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Hull Structure Integrity Management in Floating Structures–FSO Puteri Dulang Case

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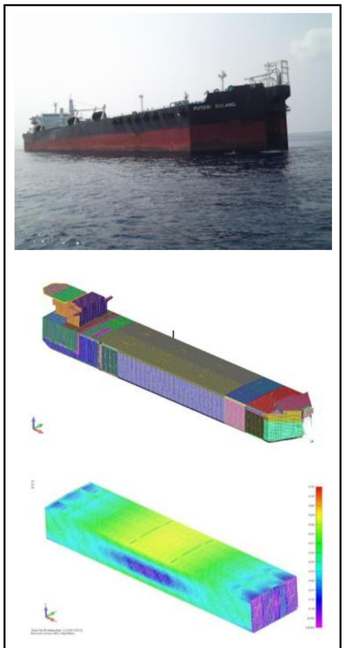
Graphical abstract



Abstract

This paper highlights the key differences in practices employed in managing hull structure integrity of permanently moored floating offshore structures as against sailing vessels which are subject to periodic dry docking. During the design phase, the structural integrity management over the life of a sailing vessel is primarily taken into account by means of Class prescribed Nominal Design Corrosion Values which are added to minimum scantling requirements calculated based on strength and fatigue criteria. In contrast, for permanently moored offshore installations like FPSOs, FSOs etc. the hull structure integrity over the entire design life of the asset is a key design consideration both for new buildings and conversions. Analytic methods and tools (primarily those developed by Class Societies) are available to evaluate the strength requirements (based on yielding, buckling and ultimate strength criteria) and fatigue life of the hull structure. Typically three levels of analysis with increasing degree of complexity and analysis time are used to predict the structural response and fatigue life of the Hull during design phase. The degree of detailed analysis required needs to be determined in light of the expected optimization in terms of savings in scantlings for new building or for steel renewal requirements in case of conversions.

Keywords: Hull structure; finite element analysis; global structural strength; fatigue analysis

1.0 INTRODUCTION

There are currently 8,881 cargo tankers,[1] 186 FPSO units[2] and hundreds FSO units of various sizes being operated worldwide which have had their hull undergone structural integrity verification review and certification by classification societies as one of the compulsory Flag State requirements. Among the leading classification societies are American Bureau of Shipping (ABS), Bureau Veritas (BV), Det Norske Veritas (DNV) and Lloyd's Register (LR).

Offshore floating structures which are FPSO and FSO units in particular, could either be converted from oil tankers or purposely built for their specific functions. These offshore floaters will approximately have the same hull shape and scantling design with oil tankers and share the common class rules and regulations for its hull and marine design.

Despite having these similarities, among the key differences between offshore floaters and oil tankers are mainly the operations and safety requirements, topside layout and arrangement, service location, rules and regulations in the operating area, survey and maintenance, etc.

The hull structure scantlings for offshore units can be optimized from the scantling requirements of tankers for unrestricted service to varying degrees depending on the environmental severity, cargo composition, required design/service life and degree of oxygen concentration in the inerting medium inside cargo tanks. The optimization in scantlings from the values prescribed by class rules is achieved by means of first principle analysis which is in general quite intensive in terms of modeling and analysis time. The level of intensity in modeling and analysis is determined by the expected degree of optimization that can be achieved in terms of hull scantlings and other economic factors.

This paper will highlight the key differences in managing the hull structural integrity of sailing tankers as against permanently moored floaters as well as provide an overview of the different levels of analysis that can be employed for the optimization process including the expected optimization in scantlings using the life extension analysis of FSO Puteri Dulang as a case study.

2.0 HULL STRUCTURE INTEGRITY MANAGEMENT FOR OIL TANKERS

Oil tankers are designed for the carriage of crude oil and/or petroleum products for domestic and international routes. Independent ship owners control a majority of the tanker tonnage. These owners tend to build versatile vessels that are less likely to become obsolete due to market and environment changes. This practice has led to a commonality in vessel sizes and configurations. This commonality enables shipyards to build large series of the same design, which significantly reduces the cost of construction.

Table 1 shows the number of the world oil tanker fleets by size of vessel in operation and in shipyards order book.

Table 1 World oil tanker fleets[1]

Size	No. of units	Deadweight ('000 Tonnes)	Order book no.	Deadweight ('000 Tonnes)
Handy	802	29,563	169	8,003
Panamax	397	28,513	28	2,069
Aframax	900	96,550	80	8,953
Suezmax	492	76,089	59	9,116
VLCC	585	178,422	24	7,537
ULCC	40	13,078	33	10,560
Total	**3,216**	**422,215**	**393**	**46,231**

Note:
VLCC-Very large crude carrier,
ULCC-Ultra large crude carrier

For standardized hull sizes, classification societies' rules and guidelines dictate the methodology for determining the hull members' scantlings. Further optimizations from Class' prescribed values are possible by means of first principles analysis. Corrosion allowances are added to the net required hull scantlings as prescribed under Section 6/3.2 of Common Structural Rules for oil tankers.

Local corrosion addition,

$$t_{corr} = t_{was} + 0.5\ mm \qquad (1)$$

where

t_{was} = total wastage allowance of the considered structural member
$= t_{was-1} + t_{was-2}$
t_{was-1} = Wastage allowance for side one of the structural member considering the contents of the compartment to which it is exposed
t_{was-2} = Wastage allowance for side two of the structural member considering the contents of the compartment to which it is exposed

The following Table 2 from Common Structural Rules for Tankers provides wastage allowances for various structural members of a tanker hull based on location and compartment type.

