STRUCTURAL ASSESSMENT OF CONVERTED FLOATING STORAGE UNITS

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**ABSTRACT**

This paper describes the hull structural assessment process for evaluation of single and double hull tanker designs in the context of conversion into future FPSO systems. The relevant design aspects of the hull structure are also analyzed. Typical designs have been selected and Hull Girder Strength and Primary and Secondary Structural Components are analyzed regarding yielding, buckling and fatigue strength aspects. The typical defects and the main degradation modes based on the return of experience with tankers are also discussed in order to evaluate the different hull structure designs.

**KEY WORDS**

Design; conversion; steel renewal; structure assessment; fatigue; corrosion; refurbishment.

**NOMENCLATURE**

FPSO  Floating Production, Storage and Offloading system  
FSO  Floating Storage and Offloading system  
HTS  High Tensile Steel  
IMR  Inspection, Maintenance and Repair  
MARPOL  International Convention for the Prevention of Pollution from Ships  
MIC  Microbial Induced Corrosion  

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INTRODUCTION

Although we see a shift towards new-build FPSO’s, in particular for developments in harsh environment conditions, conversion seems to remain the basis for several projects in areas where benign environmental conditions are predominant, such as West Africa, Southeast Asia and Brazil. The possibility of fast track schedules to have an early first oil date is also an important parameter in the decision process for selection of the floating unit type of hull: converted or new-build.

Data concerning VLCC tankers built between 1973 and 2004 have been reviewed in order to identify the main types of oil tankers still operating and that may be available for FPSO conversion projects. In-service VLCC tankers can be divided into two main groups: single hull and double hull tankers. Single hull designs have been in general delivered until 1995. Despite the first projects in the early 90’s, most double hull tankers have been built after 1995, following MARPOL resolutions 13F and 13G.

The various aspects concerning the hull design characteristics and review of the ship’s historical information, including operation conditions, maintenance procedures and records of survey and inspections are reviewed based on Bureau Veritas and the industry experience on oil tankers. We thus identify the main parameters to be considered during the hull selection process and the refurbishment work required to fit the structure for conversion. The experience from previous FPSO conversion projects is also considered and the several steps necessary to achieve the hull structural assessment are described in the paper, incorporating the lessons learned from these projects.

OIL TANKER MARKET

Approximately 56% of the tankers built between 1973-2004 are double hulls and 43% single hulls. One of the main characteristics of a single hull design built after 1985 is the extensive use of HTS. Figure 1 shows that there are few tankers built between 1973-85 still available for conversion into floating units. Consequently, single hull and double hull tankers built after 1985 and 1995, respectively, are natural candidates for conversion into FPSO. Table 1 indicates that the decision making process to select the hull will balance between the expected higher cost for refurbishment of a single hull at conversion and the higher cost to purchase a double hull tanker. In 2004, approximately 45 FPSO’s operating had the hull built before 1985, 4 between 1985-95 and 1 after 1995.

Figure 1: Oil Tankers Operating (2004)
<table>
<thead>
<tr>
<th>Year</th>
<th>Oil Tankers – Average Sale Price (m USD)</th>
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<tr>
<td>Ships operating</td>
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<td>185</td>
</tr>
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</table>

**TYPICAL OIL TANKER DESIGNS**

For analysis of the different types of hull designs, oil tankers have been subdivided into three main categories described below.

**Single Hulls (mid 70’s - 1985)**

Such vessels are relatively cheaper and their primary and secondary structures tend to be stiffer than in hulls built after 1985, when high tensile steel began to be used extensively. A number of different designs can be identified, comprising American, French, German, Swedish and Japanese standards among others. The industry has good experience with oil tankers and an extensive list of areas prone to defects due to stress concentration and corrosion is given by the Tanker Structure Cooperative Forum (1986, 1992, 1997). Nevertheless, it is well known that the occurrence of corrosion and other defects might vary according to the shipyard design, fabrication standards, workmanship and the operation and maintenance procedures adopted during the trade period.

There are a number of differences and particularities inherent to each shipyard design, but one of the most important characteristics is the primary structure arrangement. Generally two main types of structural arrangement are noticed:

- Longitudinal ring stiffener system comprising deep girders within center and side tanks, supporting the transverse bulkheads horizontally stiffened. There are no horizontal stringers.
- Horizontal system comprising in general four stringers within center and side tanks, supporting the transverse bulkheads vertically stiffened. In general a longitudinal ring is provided in way of the center line girder.

