Conversion of an Oil Tanker into FPSO:
Strength and Reliability Assessment

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Abstract

The paper presents the conversion of an oil tanker into FPSO considering strength criteria. Also, a reliability assessment of FPSO hull girder is conducted based on initial yield and ultimate strength. From the first perspective, we look into the influence of the anticipated operation site of the FPSO on the volume of replacements and repairs needed. In particular, it is investigated how the operating site affects the requirements and consequently, the decision to proceed with the conversion or not. Two areas with different environmental conditions have been selected as operation sites, one in the North Sea and one offshore Nigeria. Two shipyards, one in Singapore and one in Spain, have been selected as a departure location for each site in order to define the most unfavorable transit condition regarding loads induced by wave. The methodology followed for the conversion procedure is based on ABS (2015) ‘‘Rules for building and classing Floating Production Installations’’. For the reliability analysis, a First Order Reliability Method (FORM) is employed in order to quantify the uncertainties of loads and resistance and derive the probability of failure for the two limit states investigated. A numerical application is implemented in order to demonstrate the capability of the analysis developed.

1. Introduction

Floating Production Storage and Offloading unit (FPSO) is a type of floating tank system designed to receive all the crude oil from wells, process it and store it until the oil can be offloaded to shuttle tankers or be transported through pipelines to shore. Such a system is a reliable solution for deep water marginal fields exploitation and has several advantages such as redeployment capability and cost-effective solution over fixed platforms. Conversion of a tanker to FPSO is a basic option as in August 2016 from the 169 FPSOs operating worldwide 70% consists of conversions and only 30% were purpose built FPSO units.

Our work is focused on the conversion of an existing VLCC tanker into FPSO. A simplified methodology will be presented for the conversion procedure on the basis of different environmental conditions of the two intended sites of operation, i.e. N. Sea and offshore Nigeria. The aim is to define the maximum global loads that the hull girder is subjected to.

Next step of our analysis is to meet the requirements of ABS Rules [1] regarding the hull structure acceptance criteria. The environmental loads are modeled using a software provided by ABS. Firstly, hull girder yielding strength and then, local scantling evaluation is performed. Taking into account corrosion models in order to evaluate the structural degradation at the time of conversion in the shipyard and rule criteria, we determine the appropriate repairs and renewals needed. Finally, a critical connection is assessed in terms of fatigue strength.

In the last section of this paper, a Structural Reliability Assessment (SRA) is implemented. Generally, SRA investigates the probability of a structure to successfully complete its design requirements and leads to safety measures that a design engineer has to take into account. The inherent probabilistic nature of design parameters, material properties and loading conditions involved in structural analysis is an important factor that influences structural safety. The implementation of any reliability method depends to a large extent on quantifying these uncertainties. Hence, our effort is focused on this direction, i.e. the modeling of load and strength variables by probability density functions. A numerical application accounting for hull girder primary failure modes is presented based on FORM method and the results are discussed.

2. Conversion procedure/methodology

The selected vessel for the conversion is a VLCC tanker with main dimensions as presented in table 1. In general, the methodology we followed is illustrated in figure 1 and only an overview can be given. Main purpose of this procedure is the investigation of loading conditions and the definition of the most unfavorable conditions regarding the global loads that the FPSO is subjected in still water.

Table 1: *Converted tanker/FPSO principal dimensions*

Vessel Main Particulars	
Length between perpendiculars, L	320.0 m
Breadth moulded, B	60.0 m
Draft moulded, T	22.5 m
Depth moulded, D	30.5 m
Block Coefficient, C_b	0.821

The mooring system selection is based on past experience showing that turrets are used frequently in North Sea and spread mooring in Nigeria. An external turret with a total weight of 9000 tones is incorporated on the bow of vessel allowing the vessel to rotate and obtain its optimum orientation in response to waves, winds and currents in a severe environment such as that of N. Sea. Spread mooring system consists of a light equipment with 12 mooring lines located at strategic points on the hull of the vessel keeping it on a stable directionality. The lightship weight distribution has been based on a typical FPSO arrangement of similar size that modified appropriately. Software AVEVA Marine has been used for the compartmentation of FPSO tanks. A model of that is presented in figure 2 with the corresponding capacities of main tanks on both regions. Some differences observed are caused by trim and draft requirements which vary due to the lightship weight distribution resulted mainly from the different mooring system selected. The final stage is the study of loading conditions. The most representative for strength assessment according to ABS rules have been investigated and the results are presented in figure 2. Main purpose has been the control of trim and draft variations, the minimization of free surfaces with appropriate loading/offloading pattern and the stability criteria checking in intact condition (according to IMO resolution A.167). The main conclusion someone can notice is that maximum still water bending moments occur on the two extreme conditions. Having obtained global loads in still water, we can proceed with strength analysis, as soon as we examine the environmental data of the installation regions.

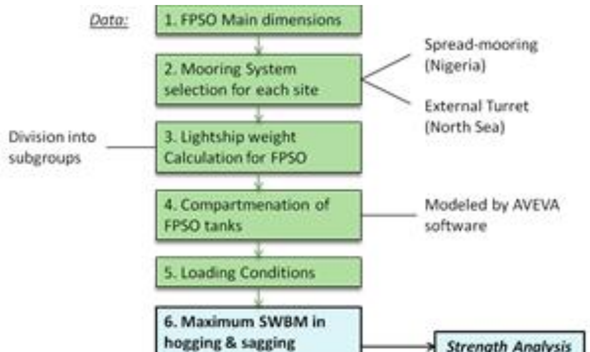
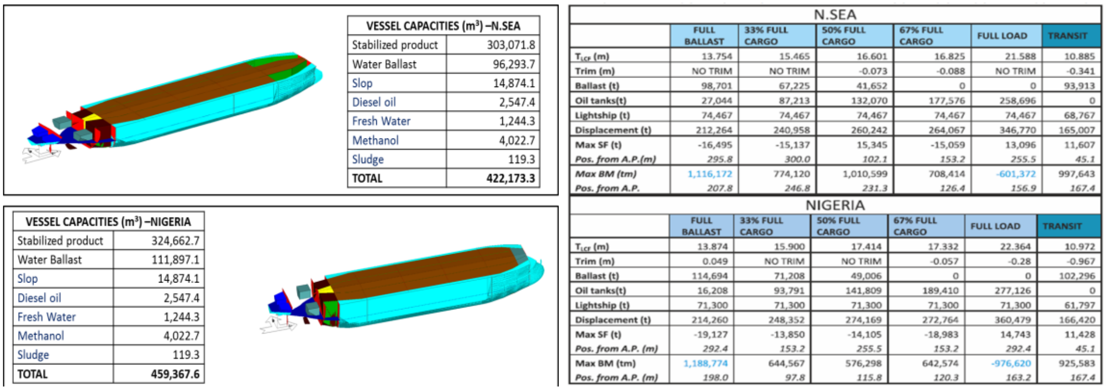


Figure 1: *General procedure of VLCC conversion to FPSO*



VESSEL CAPACITIES (m^3) –N.SEA	
Stabilized product	303,071.8
Water Ballast	96,293.7
Slop	14,874.1
Diesel oil	2,547.4
Fresh Water	1,244.3
Methanol	4,022.7
Sludge	119.3
TOTAL	**422,173.3**

VESSEL CAPACITIES (m^3) –NIGERIA	
Stabilized product	324,662.7
Water Ballast	111,897.1
Slop	14,874.1
Diesel oil	2,547.4
Fresh Water	1,244.3
Methanol	4,022.7
Sludge	119.3
TOTAL	**459,367.6**

N.SEA

	FULL BALLAST	33% FULL CARGO	50% FULL CARGO	67% FULL CARGO	FULL LOAD	TRANSIT
T_{LCF} (m)	13.754	15.465	16.601	16.825	21.588	10.885
Trim (m)	NO TRIM	NO TRIM	-0.073	-0.088	NO TRIM	-0.341
Ballast (t)	98,701	67,225	41,652	0	0	93,913
Oil tanks(t)	27,044	87,213	132,070	177,576	258,696	0
Lightship (t)	74,467	74,467	74,467	74,467	74,467	68,767
Displacement (t)	212,264	240,958	260,242	264,067	346,770	165,007
Max SF (t)	-16,495	-15,137	15,345	-15,059	13,096	11,607
Pos. from A.P.(m)	*295.8*	*300.0*	*102.1*	*153.2*	*255.5*	*45.1*
Max BM (tm)	1,116,172	774,120	1,010,599	708,414	-601,372	997,643
Pos. from A.P.	*207.8*	*246.8*	*231.3*	*126.4*	*156.9*	*167.4*