Table 2 Local wastage allowance for one side of structural elements[3]

Compartment Type	Structural Member		Wastage Allowance (mm)
Ballast water tank and chain locker	Face plate of PSM	Within 3m below top of tank [(a)]	2.0
		Elsewhere	1.5
	Other members [(c)]	Within 3m below top of tank [(a)]	1.7
		Elsewhere	1.2
Cargo oil tank	Face plate of PSM	Within 3m below top of tank [(a)]	1.7
		Elsewhere	1.4
	Inner-bottom plating/bottom of tank		2.1
	Other members [(c)]	Within 3m below top of tank [(a)]	1.7
		Elsewhere	1.0
Exposed to atmosphere	Weather deck plating		1.7
	Other members		1.0
Exposed to sea water	Shell plating [(b)]		1.0
Fuel and lube oil tank [(d)]	Top of tank and attached internal stiffeners		1.0
	Elsewhere		0.7
Fresh water tank	Top of tank and attached internal stiffeners		1.0
	Elsewhere		0.7
Void spaces	Spaces not normally accessed, e.g. access only via bolted manhole openings, pipe tunnels, etc.		0.7
Dry spaces	Internals of deckhouses, machinery spaces, pump room, store rooms, steering gear space, etc.		0.5

Notes
a. Only applicable to cargo and ballast tanks with weather deck as the tank top.
b. 0.5mm to be added for side plating in the quay contact region as defined in Section 8 of [3]
c. 0.5mm to be added to the plate surface exposed to ballast for plate boundary between water ballast and heated cargo oil tanks. 0.3mm to be added to each surface of the web and face plate of a stiffener in a ballast tank and attached to the boundary between water ballast and heated cargo oil tanks. Heated cargo oil tanks are defined as tanks arranged with any form of heating capability (most common type is heating coils).
d. 0.7mm to be added for plate boundary between water ballast and heated fuel oil tanks

During operations, the structural members are subjected to corrosion over a period of time. During regular scheduled intermediate / special surveys of tankers, the condition of structural members is assessed by means of visual inspection, close-up surveys and thickness gauging measurements. The criteria for steel renewal can be broadly classified as local and global. In general steel renewal is required if either the local or over all hull girder wastage allowance is exceeded as a result of corrosion. As such there are two main types of wastage allowances to be considered – local wastage allowance and overall hull girder wastage allowance.

2.1 Renewal Criteria Based on Local Wastage

In general steel renewal is required if the measured thickness, tm is less than the renewal thickness, t_{ren}

$$t_{ren} = t_{as\text{-}built} - t_{was} - t_{own} - t_{corr\text{-}2.5} \quad (2)$$

where

$t_{as\text{-}built}$ = As-Built thickness
t_{own} = Additional wastage allowance specified by Builder/Owner if any
$t_{corr\text{-}2.5}$ = 0.5 mm wastage allowance in reserve for corrosion occurring in the two and a half years between Intermediate and Special surveys

2.2 Renewal Criteria Based on Overall Hull Girder Section Properties

In order to determine whether steel renewal is required based on residual hull girder sectional properties, the following actual sectional properties are to be verified. These properties are to be calculated using measured thicknesses.

(a) Vertical hull girder moment of inertia, about the horizontal axis, I_v
(b) Hull girder section modulus about the horizontal axis – at deck-at-side, $Z_{v\text{-}dk}$
(c) Hull girder section modulus about the horizontal axis – at keel, $Z_{v\text{-}kl}$
(d) Hull girder section modulus about the vertical axis – at side, $Z_{h\text{-}side}$
(e) Hull girder vertical shear area, $A_{v\text{-}shr}$

Steel renewal is required by replacement of local corroded structural elements if any of the above calculated section properties is lower than the minimum required value.

The minimum allowable hull girder sectional properties in the corroded condition are calculated using the same corrosion thickness reductions that are used during the new building stage, thus linking the new building and ship in operation criteria. The minimum allowable hull girder sectional properties are to be calculated in accordance with Section 4/2.6 of the Common Structural Rules for Oil Tankers. The calculation is to be based on a member thickness, t given by:

$$t = t_{as\text{-}built} - 0.5\, t_{corr} - t_{own} \quad (3)$$

The renewal criteria for other local forms of corrosion such as pitting, grooving and edge corrosion are defined in Section 12 of the Common Structural Rules for Oil Tankers. In addition, fatigue cracks detected during close-up surveys are also rectified through local members/brackets renewal.

Thus structural integrity management for trading oil tankers is achieved by means of periodic surveys and steel renewal during their operational life. In theory, it is possible to extend the life of a trading tanker indefinitely by means of these periodic structural integrity management interventions.

3.0 HULL STRUCTURE INTEGRITY MANAGEMENT FOR OFFSHORE FLOATING STRUCTURES

The key difference in managing structural integrity of offshore floating structures over their design lives is that the integrity management is built into the design stage itself. This is due to the expensive nature of having to do steel repairs/renewals offshore both due to the work itself as well as lost revenue from the asset due to the production downtime that the work entails. Hence it is the normal practice to design structures such that no major structural repairs or steel renewal will be required for the entire operational life of the asset. As such unlike sailing tankers these assets will have a fixed design life and a designated offshore field location for which it will be designed.

Hull structure design for ship shaped floating offshore installations, be it a new building, conversion from a sailing tanker or the life extension or relocation of an existing operating asset, proceeds through various stages. Each level of analysis comes with increasing degrees of modeling and analysis time/complexity. Often simplified methods are sufficient to estimate hull structure behavior (and hence design of the new structure/reinforcements/renewals required as the case may be) with sufficient accuracy. The level of conservatism in the predicted responses (and consequently the quantity of steel required for new structure/reinforcements/renewals as the case may be) can be progressively decreased with increasing levels of modeling and complexity in analysis. The following sections will outline the generic methodology involved in each of these levels of analysis which will further serve as a guideline to the designer for deciding on the level of analysis required under each situation.

3.1 Global Hull Girder Strength and Fatigue Analysis of Longitudinal Connections Using 2D Mid-ship Section Model

The first stage in the hull structure design of a ship shaped floater for offshore service is the design / strength and fatigue check using the mid-ship section. Typically software packages from Classification Societies are utilized for this. These packages essentially perform a rule based check of the modeled mid-ship scantlings. The structural rules are in- fact adaptations of common structural rules for tankers with the loading conditions and external loads (Wave Bending moments, external pressures etc.) modified to suit the offshore operation of the unit. Some of the typical packages used for this analysis are FPSO EAGLE (from ABS), MARS 2000 (from BV), Nauticus Hull (from DNV), RulesCalc for FOI (from LR) and so on. The analysis approach in all these packages is similar as mentioned above, although there are differences in the ways each package consider loads (particularly external loads such as wave bending moments, external pressures etc.) For the purpose of this paper the approach by ABS in their package FPSO EAGLE is considered.