Fatigue was clearly not the main concern in the design of connections of primary and secondary elements for such type of vessels, but in some way, it seems to have been compensated for with a stiffer structural arrangement, larger corrosion margins and less use of HTS. During this period, oil tankers were built worldwide in different shipyards, some of them having poor fabrication standards.

**Single Hulls (1986 - 1995)**

The structure design of such ships was optimized by means of finite element calculations and the extensive use of HTS to reduce the weight of steel. The hull structure design has used ST355, ST315 and ST235 steel types in different manners, in particular in the side shell plates, stiffeners and web frames. Some of them are built using only HTS in the cargo area. The use of HTS, in particular in the side shell area around the neutral axis, was found to be one of the main causes of problems associated to this type of vessel. Fatigue cracks of side shell longitudinal connections to transverse primary structures are probably the most typical defect of such designs, as fatigue strength of side shell longitudinals and corrosion margins are affected by the less stiff structural panels at bottom and side shell areas.
Side shell panels built with ST355 have an extensive record of defects and likely have been reinforced with additional brackets after construction. Another important parameter is the use of asymmetric profiles, i.e. angle stiffeners in the side shell and bottom panels. The use of angles at those locations having high probability of failure should be especially considered when evaluating candidate hulls for conversion: in particular, when associated with the use of steel ST315 and ST355.

**Double Hulls (1996 and forward)**

The double hull milestone is 1998/99, when new builds experienced a sharp increase and typical Japanese and Korean shipyards have been consolidated as the main references on double hull designs. In the same way as for single hulls, the Tanker Structure Co-operative Forum (1995) has published guidelines listing the areas prone to defects due to stress concentration and corrosion. But again the occurrence of corrosion and defects vary according to the shipyard design, fabrication standards, workmanship and the operation and maintenance procedures adopted during the trade period. Nevertheless, such designs profit from improvements on fatigue assessment methodologies, design of connection details and fabrication standards over the past 10 years.

Different from the second category of single hull tanker designs, ST355 is almost no longer used and typical steel distribution combines ST315 at bottom and upper deck areas with ST235 around the neutral axis areas. The latter with, in general, a percentage not less than 30% of the total cross section.

Double hull designs have the number of structural connections increased up to 15% due to the inner bottom and side longitudinal bulkhead stiffener connections to the transverse floors and web frames, where despite the easier access for inspection, might increase the inspection effort of critical joints during the FPSO service. Double hull tankers have an optimized hull design, in general with less than 5% margin in comparison with the class requirements, in particular at lower areas of the transverse section. Asymmetric profiles, such as angle stiffeners are again one of the most important aspects regarding fatigue strength for side shell longitudinal end connections. The use of angles, in particular at those locations having high probability of failure, should be specially considered when evaluating hulls candidate to conversion.

Vessels built after 1997 have a similar structural arrangement. One of the most significant differences between such designs is the position of the cross-ties, fitted either within the center cargo tanks or within the side cargo tanks. It is noticed that for the first one, the side shell and the lower hopper structures used to have higher deflections. It means that special attention

![Figure 2: Steel Arrangement – Double Hull (left) and Single Hull (1986-95) (right)](image-url)
should be paid to side and inner shell longitudinal stiffeners connections, horizontal girders and hopper connections with the inner bottom and inner hull structures.

For designs where the cross-ties are fitted within the side cargo tanks, side shell structure deflections are decreased and stress levels are expected to be reduced. On the other hand, longitudinal bulkheads are expected to have increased deflections, in particular at alternate loading conditions where center tanks are filled full and side tanks are empty. Therefore, special attention should be paid to the inner longitudinal bulkhead connections and in way of horizontal stringers.

**FPSO TYPICAL PROBLEMS**

There are approximately 97 FPSO’s and 74 FSO’s in operation or available worldwide (International Maritime Associates 2004). Over 60% are conversion projects and some have experienced structural anomalies and defects. Deterioration processes such as fatigue and corrosion were initiated during the tanker trade period and will be present during the FPSO’s service life, although they may be present in a different degree of intensity.

A number of FPSO’s have been converted on the basis of the Classification Society rules requirements, unless additional requirements were specified by operators. This means that inspections at conversion were carried out within the scope of Class Renewal Survey based on a 5-year cycle, where substantial corrosion of structural components was verified in accordance with applied rules. Surveys were carried out in order to identify anomalies and defects, and necessary repairs were performed in order to bring the structure to as-built configuration.

