COMPLETE PLANNING OF A FPSO CONVERSION TAKING INTO ACCOUNT STRENGTH AND FATIGUE ASPECTS

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Abstract

There is an ever-increasing trend to convert existing tank vessels into Floating Production Storage/Offloading Systems (FPSOs). These FPSOs, in many cases, are to be on site for upwards of twenty years. With an extended period of time on station, careful planning needs to take place before the actual shipyard conversion. Overall hull girder strength, local structural member strength, corrosion, and fatigue need to be taken into account in this planning process, not only for the current state of the vessel, but also in the projected condition to avoid costly repairs that would require time off site.

Required structural member strength and hull girder strength can be significantly different than that required for unrestricted worldwide tanker service. Many of the wave environments in which FPSOs operate are usually more benign than those wave environments that classification Rules have historically considered in design. The reduction in environmental loads should be credited in determining the required strength on site. This paper will present a procedure and methodology using the ABS/SafeHull technology to determine the site specific structural strength requirements taking into account all of the relevant failure modes that may be experienced by the vessel.

Once the strength for the specific operating site is known, the current state of the vessel can then be assessed to determine what areas of the structure will need to be reinforced to ensure adequate performance for the desired time on site. To ensure this longer span between shipyard visits, corrosion must be directly addressed and predicted in the planning process. The results of this predictive corrosion analysis must then be incorporated into determining the level of renewals required at the time of conversion.
It is well known that fatigue is a cumulative damage phenomena, therefore it
must be treated in a separate manner than that of strength. An assessment
must be made to determine the number of fatigue cycles consumed during
the “ship phase” (the time spent in tanker service before the conversion) and
the number of fatigue cycles that will be consumed during the “FPSO
phase.” The prediction of fatigue cycles consumed on site must take into
account all of the operating parameters such as environmental data for the
site, weathervaning of the vessel, zero speed, etc... Once the determination
of these two components has been made, the predicted damage is compared
against the fatigue resistance that is inherent in the detail under
investigation. This comparison can then be used to plan repairs necessitated
by fatigue. This paper will present a detailed methodology using the
ABS/SafeHull technology to quickly ascertain past and future fatigue
performance.

As can be seen, it is very important to consider all aspects of the structure
and failure modes when planning a FPSO conversion, both at the time of
conversion and at the end of the desired service life. Proper conversion
planning will alleviate any costly down time that could be required for
structural repairs of the vessel.

INTRODUCTION

During the past number of years there has been an ever increasing trend to
convert existing oil tankers into Floating Production Storage/Offloading
Systems (FPSOs). Converting existing tankers is, in most cases, more
economically feasible and faster than building new production/storage
facilities for the same purpose in somewhat marginal fields. Conversion also
allows for the extended use of these single skin tankers which are gradually
being phased out for regular oil trading due to increased environmental
regulations.

In many cases, these FPSOs are designed to be left on site for upwards of
twenty years. Complete planning of the conversion is very important in
achieving this desired service life without necessitating to come off station
for repairs. It has been shown in Reference 1 that performing repairs while
the FPSO is on site can be time consuming, costly, and reduces the overall
productivity of the unit. Removing the FPSO entirely off site will also be
very costly in terms of the shipyard cost and the time that the unit is not on
site performing its intended job. Therefore, by careful planning, basic
structural repairs and renewals can take place at time of conversion
eliminating the need to perform these repair items in the future.
In most FPSO conversions, the basic structural arrangement is kept intact in way of the cargo block region, whereas in the turret region there are major changes and additions to account for the mooring loads, risers, bearings, etc. As a majority of the steel renewals will take place in the cargo block, emphasis will be given in preparing an adequate plan for this region to ensure desired service. However, the ideas and thought processes developed for the cargo block region can be extended for use in other regions of the vessel.