The initial 2-D analysis under ABS is termed as Initial Scantling Evaluation (ISE). Under ISE, the mid-ship section of the vessel is modeled using As-Built scantlings (or preliminary design scantlings for new Build). The connection details of all longitudinal members to transverse webs and bulkheads are also modeled in ISE. The adequacy of the scantlings is verified in accordance with ABS Rules for Building and Classing Floating Production Installations. The key differences in these rules from those of tankers are in terms of offshore specific loading patterns in cargo tanks and the site specific environmental loads. The loading patterns considered for various drafts are those defined in Part 5A, Chapter 3, Section 2 of ABS Rules for Building and Classing Floating Production Installations. For considering site specific environmental loads, the approach undertaken by ABS is one that involves scaling of external load parameters from the values prescribed in the Class rules for tanker structures for unrestricted service (in which case the North Atlantic Ocean during winter will be the governing environment).

The Sea Environment Assessment System (SEAS) module in FPSO EAGLE is used to generate scale factors for strength and fatigue check based on the vessel hull form and the environment data for the site where the unit is intended to be located. In SEAS, the vessel's intended field metocean data, Response Amplitude Operator (RAO) of the vessel and the vessel hull form are used as the input in order to generate the α-factors and β-factors. The α-factor is used to compare fatigue damage between the site-specific environment and a base environment i.e. North Atlantic condition. An α-factor of 1.0 corresponds to the unrestricted condition of a seagoing vessel. A value of alpha greater than 1.0 indicates a less fatigue inducing environment compared to the North Atlantic environment, and vice versa.

β-factors represent direct function of the long-term environmentally-induced loads at installation site which involves 13 components as presented in Table 3.

Table 3 β-factor components

Beta Component	Load Component
1	Vertical wave Bending Moment
2	Horizontal wave Bending Moment
3	Port Side Pressure
4	Starboard Side Pressure
5	Vertical Acceleration
6	Transverse Acceleration
7	Longitudinal Acceleration
8	Pitch Motion
9	Roll Motion
10	Vertical Relative Motion
11	Wave Height
12	Vertical Shear Force
13	Horizontal Shear Force

A β-factor value of greater than 1.0 indicates a more severe wave induced load environment than the North Atlantic environment, and vice versa.

Often, for benign environmental conditions, due to the above scaling effect the required scantlings for the offshore unit are lower than those required under tanker rules. Hence, for converted units it is very much possible that certain structural elements can be retained without renewal if their scantlings meet the re-assessed scantling criteria from ISE. The SEAS module also offers a means to estimate the accumulated fatigue damage on an existing unit based on its historic location or historic sailing routes. The global wave data within the program database is used for the fatigue damage calculation. The ABS wave data base consists of 1102 grid cells covering the entire ocean surface of the world. (Figure 1). For each cell a wave scatter diagram is stored with its associated directional probably distribution.

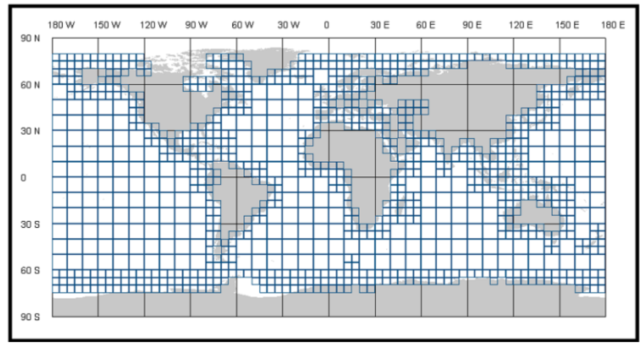


Figure 1 ABS wave database grids

In ISE, the estimated fatigue damage from historical routes/sites is combined with the predicted fatigue damage at the intended site of operation of the unit to predict the remaining fatigue life of each longitudinal connection modeled.

The software packages from other Class Societies also follow a similar approach with some differences in the method of estimation of site specific load parameters. This can be either be a simplistic approach whereby the load parameters are scaled based on specific regions of the world oceans (e.g. Tropical Zone in BV Mars 2000) or a more elaborate hydrodynamic analysis to estimate the site specific load parameters directly (e.g. direct calculation method under DNV).

The 2D-analysis however does not cover local strength and fatigue check of transverse sections. A more detailed finite element based analysis need to be carried out for this. However, the 2D analysis is more than sufficient to make a preliminary estimate of the steel renewal/additions and fatigue bracket modifications required for a conversion project (or the initial mid-ship configuration and Material take off in the case of a new Build).

3.2 Three-Hold Finite Element Analysis

The 3-Hold analysis, termed as Total Strength Assessment (TSA) under ABS terminology is a more detailed analysis which in intended to check the adequacy the structural configuration and the initially determined scantlings from ISE phase. The validation of the re-assessed scantlings (or new selected scantlings in case of a New-Build unit) is done by means of performing a finite element structural analysis by using either a three cargo tank-length model or a full cargo block-length model.

The Finite Element model of the cargo holds is constructed using net scantlings, i.e., Gross scantlings - Nominal Design Corrosion values. Boundary conditions are applied and still water shear forces and bending moments corresponding to each loading condition are applied to the model. The structural analysis using the finite element model involves strength checks of all the major portions of the hull structure for failure modes associated with yielding, buckling and ultimate strength. As a first step for screening a coarse mesh model (mesh size equal to stiffener spacing) of the cargo holds is constructed and the relevant load cases are run after applying all boundary conditions and obtaining a close enough match of the bending moment and shear force distribution for each loading condition. All structural members including plating, longitudinals/stiffeners, web plates and flanges are checked for the yielding criteria. Buckling check is also carried out for all modeled plate panels, longitudinals/stiffeners, stiffened panels, deep girders and webs. This first level of screening will identify potential areas of concern in terms of yielding and buckling. These areas are further selected for local fine mesh modeling (mesh size equal to stiffener spacing / 4) and analysis is repeated in order to get a more accurate estimate of the stresses in the corresponding areas. A fatigue check is also carried out on the FE model. The typical areas of concern for fatigue check are

- Intersection of two or more structural members
- Bracket toes of main supporting members
- Openings in way of critical locations
- Intersections of longitudinals with transverse and cut outs.

For fatigue check local detailed fine mesh models (mesh size equal to the thickness of the member modeled) are created from the global model to check for fatigue hot spot stresses. For each detail considered the past fatigue cycles can also be taken into account (for converted units) in order to arrive at the remaining fatigue life in the same manner as in ISE.