NIGERIA

	FULL BALLAST	33% FULL CARGO	50% FULL CARGO	67% FULL CARGO	FULL LOAD	TRANSIT
T_{LCF} (m)	13.874	15.900	17.414	17.332	22.364	10.972
Trim (m)	0.049	NO TRIM	NO TRIM	-0.057	-0.28	-0.967
Ballast (t)	114,694	71,208	49,006	0	0	102,296
Oil tanks(t)	16,208	93,791	141,809	189,410	277,126	0
Lightship (t)	71,300	71,300	71,300	71,300	71,300	61,797
Displacement (t)	214,260	248,352	274,169	272,764	360,479	166,420
Max SF (t)	-19,127	-13,850	-14,105	-18,983	14,743	11,428
Pos. from A.P. (m)	*292.4*	*153.2*	*255.5*	*153.2*	*292.4*	*45.1*
Max BM (tm)	1,188,774	644,567	576,298	642,574	-976,620	925,583
Pos. from A.P. (m)	*198.0*	*97.8*	*115.8*	*120.3*	*163.2*	*167.4*

Figure 2: *Compartmentation on AVEVA software and vessel capacities (left). Loading conditions (right)*

3. Environmental data

In the case of FPSOs a good knowledge of the environmental conditions on operation site, as long as, for the transit route, is necessary for the design phase and the assurance of a safe operation. The offshore industry uses a 100-year return period environmental event as the basis for the strength design of its structures [2]. Based on wave significant height of 100-year return period, DNV [3] classifies the environment as *benign* or *harsh* giving the following criterion:

Benign environment	$H_{s,100-year} \leq 8.0m$ for $100 < L < 200m$
	$H_{s,100-year} \leq 10.0m$ for $L > 200m$
Harsh environment	otherwise

As stated before, the intended operation sites of FPSO are in N. Sea and offshore Nigeria. The former, is situated approximately 155km southeast of city Sumburgh of Shetland islands, in Gryphon field. The water depth is about 120m. The latter, is the Akpo field, located 200km offshore Nigeria with a water depth 1200-1400m. The sea state in these two areas is well represented by Jonswap wave spectrum. Significant wave height and range of wave period as long as other information are presented in table 2.

As far as concerning the data on transportation from the shipyard to the installation site, two different departure locations are investigated. The first is a shipyard in Singapore and the second in Spain. This decision is made in order to define the effects of wave induced loads of each route on the strength criteria, afterwards. The computation of model environment parameters has been made considering benign conditions, in the sense that the transportation occurs in a season with non-severe environmental conditions. Moreover, the wave return period is defined to 10 years [1].

Table 2: *Environmental data of the two intended operation sites*

	Nigeria	North Sea
Latitude/ Longitude	3.8°N / 5.3°E	59.2°N / 1.3°E
Site	Akpo field	Gryphon field
Environment	Benign	Harsh
Water depth (m)	1200-1400	120
Waves	*100-year return period*	
Maximum wave height (m)	7.2	26.4
Significant wave height (m)	4.0	14.4
Directionality	SW	Equal probability
Wave period range[1] (sec)	7.2 -28.0	13.7 – 28.0
Note: [1] Wave period range as given by ABS Rules formula: $\sqrt{13H_s} \leq T \leq 28\text{sec}$		

4. Strength Analysis

The strength assessment for a conversion FPSO is based on *Steel Renewal Assessment* procedure of ABS Rules [1]. Its goal is the establishment of hull structure acceptance criteria and the determination of appropriate actions during conversion, in order to assure uncorrupted operation without dry-dockings and of course, safety.

In general, the aforementioned procedure consists of two discrete phases: the determination of *reassessed scantlings* and that of *renewal scantlings*. Particularly, a reassessment of the vessel's scantlings is conducted based on specific site of the installation. The reassessed scantlings obtained, are used to establish the renewal scantlings. The latter are the rule criteria scantlings and hence, actual scantlings at the time of conversion must be calibrated based on renewal scantlings. A general layout of the procedure follows is presented in figure 3 and the main steps are discussed subsequently.

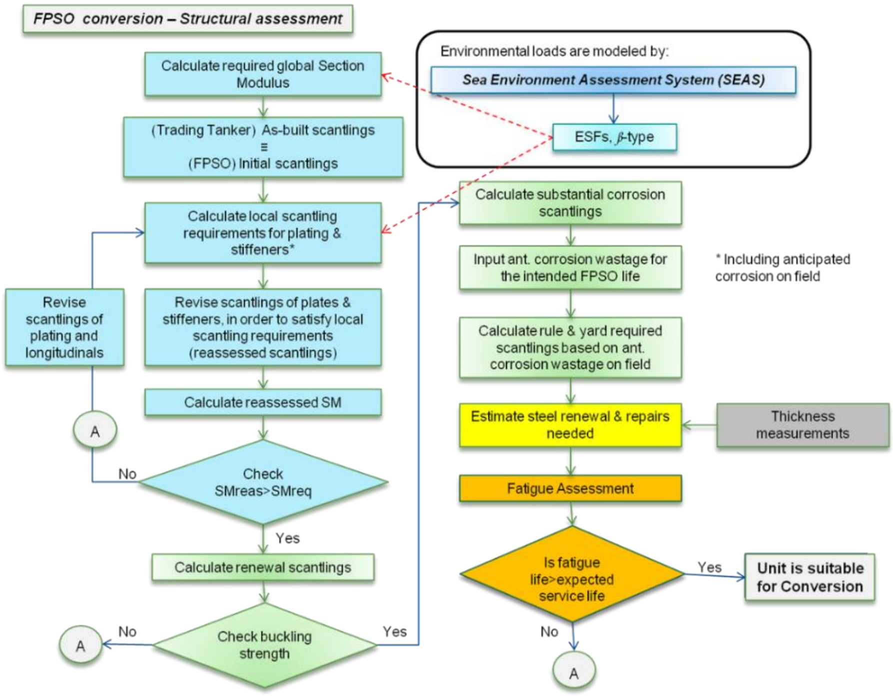


Figure 3: *An overview of the procedure followed for Strength analysis of conversion FPSO*

4.1. Environmental Severity Factors (ESFs)

Environmental conditions are modeled using *SEAS* program of ABS. The Beta (β_{NN}) type ESF are applied to the dynamic load parameters of the load components to introduce a severity comparison between the site-specific conditions and the (base) unrestricted service conditions of N. Atlantic. As a consequence, a $\beta_{NN} > 1$ indicates a more severe environment than the unrestricted case and vice versa. There are 13 dynamic load parameters in which ESFs are introduced, presented in table 3. From the output values of SEAS program someone can conclude two major things. The first, is the much more severe environment of N. Sea in comparison than that offshore Nigeria. In fact, in many cases there is an increase in the magnitude of parameters from the base of N. Atlantic environment. The second is the greater magnitude of the dynamic portion of parameter values on transportation route (from Singapore to Nigeria) in comparison with these on-site.

Table 3: *The resulted 13 dynamic load parameters or ESF β-type from SEAS software.*

		On-site		**Transit**[1]	
No.	Parameter	N. Sea	Nigeria	N. Sea	Nigeria
1	Vertical Bending Moment	0.990	0.449	0.845	0.606
2	Horizontal Bending Moment	1.088	0.616	0.884	0.699
3	External Pressure Port	1.044	0.570	0.883	0.651
4	External Pressure Starboard	1.044	0.570	0.847	0.654
5	Vertical Acceleration	1.155	0.431	0.886	0.622
6	Transverse Acceleration	1.015	0.308	0.850	0.470
7	Longitudinal Acceleration	1.110	0.581	0.887	0.676
8	Pitch Motion	1.012	0.437	0.863	0.603
9	Roll Motion	1.048	0.315	0.837	0.433
10	Relative Vertical Motion at Forepeak	1.110	0.477	0.860	0.645
11	Wave Height	0.968	0.468	0.920	0.673
12	Vertical Shear Force	0.998	0.346	0.848	0.567
13	Horizontal Shear Force	1.084	0.616	0.882	0.704

Note:
[1] The most severe transit condition is presented.

4.2. Establishing Reassessed Scantlings

The first step of this phase is the determination of required hull girder yielding strength. Taking into account still water and wave vertical wave bending moments, we compute the required section modulus amidships. Table 4 provides the resulted values for each site. Section modulus is also calculated for the initial condition (as-built scantlings) of VLCC for comparison reasons. From a first site of view, a reinforcement seems to be needed in the option of N. Sea, whereas, in Nigeria hull girder yield strength seems adequate.

Table 4: *Hull girder yielding check.*

	FPSO N. Sea (required)	FPSO Nigeria (required)	Tanker (initial)[1]
Section Modulus	94.3	72.6	87.7

Note:
[1] Initial refers to as-built scantlings. Not scantlings at time of conversion (corroded scantlings).

Next, the calculation of local scantlings is needed. External pressures, due to static and dynamic components of waves, internal pressures, due to inertia forces and added pressure heads and sloshing pressures inside tanks are considered for the determination of local scantlings of plates and stiffeners. Also, a significant component that influence the final computations is the allowable bending stress that is different for each site. The required net scantlings are evaluated and the anticipated corrosion margin for the intended service life of 20 years is adopted. ABS Rules give for each structural member the nominal design corrosion value which has to be taken into account depending on the intended service operation [1]. Generally, in terms of local scantling evaluation, the requirements on the two sites are affected mainly, by the dynamic portion of local components of pressures and the allowable bending stress which differentiates in each location.