Structurally, there are three basic items that must be considered when contemplating the renewal of the cargo block structure: hull girder strength, structural member strength, and fatigue strength. Each of the aforementioned items must be considered and verified at the time of conversion and at the end of desired service life, taking into account the effects of corrosion over time and the wave environment.

OVERALL HULL GIRDER STRENGTH

Originally, tanker designs have been verified by the class societies under a “total design moment” philosophy. This means that the structure has been assessed and deemed adequate at the time of building for a specified maximum stillwater bending moment plus a wave induced value of bending moment. The value of the wave induced bending moment corresponds to a twenty year maximum exposure on the North Atlantic trade route (America to Europe). By using this total combined value, the ship is deemed to have sufficient hull girder strength for unrestricted worldwide service. The only caveat to this method is that the vessel should never exceed the maximum stillwater bending moment in any loading condition.

The required hull girder strength is given by equation 1 and 2. Equation 1 is simple beam theory with the allowable bending stress being modified to be applicable to ship structures. Equation 2 is the International Association of Classification Societies (IACS) formulation for minimum hull girder section modulus. From experience, equation 1 and 2 will result in very similar minimum section modulus requirements for typical tanker structures. The only deviation to this is that in vessels with higher breadth to depth ratios, the IACS requirement will sometimes be significantly higher than that of beam theory.

\[
SM = \frac{M}{fp}
\]  

(1)

Where \( M \) is the total design moment and \( fp \) is the allowable bending stress.
In many cases, FPSO conversions will be placed in wave environments which are less severe than that of the original design basis. By the nature of operations, these FPSOs will also experience stillwater bending moments which will exceed those that the trading vessel was originally designed for. With this being the situation, it is prudent to give credit for the reduced severity of the wave environment. This can be done by changing the distribution of the stillwater and wave induced bending moments in the total design moment. For example, Figure 1 shows the total bending moment and components for a regular operating tanker before conversion.

\[
SM = C_1 C_2 L^2 B(C_e + .7)
\]  

(2)

Figure 2 shows the distribution of stillwater and wave induced which may be allowed upon the completion of a detailed seakeeping analysis to determine the long term wave induced bending moment on site.

As can be seen, in some cases there can be a large increase in the allowable stillwater bending moment depending upon the wave environment that the FPSO is placed. In some rare cases, it may be that the total design moment can be decreased depending upon the summation of the stillwater and site specific wave induced bending moments for cases when scantlings are somewhat marginal. However, should this be the case, serious consideration should be given to the adequacy of the vessel for the intended FPSO service. It should also be mentioned that this is not usually the case and the majority of industry and administrations feel that it is prudent and
conservative to never let the total design moment for the FPSO be less than that of the original design as a tanker.

![Figure 2](image)

**Figure 2**
Total Bending Moment and Components for FPSO on Site

The overall hull girder strength should be assessed for many sections of the hull at the time of conversion using equation 1 in conjunction with recent gaugings. This will form the basis for renewals to meet hull girder minimum section modulus as an FPSO. The next step in the process is to estimate the corrosion that will take place over the time the vessel will be on site. This calculation should take into account any coatings that will be applied, planned sacrificial anodes, previous service experience with the hull, the use of the tank, the type and temperature of the future cargo, and any other variables that may affect the corrosion rate. Once minimum corrosion rates have been decided for various structural members, the current state should be extrapolated out to the end of the desired service life to ensure adequate hull girder strength at that time. Should the hull not meet minimum section modulus, then renewals can be planned at this point in time to ensure adequacy until the end of the period.

**STRUCTURAL MEMBER STRENGTH**

The previous section dealt with the overall strength of the hull girder which mainly prevents catastrophic failure. A failure in any one individual member will not lead to this overall hull girder failure, however, many local failures may progress into this failure of the hull girder. Therefore, it is crucial that every structural member have a minimum scantling to prevent local failure, i.e. a renewal scantling.
Renewal scantlings can be based on the requirements from the ABS 1996 Rules for Building and Classing Steel Vessels\(^2\) (Part 5 Section 2, SafeHull for Tankers). These SafeHull requirements are basically local thickness requirements which account for the dynamic load acting on the member, the response of that member to the load, and the comparison of that response to the relevant failure mode\(^3\).