The problem with such an approach is that the durability of the hull structure is not properly assessed. As a consequence, these units might be subject earlier to substantial corrosion of the structural components of the structure, increasing the risk of buckling and fatigue. The following consequences may be divers, comprising low and major events if proper mitigation actions are not taken:

- reduction of storage capacity,
- non planned shutdowns for repairs,
- dry-docking for major repairs,
- structural failure, and
- leak of oil, consequently risk of pollution and explosion.

The most common anomalies found in converted FPSO’s are the following:

- excessive pitting of horizontal structures,
- substantial corrosion (grooving)
- knife edging, and
- cracks due to fatigue.

Cracks due to fatigue result from a combination of several parameters. The trading history of the vessel, site specific conditions (for harsh environments) and high stress ranges experienced during the loading and offloading cycle in the FPSO service are the main reasons. However, there are cases where poor detail designs, a low standard of workmanship and corrosion of welded joints accelerate the occurrence and the significance of these defects. Some of the most common are found in the following typical locations:

- transverse brackets at transverse ordinary frames,
- end of horizontal stringers,
- end of cross ties in way of the side shell and longitudinal bulkhead web frames, and
- end of longitudinal stiffeners in way of bulkhead penetrations and ordinary web frames.

The damage accumulated during the trading history of the vessel uses to be the most significant part of the total cumulated damage comprising tanker and FPSO phases, in particular for ships operating in severe environments such as the North Sea and North Atlantic areas. Cumulated fatigue damage due to wave cycles for an FPSO operating in benign environments such as West Africa and Brazil (Campos Basin) are in general less significant when compared with a harsher environment. For this case, the fatigue damage due to sea load may be of the same order as that observed during the tanker trade period.

The fatigue damage caused by loading and unloading cycles during FPSO operations can be also estimated and cumulated with the damage due to wave cycles, but in general the number of cycles associated to the shuttle tanker arrival is low,
consequently the cumulated damage is in general negligible. On the other hand, the effect of the loading and unloading cycle due to differential head on the oil tight bulkheads and side shell panels may lead to high stress ranges, especially in poor detail designs. Crack propagation analysis shows that the loading sequence may accelerate the growth of cracks initiated during the tanker trade period (Otegui and Orsini 2004).

**HULL EVALUATION**

Evaluation of VLCC candidates for conversion into FPSO’s may include a significant number of parameters concerning the characteristics of these vessels. The first step is to evaluate their adequacy regarding the basic requirements of the FPSO conversion project, which are associated with the field development. Storage capacity and the cargo tanks arrangement (number of tanks, subdivision, etc) are some of these parameters. One of the most important and difficult aspects to be evaluated is the effective service life of the unit, which must meet the required service life established based on the field estimated life.

Engineering assessment of the overall and local hull structure strength against yielding and buckling criteria has been quite successful for the majority of the FPSO projects. However, experience shows that an accurate assessment of the main deterioration modes of these components is a major challenge, in particular concerning fatigue and corrosion deterioration. Fatigue is related with cycle loads (due to wave and cargo loading-offloading), the structure stiffness, structural detail design, shipyard fabrication standards, workmanship and corrosion rates. The hull condition is linked to operation and maintenance aspects in such way that the condition of a specific vessel might not be the same as for a similar ship operated by different owners and in different trades. Therefore, the FPSO design life will be directly affected by the fatigue damage and corrosion wastage cumulated during the previous tanker phase.

Ideally, design review and assessment of the hull condition should be supported by a detailed inspection of the entire hull structure before selecting the vessel to be converted. A hot spot map of the hull structure, derived from a detailed hull structure assessment based on finite element analysis, is also useful for evaluation of the different hulls, although it may not be available in the early stage of the project development. Therefore, the various aspects concerning the hull design characteristics need to be reviewed in a more qualitative way, as the hot spot areas may differ for each studied vessel (Figure 3).

![Figure 3: FEM Analysis for Evaluation of Different Designs (Von Mises stress).](image)

Figure 13 above illustrates Von Mises stress distribution for two different designs along the Midship section. It is used to estimate yield criteria for ductile materials, calculated by combining stresses in two or three dimensions, and compare to the tensile strength of the material loaded in one dimension.