4.3. Establishing Renewal Scantlings

The determination of renewal scantlings for each structural member is based on equation 1 of ABS Rules [1]

$$t_{ren} = t_{reas} \times (1 - w) \tag{1}$$

where, t_{ren} is the resulted renewal scantling of each member, t_{reas} is the reassessed scantling of each member resulted from reassessment phase and w is the wastage allowance percentage (around 20%) for all members according to ABS Rules.

Buckling check is conducted based on renewal scantlings. Different modes of failure are investigated including buckling of plates in compression and shear, buckling of stiffeners in column buckling, torsional buckling and web/flange buckling. The actual stresses predicted to occur in midship section are checked with the ideal elastic buckling of plates and stiffeners in each case. The results show satisfying strength capacities for all members on both locations.

In the absence of thickness measurements at the time conversion for the evaluation of structural members' degradation due to corrosion, our assessment has its basis on measurements and developed models [4].

4.4. Fatigue strength assessment

The fatigue life of FPSO conversion can be divided in 3 phases:

- Tanker phase
- Transit phase
- FPSO phase

The accumulated fatigue damage during tanker operation, tanker phase, must be considered, as long as, the damage during transportation from shipyard to operation site (transit phase). Finally, the FPSO fatigue damage that is predicted to occur on site due to high cycle fatigue and low cycle fatigue has to be estimated. The former is caused by environmental conditions on-site, whereas the latter, due to load and offloading cycles. In the present paper, low cycle fatigue is ignored as it needs special treatment. In figure 4, a combination of the three phases is illustrated.

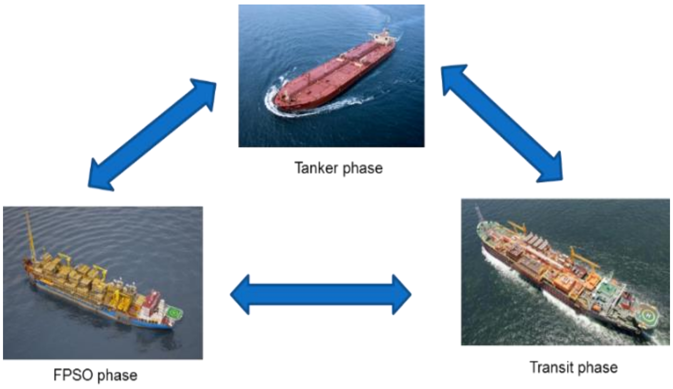


Figure 4: *The three phases for the fatigue life estimation of FPSO conversion*

The basic formulation of the above statement is based on the application of Palmgren-Miner rule [1] and is given by equation (2) as:

$$\frac{S_{\mathrm{Pr}iorConv}}{L_{P,\mathrm{Pr}ioConv}} + \frac{L_{R,\mathrm{P}ostConv}}{L_{P,\mathrm{P}ostConv}} = 1 \tag{2}$$

where, $S_{\mathrm{Pr}iorConv}$ are the service years prior to conversion, $L_{P,\mathrm{Pr}ioConv}$ is the fatigue design life prior to conversion, $L_{R,\mathrm{P}ostConv}$ is the remaining fatigue life for on-site operation, post conversion and $L_{P,\mathrm{P}ostConv}$ is the design fatigue life for on-site operation, post conversion. For the present work a critical connection of deck longitudinal stiffener with the transverse bulkhead on midship section area has been investigated for N. Sea environment. Assuming 10 years of service life prior to conversion from the initial design service life of 25 years as a trading tanker and the fact that a portion of fatigue damage consumed on transportation, the first term of equation (2) is practically equal to 0.5. Design fatigue life for on-site operation equal to 20 years is associated with the damage *DM* predicted to occur on this time period. After these manipulations, equation (2) can be written more analytically as:

$$L_{R,\mathrm{P}ostConv} = L_{P,\mathrm{P}ostConv} \times \left(1 - \frac{S_{\mathrm{Pr}iorConv}}{L_{P,\mathrm{Pr}ioConv}}\right) = \frac{20}{DM} \times \left(1 - 0.5\right) \tag{3}$$

The cumulated damage *DM* that is the requested value is mainly, a function of S-N curves, which are referred to the specific structural detail and of the acting stress range taking into account primary stresses, i.e. vertical and horizontal wave bending moments, acting on the hull girder and secondary stresses acting on the flange of longitudinal. Nominal stresses are considered as reference stresses on S-N curves rather than more localized peak stresses [1]. Cumulated damage also accounts for four different loading conditions and wave heading probabilities. The *DM* calculated from the analysis is equal to 0.41. Substituting in equation (3) we obtain a remaining fatigue life on-site equal to 25 years. This result shows that the examined connection withstands as concerns high cycle fatigue.

5. Reliability assessment of FPSO

5.1. General Concept

The goal of SRA is to rationally quantify the Load and Strength uncertainties of the structure and derive the probability of failure P_f which is related by the reliability *R* of the structure by equation (4) as:

$$R = 1 - P_f \tag{4}$$

Let us assume the ship as a hull girder subjected to loads. Figure 5 shows the pdf of load *S* and strength *R* of the girder in terms of applied bending moment and ultimate moment capacity of the girder, respectively. Both, the load and strength are assumed to follow the normal probability distribution. A simple function *g* can be obtained describing the safety margin *M* between the strength *R* of the girder and the load *S* acting on it.

$$M = g(R,S) = R - S \tag{5}$$

Equation (5) is called a *limit state function* or *performance function*. Both *R* and *S* are random variables and may assume several values. The following events describe the possible states of the structure.

$M = R - S > 0$	Safe domain
$M = R - S = 0$	Border surface between the safe and failure domain
$M = R - S < 0$	Failure domain

The probability of failure is denoted by:

$$P_f = P(R \le S) = P(R - S \le 0) = P(Z \le 0) \Rightarrow P_f = \int_{z \le 0} f_Z(z)\,dz \tag{6}$$

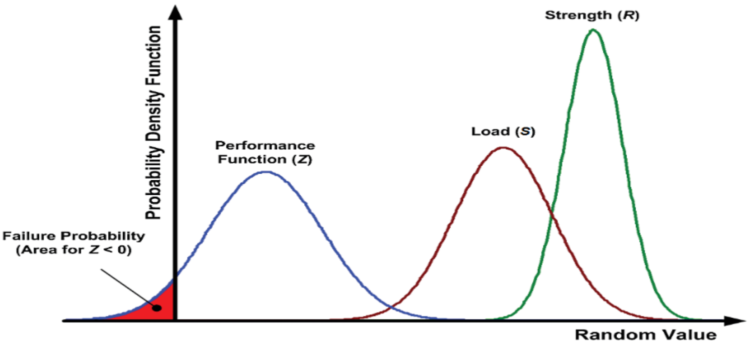


Figure 5: *Pdf of strength (R), load (S) and resulted performance function (Z)*

This probability of failure is what we want to calculate in each SRA problem. However, as mentioned in the introduction, employing equation (6) to evaluate this probability can be impractical and most of the times impossible due to the large number of random variables and joint pdf. Hence, a *Level 2* reliability method is employed in our research in order to reach this probability of failure for the different limit states we are going to introduce. To do that an accurate assessment of the variables used in our problem must be performed.

5.2. Still Water Bending Moment (SWBM)

Still water bending moment is a static effect whose magnitude depends on the loading condition and cargo distribution. In contrast with trading tankers, FPSO loading conditions vary more frequently due to different loading patterns and operational needs. The SWBM variation at the midship section on different loading conditions is illustrated in Figure 6, for the FPSO vessel intended to operate in N. Sea and offshore Nigeria.

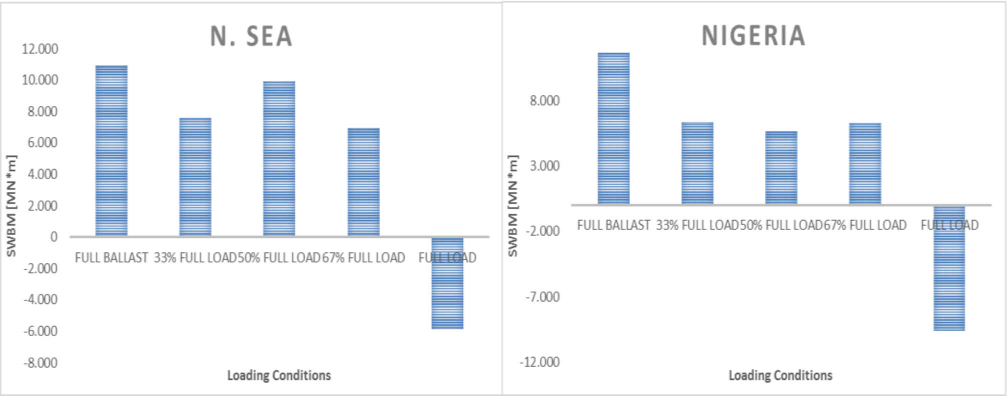


Figure 6: *SWBM maximum values of FPSO on two operation sites*

In this work, we consider all the maximum values of SWBM acting on the hull girder as deterministic values. We investigate the problem from a long-term time perspective and hence, we are interested for the probability of failure that is contributed from loading conditions and not only for the worst-case conditions. This particular issue will be analyzed later on with more details and mathematic formulations. Taking into account uncertainties related with the modeling of vessel on AVEVA software and human factor uncertainties during operation, we introduce a model uncertainty factor η_{sw} assumed to follow the normal distribution with a mean value of 1.0 and a coefficient of variation that varies (see later on section 5.7).