One would find that if a vessel was input into the SafeHull as the vessel was originally built, the minimum thicknesses that SafeHull requires would not alone meet hull girder section modulus requirements. Therefore, when determining the final SafeHull requirements, it is imperative that the minimum SafeHull thicknesses be reinput into SafeHull and iterated to meet the minimum section modulus. In most cases, this only requires increasing the minimum thickness for deck plating. Once this is done, the results are scantlings which meet both local requirements and overall global requirements (i.e. minimum 1996 Rule thicknesses).

Once the required Rule thicknesses have been determined, the renewal values can be determined. Historically, renewal values have been based on percentages of the Rule required thickness or overall section modulus. In most cases, the member must be renewed after a twenty five percent degradation, however, there are other members which are allowed to corrode more and some less before required renewals. Some members, such as the deck and bottom plate, are controlled by area loss and corresponding hull girder section modulus.

Before renewal values are determined for the purpose of planning the conversion, corrosion must be examined. Corrosion can be examined in the same manner as what was done for the overall hull girder strength. Estimations need to be made taking into account any coatings that will be applied, planned sacrificial anodes, previous service experience with the hull, the type and temperature of the future cargo, and any other variables that may affect the corrosion rate. Reference 4 gives invaluable information on corrosion in tanker structures.

Another variable that must be accounted for is the burden associated with additional surveys for members which are deemed to have substantial corrosion. Class societies may require that additional surveys be conducted on an annual basis for members that are nearing their minimum required thickness. These additional surveys cost money not only in the survey fees, but also in time lost from production, staging, etc... With this being the case, the effects of substantial corrosion must be integrated into the renewal
scantlings which are to be used in determining the steel renewal plan at the time of conversion.

Equation 3 is an example equation that can be used in determining renewals that will result in the desired service life.

\[
\text{Renewal Value} = \text{SH value}(1 - 0.25(75\%)) + \text{Anticipated Corrosion} \quad (3)
\]

where SH Value is the minimum 1996 Rule requirement. Anticipated corrosion is the value determined based on the previously discussed parameters and length of time. \((1-0.25(75\%))\) is the relationship that avoids the burdens of substantial corrosion, see reference 2 (Part 1 Section 3, Surveys After Construction. Basically, instead of the renewal value being 75% of the Rule requirement, this statement requires renewal at 81.25% of the Rule requirement plus anticipated corrosion.

Once the renewal values have been determined, the shear in the longitudinal bulkheads and side shell should be checked to ensure that the vessel has and will have adequate thickness to withstand shear in way of the transverse bulkheads. Similar to bending moment, the hull girder shear should take into account the new operating conditions that the FPSO will encounter and also the wave induced shear from the specific site.

In addition to checking the shearing strength, the renewal thicknesses of the extreme fibers of the hull girder should be checked for buckling stability under hull girder loads. The same concept applies to the webs and flanges of the extreme fiber longitudinals.

After the renewal values have been determined and verified, they can then be used in assessing the current gauged structure to determine the extent of steel renewals.

**FATIGUE STRENGTH**

A modified form of the simplified fatigue analysis presented in Reference 2 can be used to assess the fatigue performance of a FPSO conversion. The fatigue analysis in SafeHull is based on a cumulative damage theory (Palmgren Miner's Rule), meaning that the structure has a finite number of fatigue cycles that the vessel can consume during service. Once all of these cycles are consumed, fatigue failure occurs. Unlike strength, which is a maximum extreme value concern, fatigue is concerned with all the stresses and the cycling of stresses that a vessel has seen since delivery. With this
being the case, it is important to discuss the background of the SafeHull fatigue method.