A summary of various checks conducted in the three-hold analysis is provided in Table 4 below.

Table 4 3-Hold analysis – checks performed

Structural Element		Yielding Check	Buckling Check	Ultimate Strength Check	Fatigue Check
Local Structures	Plating	√	√	√(a)	-
	Stiffeners	√	√	√(b)	√(c)
Primary Supporting Members		√	√	√	√(c)
Hull Girder		√	√(d)	√	-
Hull Interface Structures		√	√(e)	√(f)	√(g)

Notes:
'√' indicates that the structural assessment is to be carried out

a. The ultimate strength check of plating is included as part of the buckling check of plating.
b. The ultimate strength check of stiffener is included as part of the buckling check of stiffener.
c. The fatigue check of longitudinal stiffeners and primary supporting members is the fatigue check of connection details of these members
d. The buckling check of stiffeners and plating included in hull girder strength is preformed against stress due to hull girder bending moment and hull girder shear force.
e. The buckling check is to follow ABS Guide for Buckling and Ultimate Strength Assessment for Offshore Structures.
f. The ultimate strength check of plating and stiffeners is included as part of the buckling check for plating and stiffeners, based on ABS Guide for Buckling and Ultimate Strength Assessment for Offshore Structures
g. The fatigue check is to follow ABS Guide for Fatigue Assessment of Offshore Structures.

Additional information on FE modeling, boundary conditions, loading of the model etc. can be had from References [4] & [5].

Under ABS methodology the loading patterns and the external loads (wave bending moments, external pressure etc.) applied in the FE model analysis is the same as those that are used in the ISE phase. As such the ISE analysis followed by the 3-cargo hold FE analysis (TSA) meets the minimum ABS class requirement on hull structural analysis of an offshore unit, be it a new build or converted from an oil tanker. In most cases these two analyses and the structural design/rectifications following them are sufficient to ensure that no further structural repairs or steel renewal will be required during the operational life of the unit offshore.

However, there is still an element of conservatism in this analysis on account of the indirect scaling of external load parameters from those of North Atlantic figures. Further optimization in structural scantlings can be achieved by going for a more accurate estimate of these hydrodynamic loads, which can be realized by carrying out a combined hydrodynamic and structural analysis on a full ship finite element model.

3.3 Hull Structure Strength and Fatigue Analysis–Spectral Approach

The spectral approach for strength and fatigue analysis involves both a full ship structural finite element model and a hydrodynamic panel model. For structural check, the hydrodynamic responses are estimated from the panel model and the corresponding loads are applied to the FE structural model for verification of responses against strength criteria such as yielding and buckling.

3.3.1 Hull Structure Analysis by Spectral Approach–Dynamic Loading Approach

The structural analysis is carried out for the worst possible environmental loading that can be expected at the particular offshore site under consideration. The general methodology can be summarized in the following Figure 2.

A 3-dimensional panel model of the vessel is to be created for computation of wave induced motions and loads through the application of seakeeping analysis codes utilizing three-dimensional potential flow based diffraction-radiation theory. Proper mass distributions, boundary conditions and roll damping effects have to be applied in this analysis. In order to assess the extreme response of the structure a combination of short term and long term analysis is used. The objective of this is to determine the ship responses on the given environmental conditions for design wave assessment purpose. The methodology is summarized in the following Figure 3.

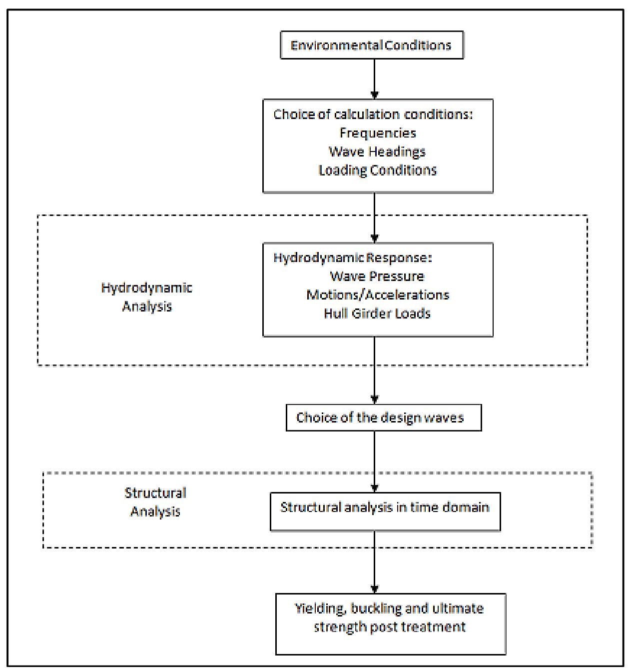


Figure 2 General methodology for strength analysis in extreme environmental conditions

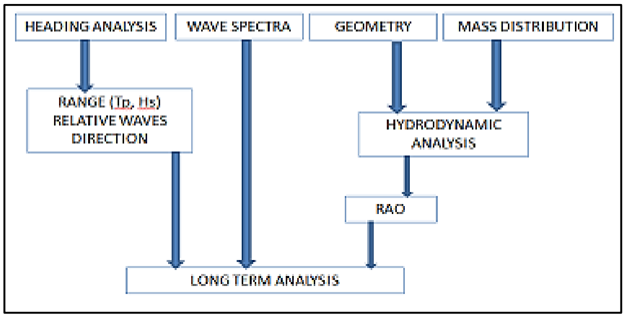


Figure 3 Spectral analysis methodology

If $S_\omega(\omega)$ represents the spectral density distribution in frequency (ω) of the wave energy and RAO(ω), the transfer function of any first order quantity, like motions, acceleration, relative wave elevation, stress etc.

The spectral density of response is given by

$$S_R(\omega) = RAO^2(\omega).S_\omega(\omega) \tag{4}$$

The spectral moments can be defined as

$$m_n = \int_0^\infty \omega^n S_R(\omega)d\omega \tag{5}$$

The following statistical parameters can be defined

$$Mean\ period,\ T_m = 2\pi\frac{m_0}{m_1} \tag{6}$$

$$Zero\ crossing\ period,\ T_Z = 2\pi\sqrt{\frac{m_0}{m_2}} = T_2 \tag{7}$$

$$Mean\ frequency\ of\ maxima,\ \mu = \frac{1}{2\pi}\sqrt{\frac{m_4}{m_2}} \tag{8}$$

The environment is usually characterized by a Jonswap spectrum.