5.3. Wave Bending Moment (VWBM)

5.3.1. Design ABS Rule value

According to ABS Rules [1] the design vertical wave bending moment values with probability of exceedance of 10^{-8} are given by equations (7) and (8), in $kN \cdot m$, for sagging and hogging.

$$M_{wv-sag} = -110\beta_{VBM} CL^2 B\left(C_b + 0.7\right)\cdot 10^{-3} \tag{7}$$

$$M_{wv-hog} = 190\beta_{VBM} CL^2 BC_b \cdot 10^{-3} \tag{8}$$

where L, B, C_b are length, breadth and block coefficient of FPSO, respectively and β_{VBM} is the environmental severity factor for VWBM. C is given by equation (9) as:

$$\begin{aligned} C &= 10.75 - \left(\frac{300-L}{100}\right)^{1.5} && \text{for } 90m \le L \le 300m \\ &= 10.75 && \text{for } 300m \le L \le 350m \\ &= 10.75 - \left(\frac{L-350}{150}\right)^{1.5} && \text{for } 350m \le L \le 500m \end{aligned} \tag{9}$$

5.3.2. Stochastic representation of long-term VWBM

The long-term distribution of the VWBM is well represented by the two parameter Weibull distribution [5]. For this distribution, the pdf is:

$$f_X(X) = \frac{k}{\sigma_W}\left(\frac{X}{\sigma_W}\right)^{k-1} e^{-\left(\frac{X}{\sigma_W}\right)^k} \tag{10}$$

where,

X = wave-induced vertical bending moment

$k = 1.1 - 0.35\dfrac{L-100}{300} \ge 0.85$, shape parameter

$\sigma_W = \dfrac{X_p}{\left(\ln N_R\right)^{1/k}}$, characteristic value of X

N_R = number of cycles corresponding to the probability of exceedance of 10^{-8}

X_p = wave-induced vertical bending moment at the probability of exceedance of 10^{-8}

The cumulative distribution function (cdf) is the integral of (10), which is:

$$F(X) = 1 - e^{-(X/\sigma_W)^k} \tag{11}$$

where $F(X)$ is the probability that the amplitude of wave induced bending moment is less than a given value X at any one of the N cycles encountered.

However, most of the times we are interested in the maximum value of wave induced bending moment over a large number of period. So, we use the extreme value distribution, giving the probability that the wave induced bending moment amplitude is less than a given value $M_{wv,e}$ over the N cycles. The cdf of it is:

$$F(M_{wv,e}) = P\left[X \le M_{wv,e}\right] = \left[1 - e^{-(M_{wv,e}/\sigma_W)^k}\right]^N \tag{12}$$

The pdf of the extreme value is maximum for $M_{wv,e} = u$, where u represents the *most probable value* of the extreme value distribution. If the N cycles are assumed to be independent and sufficiently large, it can be shown that the extreme value distribution, as given by equation (12) converges to *Gumbel* distribution:

$$F_G\left(M_{wv,e}\right) = e^{-e^{-\left(\frac{M_{wv,e}-u}{\theta}\right)}} \tag{13}$$

where,

$$\theta = \frac{\sigma_W}{k}\left[\ln N\right]^{(1-k)/k} \tag{14}$$

The mean value μ, standard deviation σ and coefficient of variation *cov* of extreme wave induced bending moment distributed according to the *Gumbel* distribution are:

$$\begin{aligned} \mu_{M_{wv,e}} &= u + 0.5772 \cdot \theta \\ \sigma_{M_{wv,e}} &= \frac{\pi}{\sqrt{6}}\theta \\ \mathrm{cov} &= \frac{\sigma_{M_{wv,e}}}{\mu_{M_{wv,e}}} = \frac{\pi}{\sqrt{6}\left(0.5772 + k\ln N\right)} \end{aligned} \tag{15}$$

In N. Atlantic, the mean encountered wave period for a ship sailing at 5 knots is 8.46 sec, which corresponds to 10^8 wave cycles in 26.8 years [6]. However, the number of load cycles does not correspond to the number of wave cycles. The mean load period depends on mainly on the load type and of the ship length and it is usually larger than the mean encountered wave period. If we assume that the mean load period is between 8.5sec and 12sec, then the number of load cycles in 25 years is between $0.66 \cdot 10^8$ and $0.93 \cdot 10^8$. Therefore, using $N=10^8$ to predict the extreme response values for various wave loads in long-term prediction calculations, the resulted extreme response values should be in the safe side [6].

The mean (annual) absolute wave period is 8.19 sec and 11.36 sec specified for N. Sea and offshore Nigeria, respectively [7]. Based on the fact that wave cycles do not correspond to load cycles and taking as reference the same period of service life, i.e. the 25 years, the total wave cycles N can be obtained. Table 5 summarizes these results.

In order to provide the pdf of Gumbel distribution on the three different cases, the different design VWBM from equations (8), (9) are considered in equations (13-15), and finally, as illustrated in figure 7, the extreme value distributions are derived on the basis of 25 service life. Notice that N. Sea and N. Atlantic, where prevail almost the same environmental conditions have near pdf, whereas it is obvious that Nigeria sea state is characterized by a much more benign environment.

Table 5: *Total wave cycles N based on mean wave period for three discrete regions*

	N. Atlantic	***N. Sea***	***Nigeria***
T_{mean} (sec)	8.46(1)	8.19(2)	11.36(2)
Wave cycles N	10^8	$0.96{\cdot}10^8$	$0.69{\cdot}10^8$
Load period (sec)	8.5 - 12	8.5 - 12	11.5 – 15.0
Load cycles	$0.66{\cdot}10^8$ - $0.93{\cdot}10^8$	$0.93{\cdot}10^8$ - $0.66{\cdot}10^8$	$0.69{\cdot}10^8$ - $0.53{\cdot}10^8$
Corresponding years	25	25	25

Notes:

[1] Encountered wave period sailing at 5 knots [6]

[2] Annual absolute mean value [7]

An uncertainty factor η_{wv} is introduced to multiply with the $M_{wv,e}$ to take into account the uncertainty induced by linear response calculation and nonlinear effects. η_{wv} is assumed to be a normally distributed random variable with a mean value of 1.0 and a coefficient of variation of 0.1 [8].

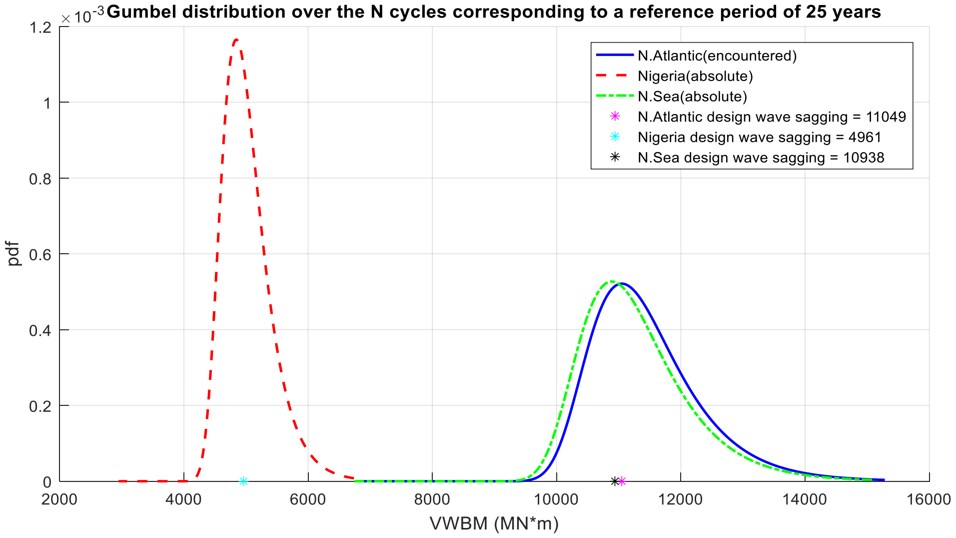


Figure 7: *Stochastic representation of VWBM following Gumbel distribution for different sea locations*

5.4. Resistance

The resistance of FPSO has been calculated in terms of Initial yielding and Ultimate strength. Although initial yield moment is generally not indicative of the true resistance of the ship's structure, it is included in the analysis because it is a common design criterion. It would be interesting for someone to see the comparisons between this limit state and a more accurate estimation of vessel's ultimate strength. Different methodologies have been employed for the determination of the aforementioned limit states. A basic parameter that affects the resistance of hull vessel is corrosion. Structural degradation has been taken into account considering annual measurements of corrosion rate in each structural member [4] and ABS Rules [1].