**Standard SafeHull Fatigue Assessment for World Wide Ocean-going Vessels**

The ABS approach to fatigue is based on the following:

- S-N Curve fatigue strength data
- Detailed stress analysis to determine appropriate stress range probability distribution
- "Spectral analysis" to predict final fatigue damage

The spectral approach is applied in the generation of a large database of parametric evaluations which is used to develop the SafeHull requirements. These requirements are expressed in terms of the "permissible stress range." This stress range is considered to be conceptually equivalent to the allowable fatigue damage determined through full spectral fatigue analysis. The user of this fatigue standard is provided with a satisfactory first level fatigue assessment procedure.

To facilitate the fatigue strength assessment process, a simplified and verified method has been developed. This method considers the expected statistical distribution of stress over time, the mathematical description of the S-N curves, the applicability of the Palmgren-Miner’s Rule, and a target value of the fatigue life. The assumption made in this method is that the long-term stress range distribution is represented by a Weibull distribution. Thus, if the extreme stress range in the target life of the vessel is known or can be calculated, the characterizing Weibull distribution “shape” factor can be used in conjunction with this and other information to produce a design parameter useful in “controlling” fatigue. This parameter can be in the form of permissible stress range, fatigue life in units of time, or a fatigue damage ratio.

It is important to understand the subtlety among the three parameters, namely, damage, long term stress, and Weibull shape parameter. They form a triangle. That is, if any two of these quantities are known, the third quantity can be obtained.

There are two processes that are relevant to the SafeHull development.

- Calibration - Spectral fatigue is used to get damage and long-term stress. From the triangle, solve for Weibull shape parameter. This is the process that leads to the specification of Weibull shape parameter in SafeHull.
The triangle is the so-called “simplified” method. Additional information on this can be found in Reference 7.

- Application - Look up the Weibull shape parameter in SafeHull, specify a target damage (or target life). Use the simplified method to get the long-term stress and call it “permissible”. Thus, “spectral” analysis is not done in SafeHull.

**Application of SafeHull fatigue assessment to FPSO Conversions**

Combining previous damage and expected damage is very important when looking at FPSO conversions. The vessel has already expended cycles during the “ship” phase of its life and will use up additional cycles during the “FPSO” phase of it’s life. The objective is to keep the total number of cycles below the number of cycles that result in failure.

For converted FPSOs, the variation and severity of the wave environments associated with the service routes and operational site greatly affect the outcome of the cumulative fatigue damage. Recognizing this, a fatigue assessment procedure which allows for assessing historical wave environmental experience and predicting future environmental exposure has been developed.

For FPSOs converted from tankers, the procedure consists of two parts. First, the historical cumulative fatigue damage of the longitudinal members, up to the time of conversion, is calculated through realistic temporal weighting of wave environments experienced along the specified service routes during the service life of the vessel. This provides an estimate of the remaining life of the structural members at the time of conversion. Second, the expected cumulative fatigue damage of these members is calculated using the site specific wave environment and operational conditions. This establishes the basis for comparison of expected fatigue life of the vessel as an FPSO and the remaining life of these members.

The screening tool relies on the full spectral fatigue analysis method but in conjunction with SafeHull. A set of stress transfer functions is built into the procedure, using the operational parameter of the site. These stress transfer functions are derived from dominant load effects such as vertical and lateral bending moments and hydrodynamic pressures.

Typical operational aspects of the FPSO considered in the calculation of fatigue damage of the longitudinal members consist of the following:

- Minimum of 20 years operational life
- Weathervaning
A so-called “rain-flow” correction factor is also incorporated within the calculations in order to compensate for the possible effects of longer term swells that may not be counted in the normal adjacent stress peak to trough cycles.

Cumulative fatigue damage based on the historical environments and service life, and cumulative fatigue damage based on the site specific environment are calculated. They are normalized by the cumulative fatigue damage calculated based on wave environments of the North Atlantic Ocean. These ratios are called environmental factors.