As a minimum scope, the tanker selection process should include for each vessel the review of the following data:

- as-built drawings: looking for detail designs prone to fatigue, percentage of HTS, corrosion additions, etc.;
UTM Reports and survey and inspection records to identify corroded areas and typical defects: look for typical defects due to fatigue, high stressed areas and buckling. Check for substantial corroded areas; repair specifications in order to evaluate; extent of scantling renewal due to substantial corrosion along the tanker service; mitigation of defects, including repairs, modifications and strengthening undertaken on board; operation and maintenance practices (type of oil, temperature, washing, corrosion protection, etc); and review of tanker trading history: tankers operating in severe weather are prone to have fatigue related problems.

Critical areas within the tank structure can be defined as locations that, due to stress concentration, alignment or discontinuity, need particular attention regarding construction, design and survey aspects. In general these locations can be divided in two main groups:

- connections of the longitudinal ordinary stiffeners with transverse primary supporting members (transverse bulkheads and web frames), and
- connections of primary supporting members.

**Ordinary Stiffener Connection with Transverse Supporting Structures**

It is through these connections that the loads are transmitted from the secondary to the primary structure members. These details are subjected to high cyclic loading through the ship’s life and they constitute one of the areas most subjected to potential fatigue problems. Repair of such details may affect the tanker refurbishment schedule, as the work required to repair, renew and strengthen these details is in general more significant than the required weight of steel.

The following parameters are considered the most important ones regarding fatigue strength of such connections:

- the location and the number of brackets (on one or both sides of the transverse primary member),
- the shape (soft toes or not) and the size of the brackets,
- the longitudinal stiffener profile (symmetrical or not),
- the misalignment of the webs of longitudinal ordinary stiffeners,
- the use of HTS in the side shell plate, stiffeners and web frames, and
- the details of slots and collar plates.

The different types of ordinary stiffener connections with the transverse web stiffeners, and how the change of type of connection may increase the fatigue strength of the detail by reducing the stress concentration factor is illustrated in Figure 4.
often fitted with single brackets. In cases where HTS is extensively used, backing brackets are fitted in way of ordinary frames along the hull length at conversion into a FPSO.

The following parameters were found to be the most significant regarding fatigue strength of side shell longitudinal connections and increased fatigue life:

- double brackets reduce stress concentration factors,
- type of steel: ST235 construction leads to stiffer structures around the neutral axis; on the contrary, ST315 and ST355 lead to less stiff structures,
- symmetric profiles avoid lateral bending of longitudinal stiffeners; angle profiles lead to lateral bending, and
- shaped brackets and flat bars reduce stress concentration factor, however, fatigue life drops quickly where flat bars are fitted.

Flexural (Figure 5) and shear (Figure 6) are the two most common failure modes regarding fatigue cracks at such type of connections.

The most common defects in single hull designs are attributed to the extensive use of HTS, in particular in the side shell construction. Some tankers built between 1985-95 had longitudinal stiffener connections locally renewed and provided with backing brackets around ten years service life in order to increase fatigue strength.

In a general way, utilization of HTS in double hull designs results in the increasing of deflections and stress levels, affecting negatively affecting fatigue life of structural connections and the effective life time of coating systems. Double hull tankers built in the early 90’s were subject to a number of typical defects due to poor design details, especially at side shell longitudinal connections to primary transverse structures and connections of the hopper to the inner bottom and side
longitudinal bulkhead. Significant improvements on design detail and workmanship have been achieved and implemented in the designs built late in the 90’s.

It is remarkable that a number of double hull tankers operating in severe environments like the North Sea and North Atlantic have reported damage at the side shell and bottom longitudinal stiffeners in way of transverse primary structure.

Scallop with or without Collar Plate

The type of scallop is another important parameter regarding fatigue of longitudinal stiffener end connections (Figure 7). The classic scallop connection (a) is a relatively large cut-out of the primary member leaving only one side welding possible for the web of the secondary stiffener against the primary member. To provide welding on the other side, a collar plate may be fitted (b). This collar plate is not in the plane of the web of the primary member, which could lead to possible problems of cracks. Nevertheless, this is less critical than the profiled slot from the fabrication point of view. The profiled slot (c) is a cut out of the transverse member, which is slightly larger than the web plate of the secondary stiffener and a larger cut-out for the flange of the longitudinal. This gives the possibility to weld from both sides of the connection between the web of the stiffener and the plate of primary member allowing a good transmission of the stresses. The risk of cracks in a bending mode is limited with this design, but there remains a probability of cracks due to a shear mode. Nevertheless, construction tolerances need to be strict.