5.4.1. Initial Yield Strength

Initial yield strength describes the resistance on serviceability limit state. It is related to the hull girder longitudinal bending moment, initial yield moment, M_{IY} which is equal to the midship cross section elastic section modulus, SM_{el} times the material yield stress, σ_y . The above is given by equation (16) as:

$$M_{IY} = SM_{el} \cdot \sigma_y \tag{16}$$

Determination of the deterministic section modulus is clearly a geometric calculation procedure. However, we have examined how the section modulus can be modeled as a random variable at discrete times on the service life of vessel using the relationships presented in Appendix A. We do that by treating the corrosion rates of plates and stiffeners as normal random variables. The yield stress of the material can be represented by a normal probability density function (pdf) taking into account a probability of non-exceedance its characteristic (or nominal) value by 1%. For high steel AH32 (used steel for deck and bottom zone of our vessel) with nominal value, i.e. characteristic value 315 MPa, a coefficient of variation equal to 0.08 has been used in probabilistic analysis [10]. The pdf of steel is illustrated in figure 8.

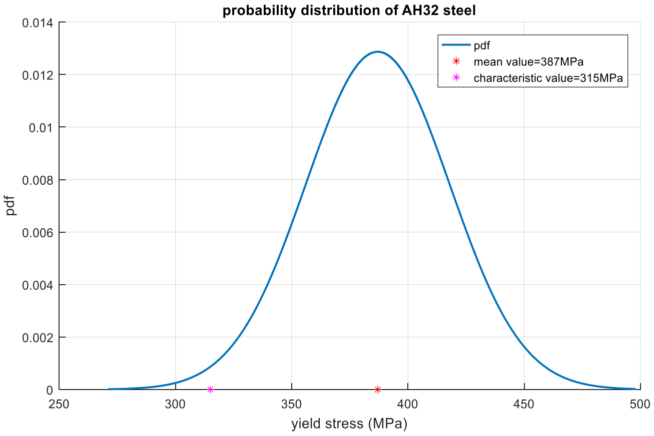


Figure 8: *Pdf of AH32 steel used in FPSO midship section*

5.4.2. Ultimate Strength

The determination of FPSO hull ultimate strength is of crucial importance. Ultimate strength denotes the maximum load-carrying capacity of hull girder in order to sustain the corresponding applied loads. There are different methodologies to compute the ultimate strength, such as, simple-beam theory approach, analytical methods (IACS Incremental-Iterative method) and Non-Linear Finite Element Methods (NLFEM).

In the present work, the ultimate bending capacity of the vessel cross section is calculated using MARS (Bureau Veritas software for structural calculation). MARS uses the Smith method in which a progressive collapse analysis method is performed in order to obtain the ultimate capacity in hogging and sagging condition.

The value of ultimate strength is considered as a fixed value. We introduce a model uncertainty factor η_u that accounts for uncertainty in the prediction of the hull girder ultimate bending capacity following a normal distribution with a mean value equal to 1.05 and coefficient of variation of 0.1 [8].

5.5. Limit State Functions (LSF)

Two limit states that define different failure events have been considered, i.e. initial yielding and ultimate strength LSF. The basic principle for the formulation of these LSF has been summarized in section 5.1. The limit state functions with respect to the initial yield failure g_{IY} and ultimate failure g_U under vertical bending moments have the following form:

$$g_{IY} = SM_{el} \cdot \sigma_y - \eta_{sw} M_{sw} - \eta_{wv} M_{wv} \tag{17}$$

$$g_U = \eta_u M_u - \eta_{sw} M_{sw} - \eta_{wv} M_{wv} \tag{18}$$

where, SM_{el}, σ_y are the elastic section modulus and yield stress of material, respectively, following a normal distribution, M_u is the deterministic hull girder ultimate strength, M_{sw} is the deterministic maximum bending moment in still water, M_{wv} is the extreme value of vertical wave bending moment following a Gumbel distribution and $\eta_u, \eta_{sw}, \eta_{wv}$ are the model uncertainty factors following a normal distribution.

For the evaluation of failure probability, it is assumed that FPSO spends part of its life time in a variety of conditions. This is in accordance with Mansour [9], who considers the combination each of the still water bending moments (full load and ballast) with both types of wave loading (hogging and sagging). In our case, we need to take into account each of the stillwater bending moments (full load, 67% partial load, 50 partial load, 33% partial load and full ballast) and combine them with wave loading (hogging and sagging), as it is shown in figure 9. The mathematic formulation of the above is given by equation (19).

$$P_f = \sum_{i=1}^{5} t_i P_{f,i} = t_{FL} P_{f,FL} + t_{IN1} P_{f,IN1} + t_{IN2} P_{f,IN2} + t_{IN3} P_{f,IN3} + t_{FB} P_{f,FB} \tag{19}$$

where,

$t_i = 0.2$ is the fraction of FPSO’s total life spent in full load (*FL*), 67% partial load (*IN1*), 50% partial load (*IN2*), 33% partial load (*IN3*) and full ballast conditions (*FB*) considering that FPSO will sent equal life on each of them

$P_{f,i}$ are the probabilities of failure in the considered limit state with full load, 67% partial load, 50% partial load, 33% partial load and full ballast condition

P_f is the total probability of failure in each limit state

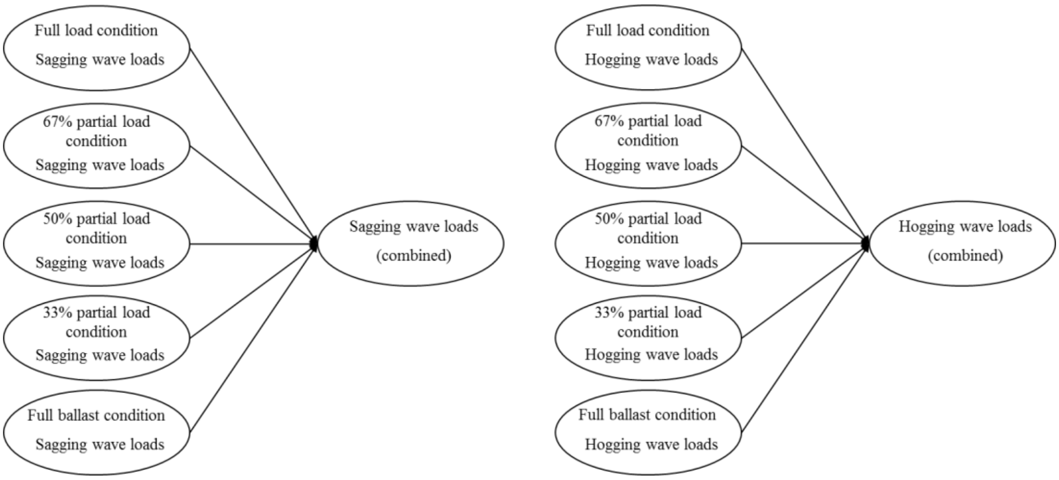


Figure 9: *Combining long-term results for FPSO*

5.6. First Order Reliability Method (FORM)

The basic concept of FORM is summarized by the following state. Given a *n* number of random variables, find that set of *n* values situated on the LSF which gives the most probable combination to failure. This point or set of points is also referred as the *design point* or *Most Probable Failure Point (MPFP)* and the minimum distance β from the origin in the standard normal space up to the design point is the *reliability index*, as shown in figure 10. FORM linearizes the performance function using Taylor series approximation. The method is to apply an iteration procedure to find the design point on the limit state surface. Once the design point is found, the probability of failure P_f is given by

$$P_f = \Phi(-\beta) \tag{20}$$

where $\Phi(\cdot)$ is the standard normal cdf. The method, also, requires changing the distribution function of each random variable in a normal distribution function. This is the so-called iterative normal tail approximation [11]

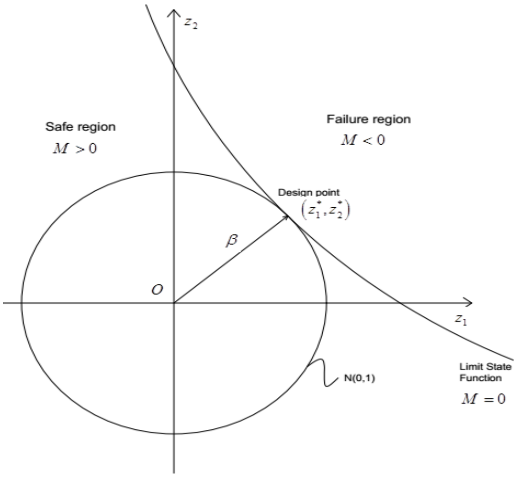


Figure 10: *Failure surface in standard space*

Generally, there are many algorithms to employ FORM. The one that is adopted here and accounts for nonlinear LSF, as also for non-normal random variables is described in the following steps and illustrated in figure 11:

1. Describe the LSF by random variables in normal (initial) space.
2. Transform the original variables *X* to standard (reduced) space *Z*.
3. Formulate the LSF on reduced space. Input k=1.
4. Transform the non-normal variables into equivalent normal variables by normal tail approximation.
5. Derive the direction cosines at the linearization point. As an initial guess for the unknown variables take the mean value of them.
6. Obtain the LSF at design point and solve for reliability index, β.
7. Obtain the new set of coordinates at design point in standard space.
8. Transform this set of coordinates on normal space.
9. If k=1 go to step 4 and iterate.
10. If the reliability index is equal to that of the previous iteration (2 digits precision), convergence is achieved. If not, go to step 4 and iterate.
11. Calculate the design point, the reliability index and define the probability of failure.