The short term corresponds to a duration of one sea state (typically 3 hours), which is considered to be stationary. Considering a random variable R being the range of response and assuming that the process is narrow banded, the probability density of response range follows the Rayleigh's distribution:

$$p(R) = \frac{R}{4m_0}e^{(\frac{-R^2}{8m_0})} \tag{9}$$

The distribution function is given by

$$P(R) = 1 - e^{(\frac{-R^2}{8m_0})} \tag{10}$$

From the above equation, the mean value $R_{1/n}$ of the random variable X, for which the probability of exceedence is 1/n is given by

$$R_{1/2} = 2.5\sqrt{m_0} \tag{11}$$

$$R_{1/3} = 4.00\sqrt{m_0} \tag{12}$$

$$R_{1/10} = 5.10\sqrt{m_0} \tag{13}$$

$R_{1/3}$ is referred to as the significant value R_S.

The average of the maximum occurring in a sea-state is, for large value of N, given by:

$$R_{max} = 2.(\sqrt{2lnN} + \frac{\gamma}{\sqrt{2lnN}})\sqrt{m_0} \tag{14}$$

Where γ is the Euler constant ($\gamma = 0.5772$)

A short term analysis, as above described, is performed for a list of sea states observed during a reference period. The long term distribution can then be obtained by cumulating the results from the short term analysis. Extreme long term values used for the calculations are usually for a 100 years return period.

Design waves are calculated in order to maximize different load parameters such as Vertical Wave bending moment, Vertical Wave Shear Force, Roll Angle, Accelerations etc. on the following bases:

- RAOs of the investigated dominant load parameters are calculated for several wave headings.
- Design wave length, period and frequency correspond to the peak value of the investigated dominant load effect's RAO
- The wave height H_D of the design wave is obtained by dividing the extreme value of DLP under consideration (so called long term value) by the RAO value of that DLP occurring at that frequency and wave heading corresponding to the maximum amplitude of the RAO, i.e:

$$H_D = \frac{Long\ Term\ Value}{RAO_{max}} \tag{15}$$

The hydrodynamic loading (pressure field, body accelerations) for each design wave is computed in the Hydrodynamic software and applied directly on the full ship FE structure model. As in the case of the 3-hold analysis the structural response is checked against the yielding and buckling criteria along with relevant fine mesh models as required.

3.3.2 Fatigue Analysis by Spectral Approach

An approach similar to that for strength analysis involving both hydrodynamic response calculations and their application to the full ship structural model to calculate the stress range and the corresponding number of stress cycles is adopted for spectral fatigue analysis. The steps involved are

- The full ship is modeled with finite elements. The model is to represent as accurately as possible the shape, the mass and the stiffness of the ship.
- Hydrodynamic loads are calculated for a number of wave (circular) frequencies and headings, both for the sea keeping problem (diffraction and radiation) and for the sloshing problem in each tank, using a suitable 3D linear diffraction and radiation hydrodynamic software (eg: HydroSTAR)
- The structural response transfer functions (stress RAO's) are obtained. For each wave frequency and heading the stress is determined by FE analysis with the loads (pressure field, body accelerations) obtained from the 3D diffraction radiation hydrodynamic analysis.
- The external wave loads and internal pressures are applied on the complete ship model and are ultimately transferred to the fatigue fine mesh through a Top-down procedure.
- Spectral response is obtained by combination of the stress transfer functions (RAO) with metocean spectrum and according to the heading analysis.

- Evaluation of the fatigue damage, by summation (Miner Sum), from the long term stress range distribution.

Long term response distribution which is obtained by cumulating the results from short term analysis is used in conjunction with selected S-N curve to determine the damage ratios for a particular location under consideration. For further details including cumulating methods of all maxima over all sea states (i.e., each response cycle) are covered in Reference (7).

Thus, the spectral approach provides a more realistic estimate of the long term and short term distribution of load parameters which are otherwise taken based on empirical formulae provided in Class rules (with some scaling of factors to account for difference in environmental severity from North Atlantic environment). As such for benign conditions the inherent conservatism in applying load parameters based on empirical rules formulae can be reduced by means of spectral analysis. However due to the modeling and computational intensity involved in a full-ship analysis the designer / engineering manager has to exercise sound judgment in deciding to opt for a spectral analysis in view of the savings in terms of steel that can be reasonably expected to be had as a result of the spectral analysis.

4.0 FSO PUTERI DULANG LIFE EXTENSION CASE STUDY

Puteri Dulang vessel was purposely built as an FSO by Mitsubishi Heavy industries (MHI) in Nagasaki, Japan. Her keel was laid in 1990 and is currently operating in Dulang field (PM-305, east of Malaysian Peninsula) since 1991. The vessel is permanently moored from an external turret with six mooring chains connected to a chain table at its base. The main particulars of the vessel are presented in Table 5. Figure 4 presents the capacity plan of FSO Puteri Dulang while the midship section is shown in Figure 5.

Table 5 FSO Puteri Dulang main particulars

Particulars	Details
Classification (Hull)	+A1 Offshore Installation Storage Barge, Class No:9100158
Classification (Mooring System)	+A1 Offshore Installation Single Point Mooring, Class No:9106658
LOA	250.76 m
LBP	230.00 m
Scantling Length	223.10 m
Breath Moulded	39.50 m
Depth Moulded	22.70 m
Summer Draft	16.32 m