![Scallops of Longitudinal Stiffener Connections](image)

Figure 7: Scallops of Longitudinal Stiffener Connections

Connections of Primary Supporting Members

The most critical types of joint are the welded angles and cruciform joints that are subjected to high magnitudes of tensile stresses. The following parameters are considered the most important parameters regarding fatigue strength of such connections:

**Angle connection** - The most general type of welded joint is the angle connection found mainly in the following structures:

- double bottom in way of transverse bulkheads with lower stool,
- the double bottom in way of hopper tanks,
- the lower part of transverse bulkheads in way of the lower stool (if any), and
- the lower part of inner side in way of hopper tanks.

**Cruciform joint** - The cruciform connection is a particular case of the angle connection. Indeed, the angle between the plates is now at a right angle. The cruciform connections may be found in:

- the double bottom in way of transverse bulkheads without lower stool,
- the double bottom in way of the inner side when there are no hopper tanks, and
- the double bottom in way of longitudinal bulkheads.

**Complex connections** – Connections can also involve both angle and complex cruciform features as shown in Figure 8.
Corrosion Assessment

In general, in-service single hull tankers are found to have moderate corrosion rates and thickness diminution. However, there are some cases where excessive pitting in the bottom and top tank in cargo tank plating have been reported due to microbial attack in areas where coating protection is not provided. Cargo tanks of typical single hull tankers may not have been provided with corrosion protection systems, i.e. coating and anodes. Consequently, residual water from oil cargo causes grooving and pitting corrosion in the upper surface of horizontal structures like stringers and bottom plating at the aft end of the cargo tank.

The normal corrosion rate in the cargo tank uncoated areas of double hull tankers is expected to be moderate based on the previous experience with SBT tankers, where horizontal structures like stringers and bottom plating would be areas to be subjected to special attention. However, cases of accelerated corrosion rate in cargo tanks have been reported, as an increase of the pitting corrosion rate in cargo tank bottom plating. Double hull designs can be found having cargo tanks partly painted with an epoxy coating on the under deck (to 3 m below) and eventually the tank top plating (inner bottom), varying depending on owner requirements. But areas where coating fails may have accelerated corrosion, in particular in the deck head areas subject to increased deflections and stress levels due to the use of HTS.

Accelerated corrosion in cargo tanks may be due to microbial attack from bacteria in the cargo oil. Cargo temperatures in double hull tankers can be up to 20°C higher than in single hulls due to the insulation provided by the inner hull. These higher temperatures provide the necessary conditions for the microbes to remain active longer and produce corrosive acidic compounds increasing the risk of MIC. Higher temperatures mean that the humidity is also higher, increasing the amount of water vapour in the air space above the ballast and cargo tanks. Therefore, the coating on ballast tank bottom shell remains continuously wet, having mud settled in particular at aft locations due to the ship trim. This accumulation of mud could also generate a higher risk of MIC. Corrosion prevention systems are likely provided in ballast tanks. In order to prevent accelerated corrosion of the under deck and the tank bottom areas, a number of operators require painting of these areas also in cargo tanks.

The total surface area to be coated and maintained in double hulls can be up to three times larger when compared to single hull tankers. Consequently, the maintenance of coating systems is one of the most important aspects regarding the hull structure condition.

The following main aspects should be considered in order to evaluate the durability of the coating system of cargo and ballast tanks:

- coating specification,
- coating preparation and application, and
- workmanship during construction (grinding of sharp edges for instance).

Double hull tankers have increased structural flexing compared to single hull designs which leads to higher cracking potential of the coating, in particular in the deck, inner shell and inner bottom areas.
HULL STRUCTURE ASSESSMENT

Assessment of the FPSO hull structure should verify the adequacy of the tanker hull with the project specification, it means the strength of global and local structures, considering storage capacity, topsides additional weight and specific environmental loads.

The refurbishment work necessary to fit the hull for conversion is not the most expensive cost regarding the whole conversion, however, it plays an important role in the conversion schedule, as delays caused by the work in the hull might delay the unit commissioning. Repair and strengthening work prior or at conversion will also affect the unit along its service life. Therefore, structural analysis is helpful to define the scope of the inspections and consequently to specify the required steel renewal and modifications at conversion.

Hull structural assessment is a multi-step analysis procedure, where global coarse mesh analyses (Figure 9) are used followed by local fine mesh analyses at critical locations, selected based on the coarse mesh results and experience. The structural analysis is based on the design load parameters given by the hydrodynamic analysis.