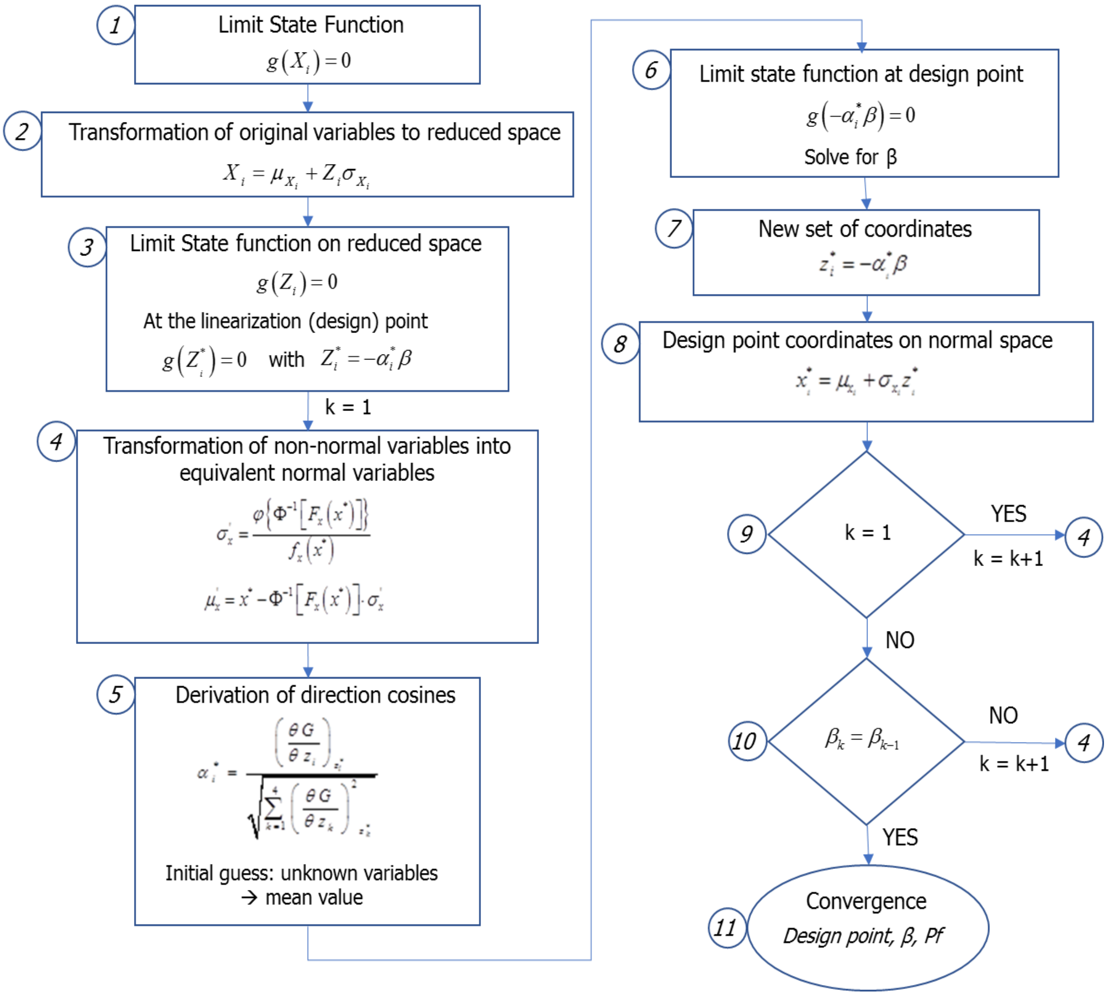


Figure 11: *Employed FORM algorithm*

5.7. Numerical application

The methodology presented in this section has been applied to the SRA of the FPSO, in both locations, taking into account equations (17) and (18) for implementation of hull girder initial yielding and ultimate strength. The assessment has been performed on discrete times, i.e. 20, 25 and 30 years of service life. In order to have a common reference initial condition of hull structure for both installation sites, we obtained as-built scantlings of tanker at time zero (conversion stage). Also, structural degradation due to corrosion is reduced with the same rate for Nigeria as for N. Sea. Table 6 provides a summary of the variables that has been used in the analysis and their sensitivity by the different scenarios examined in the problem. For example, someone can notice that extreme wave induced vertical bending moment is affected by all possible different scenarios.

***Table 6**: Sensitivity of defined variables by the different parameters*

	Scenario		
Variable	Location	Load case (hog/sag)	Service years
η_u	-	-	-
η_{sw}	-	-	-
η_{wv}	-	-	-
M_{sw}	✓	✓	-
$M_{wv,e}$	✓	✓	✓
M_u	-	✓	✓
SM_{el}	-	-	✓
σ_y	-	-	-
Notes: (✓) denotes effect of the scenario on the variable (-) denotes non effect of the scenario on the variable			

In terms of still water bending moment representation, all loading conditions have been considered as fixed values combined with vertical wave sagging and vertical wave hogging moments with the way presented in section 5.5 and figure 9.

The physical meaning of the model uncertainties factors used in the problem has been discussed previously. Their mean value, coefficient of variation and distribution is presented in table 7. As stated previously, model uncertainty factors for extreme wave bending moments and ultimate strength has been supported to previous works [8]. That is not the case for still water bending moment model uncertainty factor and for that reason we implemented our analysis with two different values of *cov*, that is 0.1 and 0.3.

For the calculation of section modulus on deck, we implemented the formulations as described in Appendix A considering corrosion rates of members as normal random variables with mean values as described by data measurements on double hull oil tankers and FPSOs [4] and a standard coefficient of variation equal to 0.10 [12]. The resulted mean values and variance of midship section modulus on deck are shown in table 8.

FPSO hull girder ultimate bending capacity has been computed by MARS software. The relationship between the applied curvature, κ and the reaction moment, M is illustrated in figure 12, for both hogging and sagging. The input net scantlings have been introduced as specified by ABS Rules [1] for 20, 25 and 30 years of service life. The ultimate bending moments are presented numerically in table 9.

The vertical wave bending moment extreme value distribution for the different time periods on two sites is illustrated in figure 13. Someone can observe a rational shift of the pdf to increased values of VWBM as the time period vessel is subjected to waves is increased and so, total number of wave cycles increases. The figure also demonstrates the discrepancies, in terms of location and the corresponding sea state, of the magnitude of most probable values of extreme VWBM.

Table 7: *Stochastic representation of model uncertainty factors*

Symbol	Mean	cov	Distribution
η_u	1.05	0.10	Normal
η_{sw}	1.00	0.10 & 0.30	Normal
η_{wv}	1.00	0.10	Normal

Table 8*: Calculated section modulus of midship cross section on different time periods*

Section modulus on deck			
Service years	Mean	Variance	units
20	81.89	0.61	m^3
25	79.96	1.94	m^3
30	78.03	4.82	m^3

Table 9: *Midship cross-section ultimate bending capacity for corroded (net) scantlings*

	20 years	25 years	30 years	units
M_u *(hog/sag)*	29 103 / 23 032	28 496 / 22 412	*27 811 / 21 736*	MN·m

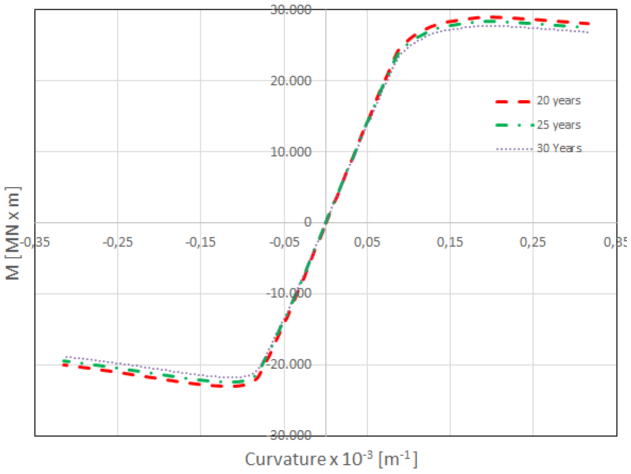


Figure 12: *Hull girder bending capacity on hogging/sagging with corroded scantlings*