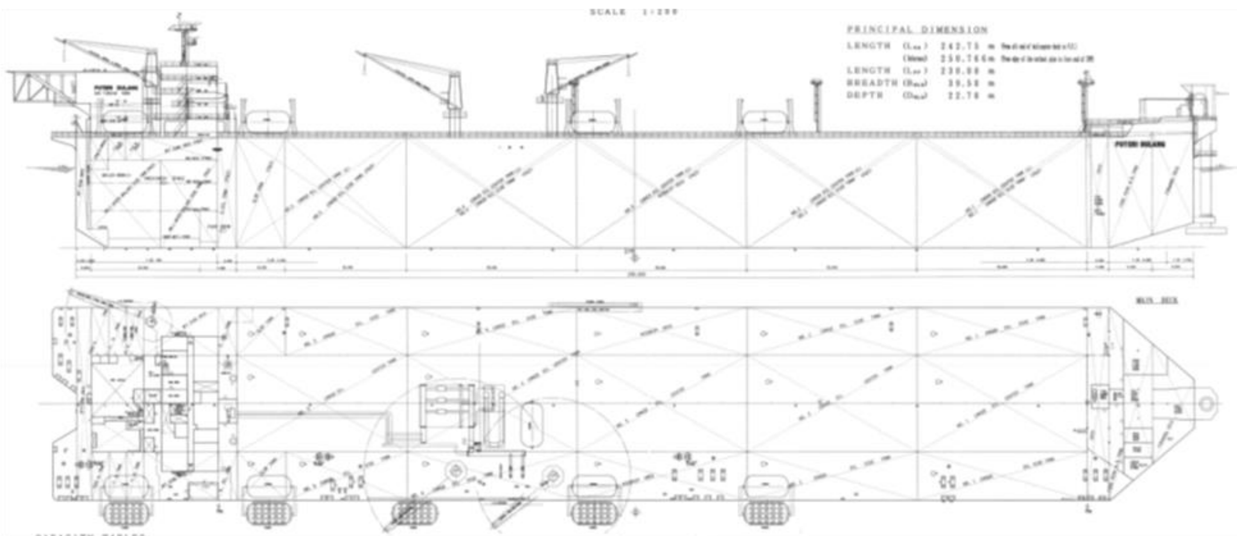


Figure 4 Puteri Dulang FSO capacity plan

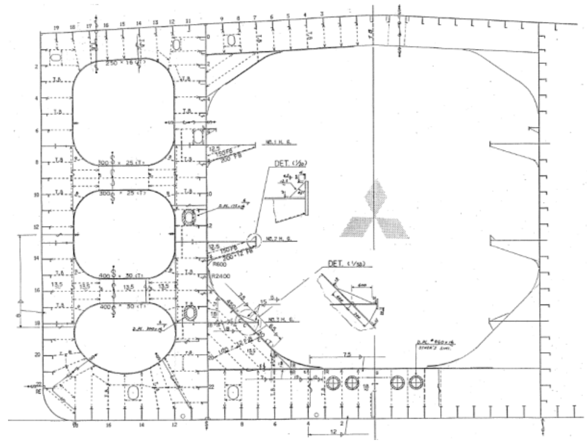


Figure 5 Puteri Dulang FSO midship section

The initial owner of the Puteri Dulang FSO was Petronas Carigali Sdn. Bhd. (PCSB) before the ownership was taken over by MISC Berhad in 2008. The charter contract for the vessel has been extended by an additional 14 years. As part of the charter contract, MISC is responsible to perform Repair and Life Extension (RLE) scope in order to ensure that the FSO could meet the extended operational service life requirement.

As part of the life extension work for establishing structural adequacy and/or estimation of steel renewal work if required, hull structural strength and fatigue damage estimation studies were required to be carried out. These studies have been carried out by Bureau Veritas while MISC also carried out preliminary structural investigations in-house using ABS software i.e. Eagle FPSO.

The following sections will summarize the results from the abovementioned studies.

4.1 Structural Analyses Results

The results from FSO Puteri Dulang structural analyses are presented below.

4.1.1 Two-Dimensional analysis

The 2D structural analysis of FSO Puteri Dulang was done using Eagle FPSO (ISE) software. This analysis permits an assessment of the vessel's main hull girder scantlings in general and will lay the basis for the fatigue assessment of longitudinal stiffeners' connections. It will also highlight the areas where the 3D assessment of the structure is required to verify the adequateness of the remaining scantlings.

A design life of 15 years was used in the analysis and the analysis was run under site specific environmental conditions.

Typical results summary from ISE software are presented in Figure 6 which highlights certain areas on the inner longitudinal bulkhead plating and some stiffeners as failing to meet the minimum scantling requirement in accordance with ABS rules for an offshore unit with the specific design life.

Based on the above result a total steel renewal of 435.7 tons is required to be carried out in order for the FSO to meet intended service life of 15 years. These numbers are based on the minimum required plate thicknesses and stiffener sectional moduli after incorporating corrosion additions for next 15 years.

4.1.2 Three-hold Analysis

In the 3 hold analysis for FSO Puteri Dulang, the model was generated consisting the three middle tanks i.e. COT 2, 3 and 4. Figure 7 shows the port half of the model which was generated using FEMAP. Six different loading conditions were used to act as the internal loads. External loads were applied based on the requirements mentioned in [10].

The analyses checked for yielding, buckling and fatigue criteria. The yielding and buckling criteria are described in [11] and [12].

Figure 8 and Figure 9 show some of the post processing models as the result from the 3 hold model analyses in yielding and buckling criteria. The admissible stress values for failure under yield criteria were 192 MPa (for mild steel), 257 MPa (AH32) or 290 MPa (AH36) while elements with a buckling ratio of more than 1.0 failed under buckling criteria.[11,12]

The total steel renewal required after 3 hold cargo model analysis has been performed was **145.99 tons**.

For fatigue analysis, 19 locations of concern were analysed using local fine mesh models. Of these 2 locations were found to exceed the damage ratio of 1 for the stipulated design life.

4.1.3 Full ship DLA and SFA

A full ship FE model was created by using FEMAP software for the spectral analysis. A separate full ship hydrodynamic panel model was created for hydrodynamic analysis using Hydrostar. The first order responses from Hydrostar were applied to the structural FE model using HOMER. The methodology as detailed in section 3.3 was used in this study. Figure 10 shows the complete ship 3D model. The model was analyzed for yielding, buckling and fatigue criteria.

No part of the model showed yielding ratio exceeding admissible criteria (yielding ratio > 1) for all loading conditions as can be seen in Figure 11.

Figure 12 shows the result for buckling criteria for hold no.3.

The same 19 locations were investigated for fatigue damage using fine mesh models. There is only one location where fatigue damage exceeded 1 for the design life extension, as compared to two points obtained using 3 hold cargo model analysis as shown in Figure 13.