Unlike new build hulls, the structural assessment of converted FPSO’s requires two phases to be considered: tanker and FPSO, as an FPSO presents specific new characteristics when compared with trading tankers. The main characteristics of the FPSO are the following:

- the unit is fixed on a specific site, generating specific loads;
- the unit is permanently moored (no dry dock is planned for inspection and maintenance);
- additional loads are generated by the mooring system, risers and topsides; and
- continuously loading and unloading on site (constant variation of draught), which is different from that of a tanker which are generally only operated in full and ballast conditions.

Therefore, the specific assessment of the FPSO hull structure needs to take into consideration such particularities in order to properly verify the several limit states given in Table 2.

Figure 9: Structure Finite Element Analysis Model
TABLE 2: LIMIT STATE VERIFICATION

<table>
<thead>
<tr>
<th></th>
<th>Yielding</th>
<th>Buckling</th>
<th>Ultimate Strength</th>
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To assess the FPSO at conversion, corrosion wastage should also be incorporated into the calculation models. The corrosion forecast is in general estimated from review of the latest Ultrasonic Measurement Report before conversion.

Design Loads

Site specific conditions need be taken into account in the hull structure assessment of the FPSO, including meteorological and oceanographic data and the mooring conditions, in order to properly define the sea loads on the structure. Such data include the wave directions, the wave spectrum and the relative headings, as the hull forms, the lightweight distribution (including structure weight, topside weight, turret weight, etc.), the loading conditions and the connections with the seabed. Therefore, each project should be provided with the calculation of the hydrodynamic loads and vessel motions in the frequency domain, using the 3D diffraction-radiation method and taking account of the site water depth. At least three loading conditions are in general analyzed, comprising the full range of the FPSO loading conditions:

- minimum draught,
- intermediate draught, and
- maximum draught.

FPSO’s are generally moored by two different types of systems that influence the calculation conditions of the hydrodynamic analysis:

- spread moored design: the unit is maintained in a constant position independent of the sea and current heading, while the environmental loads have a predominant direction. Generally, the mooring lines are connected to the main deck at the fore and aft ends.
- turret moored design: the unit is free to weathervane and has a natural tendency to orientate in the direction of the most severe environment component. The mooring lines are connected to the turret, generally located in the fore part of the unit.

The hydrodynamic analysis results in the longitudinal distribution of the following parameters for the offshore unit at the intended site:

- wave induced bending moment,
- wave induced shear force,
- total accelerations in all directions, at the center of gravity of each compartment and at relevant positions in topside areas,
- relative wave elevation, and
- sea pressure on the shell.

The outputs of the hydrodynamic analyses determine the design load parameters to be applied to the structural model in order to assess the scantlings of the structure. The values of the parameters may be modified to include safety margins or adjusted.
Hull Girder Strength

The first step of the hull structure assessment is in general the verification of the global hull girder strength along the unit’s length. A yielding check is performed, comparing the bending moment applied to the structure with the bending moment capacity provided by the actual hull scantling configuration. The bending moment applied to the structure is given by the maximum allowable still water bending moment derived from the assessment of the loading conditions of the unit (operation, transport, maintenance, etc) and VWBM derived from the wave load parameters assessment.

It should also be checked that the bending moment applied to the structure is lower than the ultimate bending moment capacity of the hull girder, taking into account a safety factor increased compared to ships. The maximum permissible still water bending moment (SWBM) and shear force (SWSF) are derived from the wave bending moment (VWBM) and the wave shear force (VWSF) values obtained from the hydrodynamic analysis results.

Calculations show that in general SWBM and SWSF could be increased for benign environmental conditions, such as in Angola and in Nigeria for instance, but varying depending on the ship characteristics. The additional reserve of strength due to less severe environments should not be fully credited to the allowable SWBM and SWSF to assure the normal ratio between static and dynamic loading applied to the hull structure. SWBM and SWSF will be driven by the maximum values of VWBM and VWSF (including safety margins) and the calculated total hull girder capacity, taking into consideration the corrosion wastage from the tanker trading service.

It should be noted that the direct analysis of the wave induced shear force will result in a distribution slightly different from the one given by the typical IACS distribution. Even though the VWSF distribution has two peak values at approximately L/3 from the hull aft and fore ends, the hull capacity needs be checked along the length of the unit and in particular at the position of transverse bulkheads, where the total shear force has its maximum value. Oil tankers often have local reinforcements in the longitudinal bulkhead and side shell plating, over one to two web spacing, aft and fore of transverse bulkheads, to allow for peak values of the total shear force.