For the calculation of the remaining life of the longitudinal members, the following equation is used in the analysis:

$$\text{Remaining Life} = \alpha_3 \{ \text{SafeHull Predicted Life} x \alpha_1 - \text{Service Life} x \alpha_2 \}$$

where

$$\alpha_1 = \text{ship route wave environmental factor for new FPSO construction where its intended site position wave environment for the design life of the vessel is different from that of the North Atlantic Ocean. If the vessel is not a new FPSO construction, } \alpha_1 \text{ is set equal to unity.}$$

$$\alpha_2 = \text{ship route environmental factor for existing tankers where its historical ship routes wave environment for the service life of the vessel differed from those of the North Atlantic Ocean. This factor is the ratio of the fatigue damage life due to the historical ship route wave environment and that of the North Atlantic Ocean. If the vessel is not an existing tanker, } \alpha_2 \text{ is set equal to unity. This factor is also used in conjunction with } \alpha_3 \text{ for the case of an existing tanker converted to a FPSO.}$$

$$\alpha_3 = \text{site environmental factor for existing tanker converted to a FPSO. This factor is a ratio of the fatigue damage life due to the site-specific wave environment and that of the North Atlantic Ocean. If the vessel is not a FPSO, } \alpha_3 \text{ is set equal to unity.}$$
Example of fatigue results of SafeHull for FPSO conversions

The example vessel has been trading unrestricted for the past fifteen years. The vessel is to be placed in the N’Kossa field for twenty years as shown in Figure 3. It can be assumed, based on the unrestricted service, that the vessel’s prior environmental experience can be represented by the normal North Atlantic wave data. The objective of the analysis is to determine the remaining fatigue life for selected longitudinal connections.

- 320.0m Length
- 53.5m Breadth
- 25.7m Depth
- 15 Years Unrestricted Tanker Service

To be placed in the N’Kossa Field (adjacent to the Congo)

The following stiffeners have been chosen for the analysis:

- Outboard Bottom Longitudinal
- Side Shell Longitudinal 15 (below load waterline)
- Side Shell Longitudinal 20 (at load waterline)
- Deck Longitudinal

Table 1 shows the results of the fatigue analysis. The results are shown for the bay adjacent to a typical midship bulkhead. Results are given for the connection on the adjacent web frame (aft) and the connection at the bulkhead (fwd).

P Life is the original life that is projected using SafeHull based on unrestricted service. S Life denotes the life that has been consumed during the “ship” phase. In this case, S Life is equal to the number of years that the vessel has been trading. In cases where the previous experience has been known and is less severe than unrestricted service, S Life may be less than the number of years in service. R Life is the number of remaining years that the detail has based on the specific site the vessel is to be placed. As can be
seen from this example, Side Shell 10 and Side Shell 15 both have fatigue lives less than the intended service for the connections. Figure 4 shows various repairs that can be made and assessed to ensure the required adequacy.

<table>
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<th>Location</th>
<th>Toe</th>
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<th>P-Life</th>
<th>S-Life</th>
<th>R-Life</th>
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<td>Fwd</td>
<td>F2</td>
<td>30</td>
<td>15</td>
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<td>30</td>
<td>15</td>
<td>31.2</td>
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Table 1
Results of Example Site Specific Fatigue Analysis

This information will allow for adequate planning at the time of conversion to ensure that the structure has adequate fatigue performance for its entire time of service on site.

CONCLUSION

It has been shown that there are adequate tools and methodologies available to completely plan for a FPSO conversion. The careful and complete planning at the conversion stage will alleviate any down time during service which would cease production and would ultimately result in substantial financial penalties.
ACKNOWLEDGEMENTS

The author would like to thank the management of ABS for their support in writing this paper. Special gratitude is also extended to Joao Pacheco and Philip Rynn for their careful reviews and comments on the manuscript.

REFERENCES