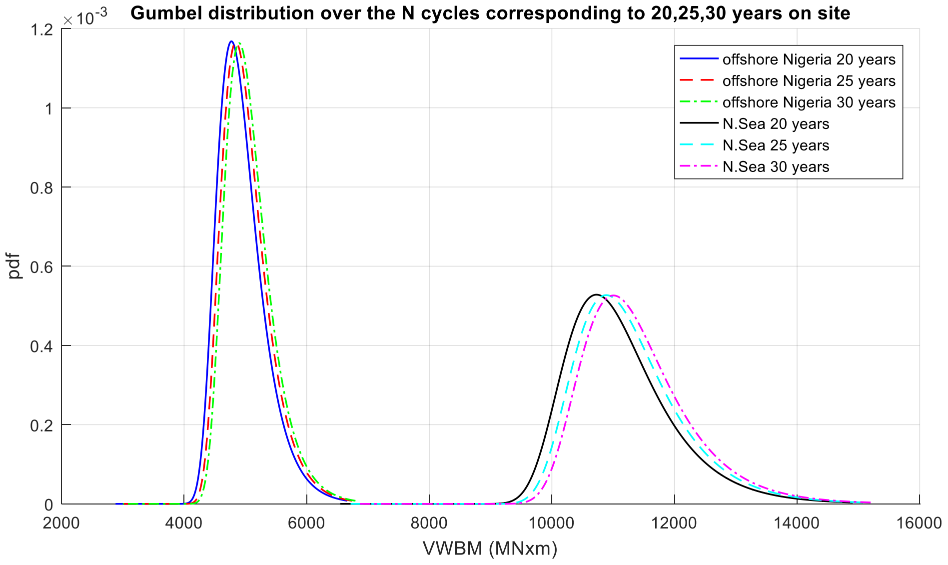


Figure 13: *Pdf of VWBM extreme value on two sites corresponding to different time periods*

It can be shown from the figures 14 to 17, that initial yield limit state is generally a much more reliable state in comparison with ultimate strength. That means that the level of probability of failure is much less than ultimate limit state. Another general comment that is quite rational is that with the increase of service life on-site the failure probability increases too, due to corrosion effects that reduce the capacity of the structure and simultaneously, due to the increased wave cycles encountered from the side of wave load. Moreover, someone can observe that the larger the coefficient of variation on SWBM load model uncertainty $\eta_{sw,}$ the less the value of reliability index and hence, the higher is the probability of failure. This makes sense because in that case, the load pdf is more ‘‘spread’’ and larger area under resistance pdf is overlapping.

The most unfavorable scenario, for both limit states, is N. Sea hogging and this is reasonable because of the following reason. The magnitude of maximum bending moment in still water that has been reported from AVEVA is equal to 10 946 MN·m, whereas the allowable SWBM in midship region for trading tanker was 8 826 MN·m as referred to loading manual. This increase of the order of 24% in hogging SWBM has as a result a large increase in loads and hence, in probability of failure.

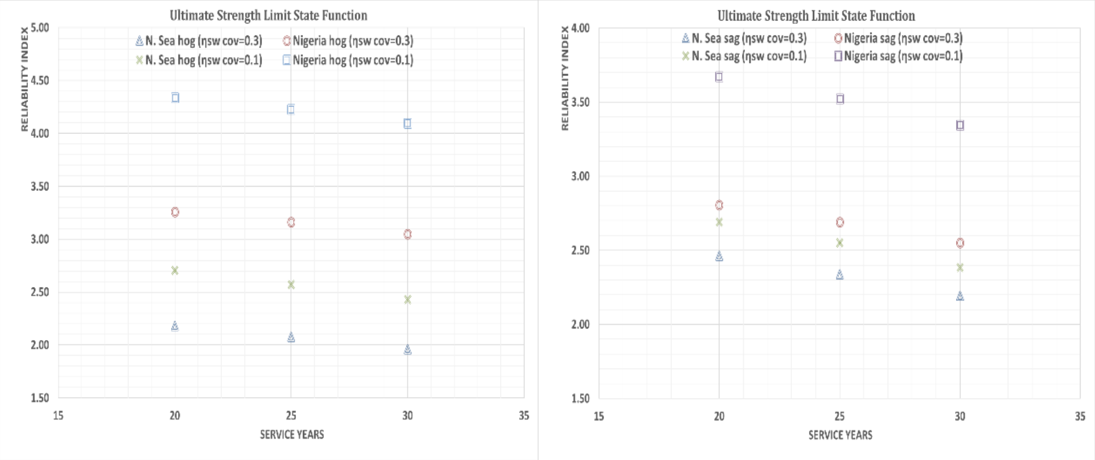


Figure 14: *Reliability index on Ultimate limit state*

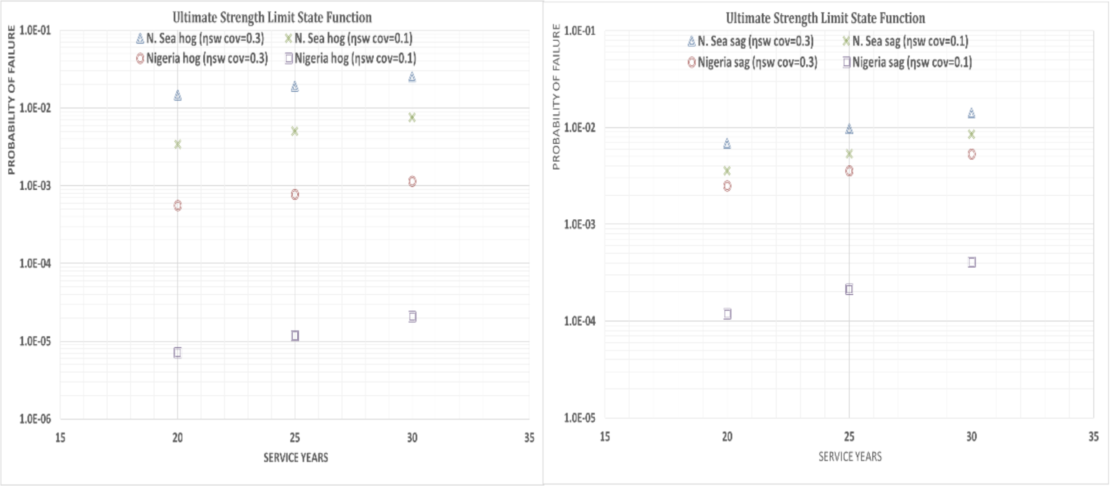


Figure 15: *Failure probabilities on Ultimate limit state*

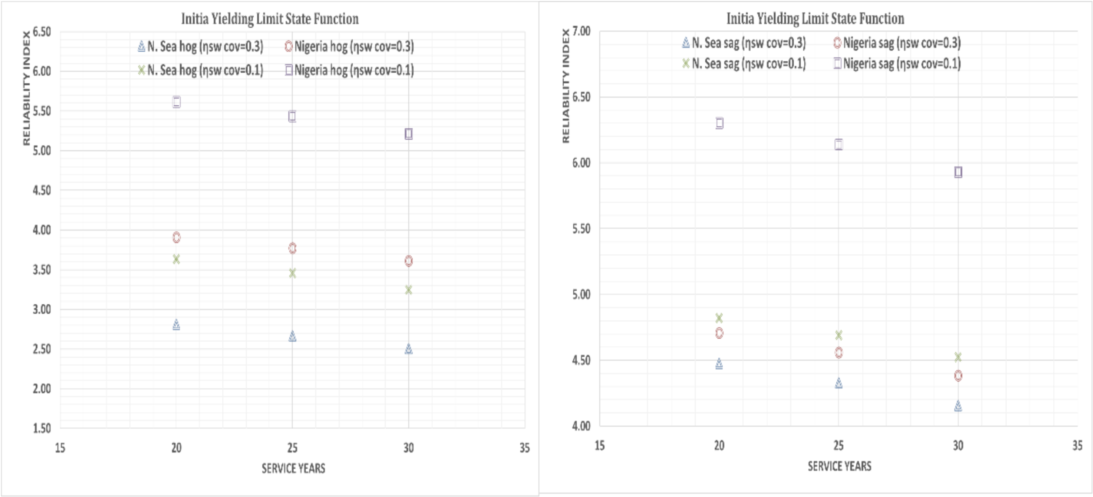


Figure 16: *Reliability index on Initial yielding limit state*

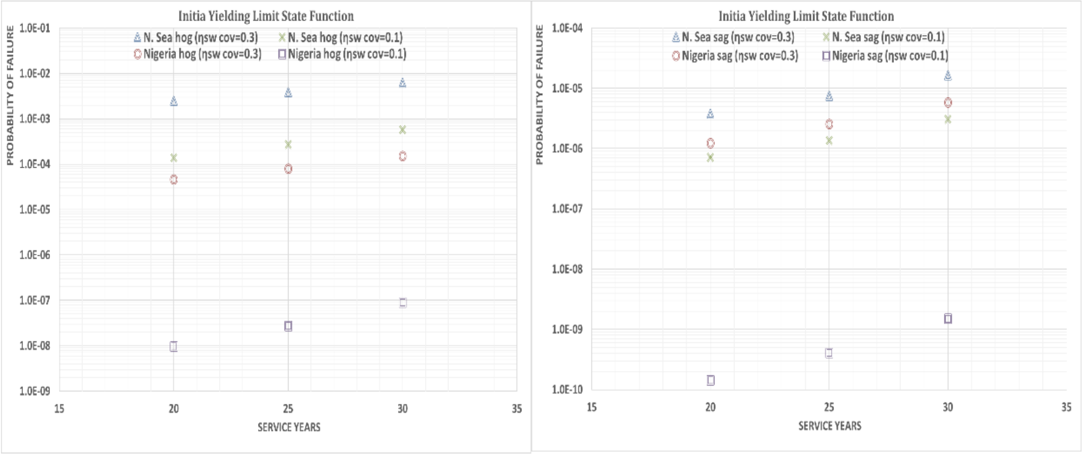


Figure 17: *Failure probabilities on Initial yielding limit state*

6. Concluding Remarks

This paper presents various aspects of FPSO hull structure, including FPSO conversion methodology, strength analysis, fatigue evaluation and hull girder structural reliability assessment.