Considering the wave load parameter results for a unit moored offshore Angola for instance, the site specific values for VWBM and VWSF are approximately 0.3 and 0.5 of the North Atlantic reference values, leading to an increase over the minimum Rule value of 0.65. Nevertheless, the allowable values would still be increased up to 50% for SWBM and up to 35% for SWSF.

Local Strength of Plating and Ordinary Stiffeners

The second step is the verification of the scantlings of the plating and the ordinary stiffeners. These elements are assessed through a 2D section model as shown in Figure 10 loaded with the design load parameters defined by the hydrodynamic analysis. A yielding check and a buckling check are carried out for stiffeners and plates.

In all cases, local loads are calculated for the expected most severe conditions. Each element is analyzed considering the compartments as being alternately full or empty, for the purpose of maximizing the loads induced on that element by the cargo carried. Similarly, for the elements of the outer shell, the external sea pressure is calculated at the full load draught when the side tanks are considered empty (cargo loading conditions), and at the light ballast draught when the side tanks are considered full (ballast loading conditions).

Strength of the Primary Structure

The first objective of the finite element analysis of the primary structure is to determine the stress distribution in the primary supporting members. It allows verifying that the scantlings comply with the yielding and buckling criteria. Two levels of meshes are generally necessary to assess the strength of the structure. The first step is the global coarse mesh model. The 3D coarse mesh model allows verify the overall behavior of the primary structure. There are two main approaches:

- The simpler and faster one is based on a three-cargo tank model, where beam theory is used to balance the model and obtain the desired bending moment and shear force distribution in the mid-tank area. VWBM, VWSF, accelerations and relative wave elevations derived from hydrodynamic analysis are used.
Complete ship model including the entire hull structure over the unit length, from aft to fore ends can be used. It is a more time consuming approach. On the other hand, accelerations and wave pressure distribution derived from hydrodynamic analysis are applied along the hull structure model in order to equilibrate it and obtain the correct bending moment and shear force distribution along the hull.

Fine mesh analyses using models as shown in Figure 11 are also performed to get more accurate stress levels in specific locations. Detailed Stress analyses are in general performed for the following typical primary structures:

- horizontal stringers in way of typical oiltight bulkhead,
- horizontal stringers in way of typical swash bulkhead,
- typical transverse ring,
- typical first transverse ring aft and forward oiltight and swash bulkheads,
- Longitudinal girders in way of oiltight bulkhead and swash bulkhead, and
- FPSO specific areas (topside supports, turret structure, hull connections and other hull attachments).
Fatigue Strength

The efficiency of the structural connections subjected to high cyclic stresses needs to be checked with respect to possible fatigue related problems. Fatigue assessment can be divided into main groups:

- connections of the longitudinal ordinary stiffeners with transverse primary supporting members (transverse bulkheads and web frames), and
- connections of primary supporting members.

The first group can be assessed by using a library of typical details to evaluate the fatigue strength of end connections of longitudinal stiffeners by mean of fatigue deterministic approach. 2D analysis is therefore carried out in order to evaluate the strength of side shell and bottom longitudinal connections along the cargo region due to fatigue flexural mode in way of each oil tight bulkheads and in way of ordinary frames. 3D finite element analysis is needed to capture the local stresses in non-standard details for use in the fatigue calculation. Therefore, very fine mesh models as shown in Figure 12 are used, having element size between once and twice the thickness of the structural element.

Assessment of detail connections should take into account both tanker and FPSO phases. Fatigue damage taking into account wave cycles and loading/unloading cycles are cumulated with the damage associated to the tanker phase in order to estimate the remaining fatigue life at conversion. Environmental loads for fatigue assessment of the tanker may be derived based on the analysis of the trading route. In cases where the trade data is not available, standard wave load parameters based on rules (Bureau Veritas 2004b) for a typical World Wide trade tanker can be used.

In general, tanker analyses are carried out based on the typical loading conditions: full load and ballast loading conditions leading to maximum sagging and hogging load cases. For the FPSO, review of the operational loading conditions comprising the loading/unloading sequences should be carried out to determine the representative loading conditions to be considered in the analysis.