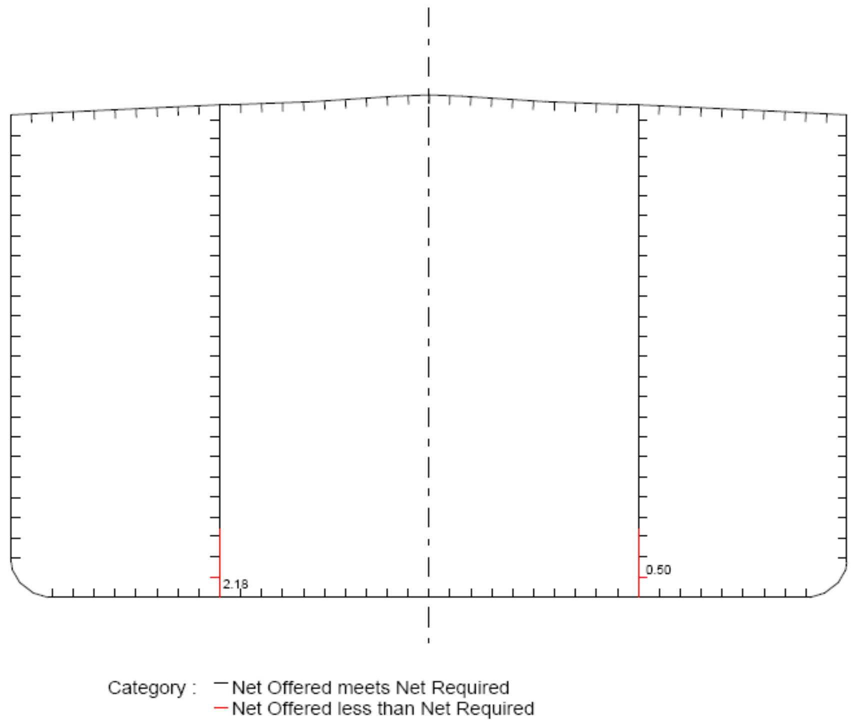


Figure 6 Plate and Stiffeners strength result summary

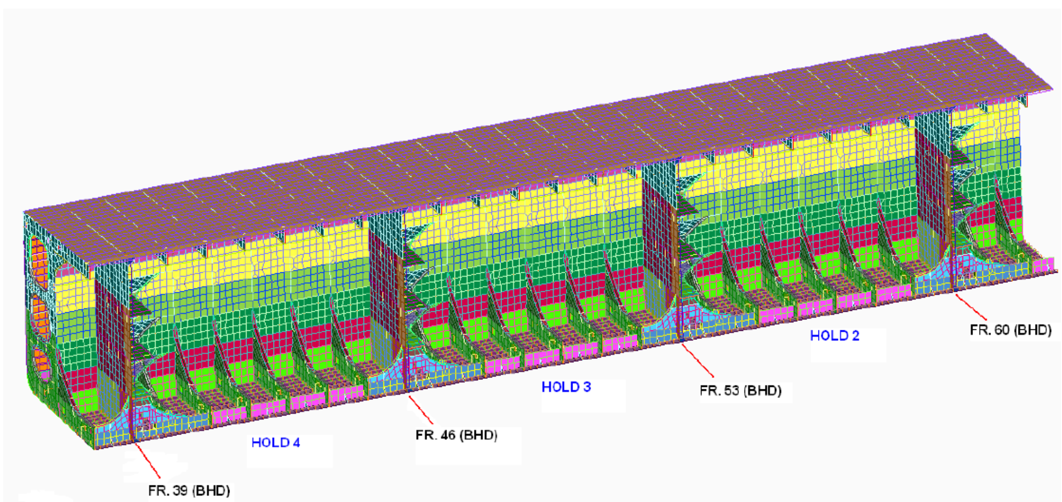


Figure 7 3 Cargo holds model (port side)

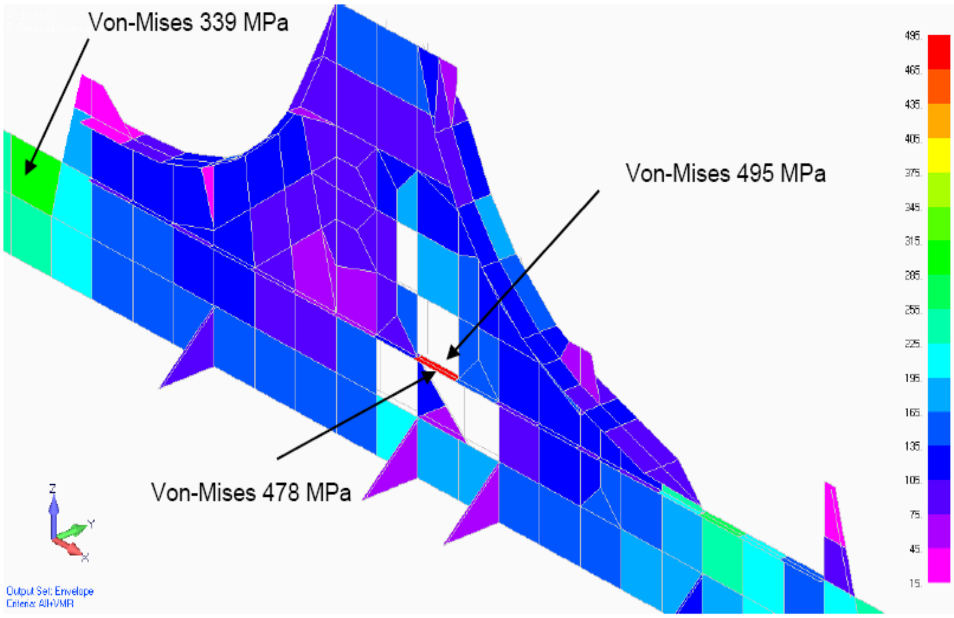


Figure 8 3D analysis yielding criteria result (sample)