The steel renewal assessment procedure implemented according to ABS Rules for the case of a conversion of a VLCC tanker to FPSO shows that the environmental conditions that prevail offshore Nigeria favor the conversion of the selected vessel, whereas for the intended site of N. Sea, the repairs and renewals needed are so extensive that the conversion seems unfavorable option. The above conclusion is verified from the fact that purpose-built FPSOs are selected mostly for harsh environments. Significant role for the establishment of criteria plays the structural degradation and the maintenance policy during its service life as a trading tanker. Important aspect need to be considered is that in benign environments, such as that of Equator region, results show that transportation from shipyard could be the dominant condition regarding wave-induced loads.

In terms of fatigue, special attention must be paid in harsh environments, firstly, because of the preexisting fatigue damage of vessel as a trading tanker and secondly, due to the increased magnitude of stress range induced by waves in comparison to N. Atlantic base environment. Results show that the examined connection withstands with respect to high cycle fatigue, but low cycle fatigue has to be considered additionally to obtain a safe result.

The approximate concepts that are inherent in structural reliability analysis are tried to be analyzed in the context of this paper. In our implementation, our objective has been an accurate representation of the FPSO hull girder strength and loads variables. Main parameters that we examined include corrosion degradation of structural members, wave sea state on each operation site and different coefficient of variation for modeling uncertainty of SWBM, all in terms of primary failure, namely, initial yielding and ultimate limit state. The results indicate an increase level of reliability offshore Nigeria site, whereas in N. Sea the probability of failure ranges in high levels. Among the different load cases, hogging and sagging, the former, give us a failure probability higher than the latter, mainly affected by the larger magnitude of SWBM. To this direction a more accurate representation of still water bending moments over the entire life of FPSO vessel is needed.

Acknowledgments

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Bibliography

[1] American Bureau of Shipping (ABS), “Rules for Building and Classing. Floating Production Installations”, 2015

[2] J. K. Paik and A. K. Thayamballi, “Ship-Shaped Offshore Installations: Design, Building, and Operation”, Cambridge University Press, 2007.

[3] Det Norske Veritas, “DNV-OS-C102 Structural Design of Offshore Ships,” no. October, 2012.

[4] J. Paik, L. Jae, H. Joon and P. Young, “A Time-Dependent Corrosion Wastage Model for the Structures of Single and Double Hull Tankers and FSOs and FPSOs” Marine

Technology, vol. 40, no. 3, pp. 201-217, 2003.

[5] B. R. S. Little, L. Member, E. V Lewis, H. Member, W. and F. C. Bailey, “Statistical Study of Wave-Induced Bending Moments on Large Oceangoing Tankers and Bulk Carriers.”, Trans. SNAME, vol. 79, 117-168.

[6] Common Structural Rules (CSR), “TB Report List for CSR BC & OT 2016-12-13 version,” no. 1, Pt 1, Ch 4, Sec 2, 2016.

[7] S. Barstow, G. Mørk, L. Lønseth, P. Schjølberg, U. Machado, G.Athanassoulis, K. Belibassakis, T. Gerostathis, Ch. Stefanakos, G. Spaan, “WORLDWAVES: Fusion of Data from Many Sources in a User-friendly Software Package for Timely Calculation of Wave Statistics in Global Coastal Waters” 13th Intern. Offshore and Polar Conference and Exhibition, ISOPE2003, Honolulu, Hawaii, USA vol. 5, 2003.

[8] N. Z. Chen, “Hull girder reliability assessment for FPSOs,” Eng. Struct., vol. 114, pp. 135–147, 2016.

[9] A. Mansour, P. Wirsching, M. Luckett and A. Plumpton, “Assessment of reliability of ship structures.”, Ship Structure Committee (SSC-398), 1997.

[10] O. Hughes, J. Paik, “Ship Structural Analysis and Design”, SNAME, 2010 .

[11] R. Rackwitz and B. Flessler, “Structural reliability under combined random load sequences,” Comput. Struct., vol. 9, no. 5, pp. 489–494, 1978.

[12] G. Soares and Y. Garbatov, “Reliability of Maintained Ship Hulls Subjected To Corrosion”, Journal of Ship Research, vol. 40, no. 3, pp. 235–243, 1996.

[13] P. H. Wirsching, J. Ferensic, A. Thayamballi, “Reliability with Respect to Ultimate Strength of a Corroding Ship Hull”, Marine Structures, vol. 10, no. 1997, pp. 501–518, 1998.

[14] G. Soares and Y. Garbatov, “Reliability assessment of maintained ship hulls with correlated corroded elements,” Marine Structures, vol. 10, no. 8–10, pp. 629–653, 1997.

Appendix A

The appendix describes the procedure of representation of section modulus and cross section properties as normal random variables [13], [14].

1. Area of the section:

$$A = \sum_{i=1}^{n} A_i = \sum_{i=1}^{n} b_i \left(t_{nom} - c_i \cdot f\left(t\right) \right) \tag{A.1}$$

Mean value: $$\mathrm{E}(A) = \sum_{i=1}^{n} b_i \left(t_{nom} - E\left(c_i\right) \cdot f\left(t\right) \right) \tag{A.2}$$

Variance: $$\sigma_A^2 = \sum_{i=1}^{n} b_i^2 f^2\left(t\right) \sigma_{c_i}^2 \tag{A.3}$$

2. Moment of Area of the section:

$$M = \sum_{i=1}^{n} z_i A_i \tag{A.4}$$

Mean value: $$\mathrm{E}(M) = \sum_{i=1}^{n} z_i E\left(A_i\right) \tag{A.5}$$

Variance: $$\sigma_M^2 = \sum_{i=1}^{n} z_i^2 \sigma_{A_i}^2 \tag{A.6}$$

3. Position of the neutral axis:

Mean value: $$\mathrm{E}(z_{NA}) = \frac{\mathrm{E}(M)}{\mathrm{E}(A)} \tag{A.7}$$

Variance: $$\sigma_{z_{NA}}^2 = \frac{\sigma_M^2}{\left[E\left(A\right)\right]^2} + \frac{\left[E\left(M\right)\right]^2}{\left[E\left(A\right)\right]^4} \sigma_A^2 \tag{A.8}$$

4. Inertia of the section:

Mean value: $$\mathrm{E}(I) = \left[\sum_{i=1}^{n} \mathrm{E}(A_i) z_i^2 + \mathrm{E}(i)\right] - \mathrm{E}(A)\left[E\left(z_{NA}\right)\right]^2 \tag{A.9}$$

where $i = \dfrac{t_i h_i^3}{12}$

Variance: $$\sigma_I^2 = \sigma_{Ib}^2 + \left[E\left(z_{NA}\right)\right]^4 \sigma_A^2 + 4\left[E\left(A\right)\right]^4 \left[E\left(z_{NA}\right)\right]^2 \sigma_{z_{NA}}^2 \tag{A.10}$$

where $\sigma_{I_b}^2 = \sum_{i=1}^{n}\left[z_i^4 \sigma_{A_i}^2 + \left(h_i^3/12\right)^2 \sigma_{t_i}^2\right]$

5. Section modulus:

Mean value: $$\mathrm{E}(SM_{bot}) = \frac{\mathrm{E}(I)}{\mathrm{E}(z_{NA})} \tag{A.11}$$

$$\mathrm{E}(SM_{bot}) = \frac{\mathrm{E}(I)}{D - \mathrm{E}(z_{NA})} \tag{A.12}$$

Variance: $$\sigma_{SM_{bot}}^2 = \frac{\sigma_I^2}{\left[E\left(z_{NA}\right)\right]^2} + \frac{\left[E\left(I\right)\right]^2}{\left[E\left(z_{NA}\right)\right]^4} \sigma_{z_{NA}}^2 \tag{A.13}$$

$$\sigma_{SM_{deck}}^2 = \frac{\sigma_I^2}{\left[D - E\left(z_{NA}\right)\right]^2} + \frac{\left[E\left(I\right)\right]^2}{\left[D - E\left(z_{NA}\right)\right]^4}\sigma_{z_{NA}}^2 \qquad \text{(A.14)}$$