Fatigue Approach

The deterministic methodology has been further developed for the FPSO’s by introducing several draughts and loading cases over the expected lifetime of the floating unit. The calculation method applied today by Bureau Veritas has been calibrated against spectral fatigue strength assessment and the methodology is applied in-house for screening of the structural details. The results of the deterministic approach are in general expected to be more conservative than those given by the spectral one.

In order to assess more precisely the fatigue damage of the structural details a spectral fatigue strength assessment may be carried out. The spectral analysis is to be carried out in the following three steps:
- hydrodynamic analysis,
- structural analysis, and
- calculation of the fatigue damage.

The hydrodynamic analysis determines the loads and the resulting motions generated by the environmental loads; the site-specific environmental loads are thus taken into account. The loads obtained through the hydrodynamic calculation are applied to the structural model. The structural model provides the RAO’s of stresses at location of interest within the model. The fatigue damage is then calculated based on statistics of stress ranges. At least three draughts (and associated loading conditions), five headings and 25 frequencies are to be taken into account, but this may be adapted depending on the type of mooring. The acceptable damage depends on the location; the accessibility for inspection, maintenance and repair; and on the consequences of failure.

**Loading Unloading Fatigue Assessment**

Fatigue damage cumulated during the FPSO phase due to wave and loading/offloading cycles is also assessed. For the calculation of the stress range due to the loading/unloading, the cycle at a return period not less than one day is to be taken into account. The damage ratio of loading/unloading is combined with the one due to the wave effect.

**Deck Transverse Capacity and Topsides Modules Integration**

Hull structure elements of oil tankers built after 1985 are in general more optimized than in previous designs, particularly the 70’s tankers often used in previous conversion projects. In addition, double hull tankers have in general higher stress levels than single hull tankers. Therefore, top tank structure strength and their integration with the topsides modules need to be carefully investigated in order to identify needs for additional strengthening.

Topside modules should be supported in way of transverse and longitudinal bulkheads and deck transverses. Finite element models, as described above, are used to verify strength of such structures and specify eventual additional strengthening of the under deck structure. FEM top down analysis is an efficient way to perform such verification taking into consideration local loads induced by topsides, but also the hull behavior due to sea loads and internal liquid loads. Global loads induced by the hull girder bending are also taken into account.

**CONCLUSIONS**

Floating storage units have become a common solution for the development of oil production systems. As these units are intended to remain on station in general over 15 years, fatigue strength of structural detail connections and corrosion become a major concern. Even if the hull is not the expensive part of the production project, as a large investment is made on the topsides and sub sea equipment, special attention needs to be paid to the effective design life of the hull. Despite the fact that

![Figure 13: Deck Transverse Model](image)
the conversion of Single Hull Tankers built before 1985 requires significant refurbishment work, it remains a worthwhile alternative for fast track projects. Some of the reasons are:

- the refurbishment of the hull leads in general to a shorter time schedule than building a new hull;
- the purchase cost is lower when compared with new builds and recent Double Hull vessels;
- the experience with 70-85’s Single Hull designs have been largely used in previous conversion projects; and
- the 86-95’s Single Hull designs were generally optimized by the use of HT steel, leading to reduced scantlings and consequently reduced corrosion margins. A number of typical defects are also attributed to the use of HT steel.

As very few large Single Hull tankers built before 1985 are still available in the market, tankers built in the period 1986-1995 become natural candidates for conversion and more design and condition assessment work should be expected in order to evaluate properly the adequacy of each hull to the project requirements. Both designs are prone to defects due to fatigue and corrosion wastage and deterioration cumulated along the trade period will affect the FPSO hull structure integrity and performance along its service life.

In the same way that the hull structure may vary as a function of the shipyard design and fabrication standards, the hull condition may change depending on the trade, operation conditions and maintenance procedures. Therefore a complete hull structure assessment should be carried out for each vessel selected to be converted, including:

- Review of the hull design characteristics and ship’s historical information, including operation conditions, maintenance procedures and records of survey and inspections should be reviewed at least in qualitative way during the hull selection process.
- FPSO Finite element analysis taking into consideration the tanker trade phase degradation modes in order to assess the FPSO hull structure design and screening of the critical areas and components of the hull.

Outcomes from the hull structural assessment should provide:

- plates and stiffeners to be renewed and/or strengthened based on the FPSO hull structure verification,
- plates and stiffeners to be renewed and/or strengthened based on the future corrosion study, and
- detail connections to be renewed, modified and/or strengthened based on fatigue analysis, taking into consideration the cumulated damage during the tanker trade and FPSO phases.

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