented on the implementation of RBI for the FPSO Girassol and the FPSO Dalia, both located offshore Angola in deep waters. The FPSO Girassol is a 2,000,000 bbls FPSO moored in 1,400m water depth, with a 300m length overall, 60m breadth and 31m depth. Its deck is 180m x 60m and supports 25,000t of topsides modules (this was before the ongoing hook-up of Rosa field). The FPSO is designed to handle 240–250,000 bopd and to operate for a time period of 20 years. See Fig. 7

![Figure 7: FPSO Girassol Angola (1st oil 2001)](image)

The FPSO Dalia is a 2,000,000 bbls FPSO moored in 1,350m water depth, with a 300m length overall, 60m breadth and 32m depth. Its deck is fitted with a set of 12 process modules, 6 pipe-rack modules and 2 manifold modules. The total weight of the topsides is 29,400 tons. The FPSO is designed to handle 240–250,000 bopd and to operate for a time period of 20 years. See Fig. 8 (the photo shows the completion of topsides installation on 11 June 2005).

Fig. 9 shows a half view of the structural model of the FPSO Dalia used for fatigue analyses for RBI purposes.
Figure 8: FPSO Dalia Angola (completion of topsides installation 11 June 2005, 1st oil 2006)

Figure 7: Half view of the complete FPSO Dalia ship model used for fatigue analyses
Inspections and repairs on these units are of prime importance given the daily oil production rate. A RBI study has been undertaken for the structural part of the units: this includes the main tanks of the hull and (for Dalia) the topsides structures as well.

For Girassol, for which the RBI implementation started first, the scope of the RBI study is bounded to the hull structure:
- The hull tanks for RBI include 12 crude oil storage tanks and the 12 water ballast tanks, 2 slop tanks, 2 methanol tanks and several cofferdams.

Dalia RBI covers:
- The hull tanks for RBI include 12 crude oil storage tanks, 12 water ballast tanks, 2 slop tanks, 2 methanol tanks and several cofferdams / void spaces.
- The topside structures for RBI include 12 structural modules, process & piping excluded.

**RBI for the hull**

The RBI of the hull, two degradation processes are considered:
- Corrosion.
- Fatigue.

Considering Fatigue, fatigue lives taken as from design are found to be very high. This is due to the fact that design conditions are for North Atlantic sea conditions that the FPSO may encounter during the long towing from the shipyard to the field but also to build more strength with regard to fatigue life. Thus probability of fatigue failure is very low. This is a very favorable key point regarding the fact that dry-docking is not possible for these units.

Some fatigue analysis of details using fine mesh models are shown on Fig.10.

**Figure 10: Fatigue analyses of a bottom longitudinal and bracket tip for Girassol FPSO**

Consequences where assessed by means of “consequence meetings”. A set of failure scenarios is first prepared for the meeting. This consists in performing a screening of the potential failures with foreseen high consequences. Second, the meetings take place. The participants of the meetings are the operator (operational & design people) and the engineering team in charge of the RBI study. Then, based on the past experience on similar units and on the way the unit will be operated, the consequences of the pre-determined failure events are determined. This includes the direct consequences and also the indirect consequences. All of these are assessed regarding the 3 usual criteria:
- Consequences to personnel.
- Consequences to environment.
- Consequences to asset.
Impact on production is often seen as the primary driver for consequences, the other risks levels being generally low from the structural point of view. During the meetings for both units, hot work repairs were found to be critical issues regarding operation on the unit.

Then risk values are established and compared to a set of the risk acceptance criteria for inspection. This criterion aims at ranking the components in a set of groups of components with corresponding inspection frequencies. These will be then harmonized with other items.

Considering corrosion, RBI focuses first on inspection of barrier to corrosion to identify early stages of degradation (example: Dalia is new and Girassol is 5 years old). This includes painting and cathodic protection by means of anodes or ICCP system for the external hull. In a second step, when plates with degraded barrier are discovered, during routine or planned inspection, prevision on degradation speed is performed using quantitative probabilistic model or, if sufficient records are available in a longer period of time, trend analysis is performed as well. Consequences of degradation of plates by corrosion are assessed during the “consequence meetings”, and a “corrosion meeting”.

This later meeting focuses on corrosion management and inspection. The risk is evaluated and compared to risk acceptance criteria set for inspection, and next inspection / is planned. This task is developed on the basis of a set of zone definition where corrosion is likely to occur. Several zones are defined as shown on Fig. 11 and correspondingly several scenarios of failure of coating, cathodic protection and corrosion are assessed.

![Figure 11: Typical zone definition for corrosion on FPSO hull](image)

**RBI for the topsides structures**

The RBI for topsides structures mainly focuses on the fatigue degradation phenomena. The first idea is to use fracture mechanics models with generic database of probability of fatigue failure. If this way of processing is valuable for ships structural details, which are almost repetitive, it is actually really another matter for structural details of topsides structures. There is a wide variety of beam welded connection from the design, with sometimes lots of complexity. The whole representation of the topsides for DALIA is presented Fig. 12... It is found not practicable to use full quantitative approach, providing full degradation models for each type of structural detail. Thus a semi-qualitative approach has been used.

This approach is based on available fatigue data and event trees where typical scenarios of topsides structural failure are represented, see Fig. 13.

Based on this event tree, on the existing quantitative risk analyses, the probabilities and consequences of terminal event are evaluated. The consequences were assessed by means of “consequence meetings” using this time process flow diagrams. This is a mandatory step, which aims at providing consequences of structural failures on the topsides and then the
consequences on personnel, environment and asset, given fatigue failure of a structural component. Then risk values for each relevant detail is determined and put into a risk matrix. This matrix uses several thresholds to define the inspection frequency as a function of the risk level.

All this work is to be performed for each module and includes module interaction as well. The work performed for the topsides structures is described in another paper, reference [10].

Figure 12: Computer model of topsides structures of FPSO Dalia for RBI analysis.

Figure 13: RBI for topside modules, typical event tree for structural failure

RBI as a stepwise approach
Offshore hydrocarbon 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 Fig. 14. The inspection plan as output of the RBI analysis is then entered in a computer database system as part of the Asset Integrity Management System. Following an inspection campaign onboard, the RBI is re-run and the database is updated accordingly. See Fig. 15.
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 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 a 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” (ensuring that the risk remains as low as reasonably practicable). It does not mean 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.

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

The paper shows how the methodology is applied and the strategy that has been chosen to provide an optimal inspection plan for these units, including both the hull and the structure of topsides modules, and how it is integrated into a more general Asset Integrity Management program.

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REFERENCES