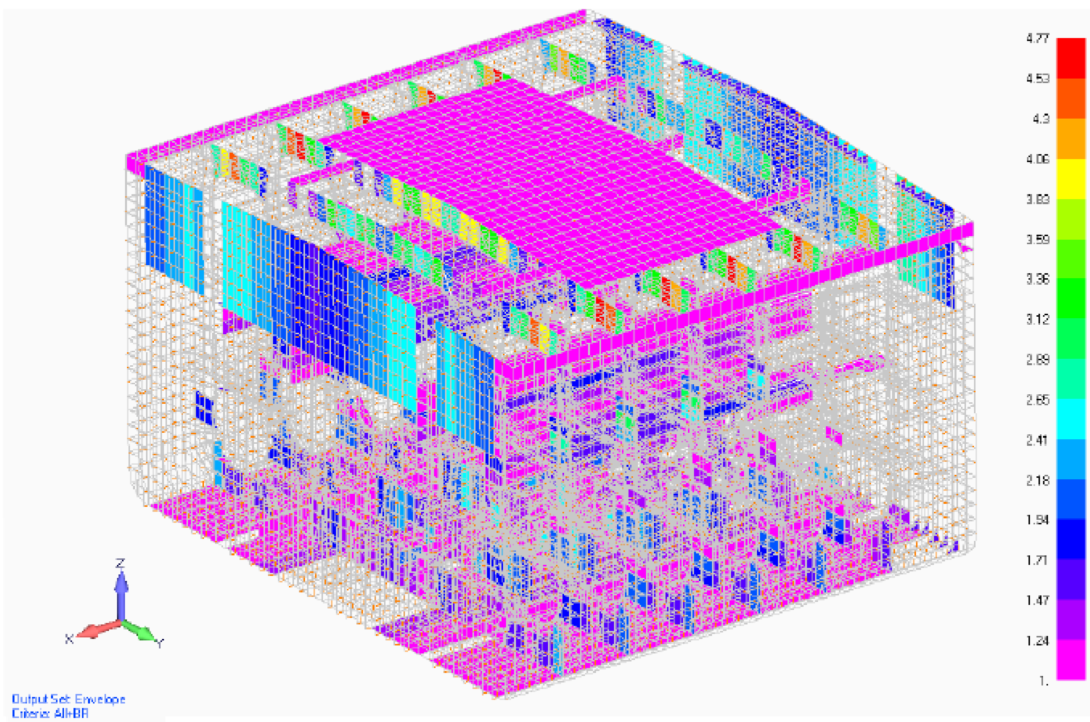


Figure 9 3D analysis buckling criteria result

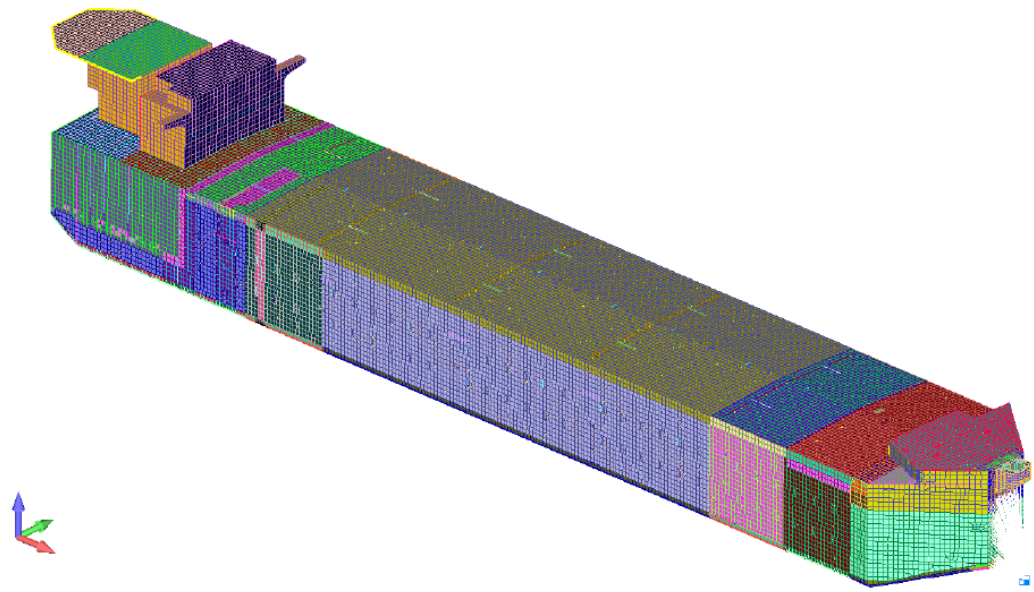


Figure 10 Full 3D model of FSO Puteri Dulang

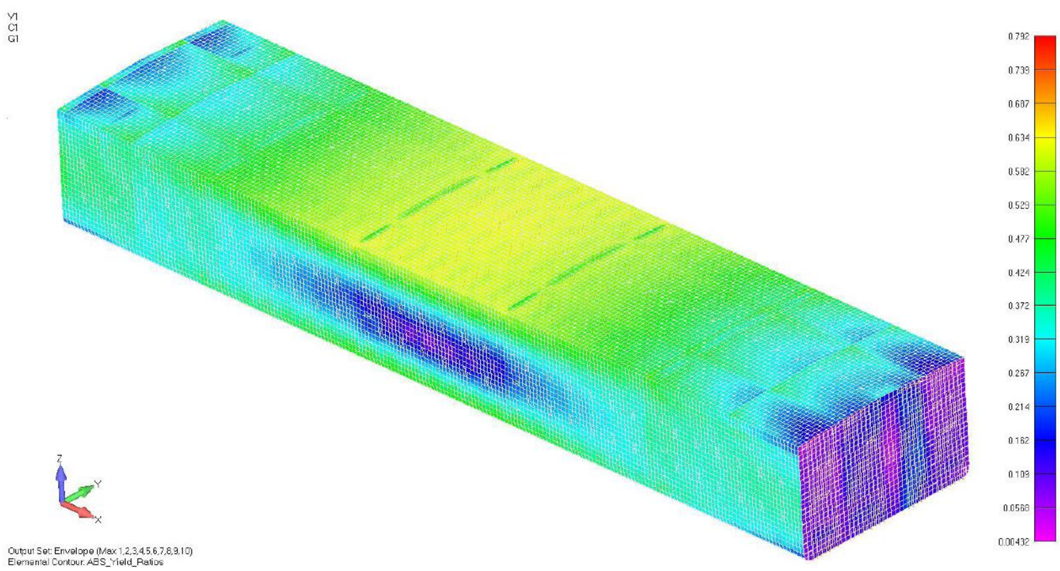


Figure 11 3D analysis yielding criteria result

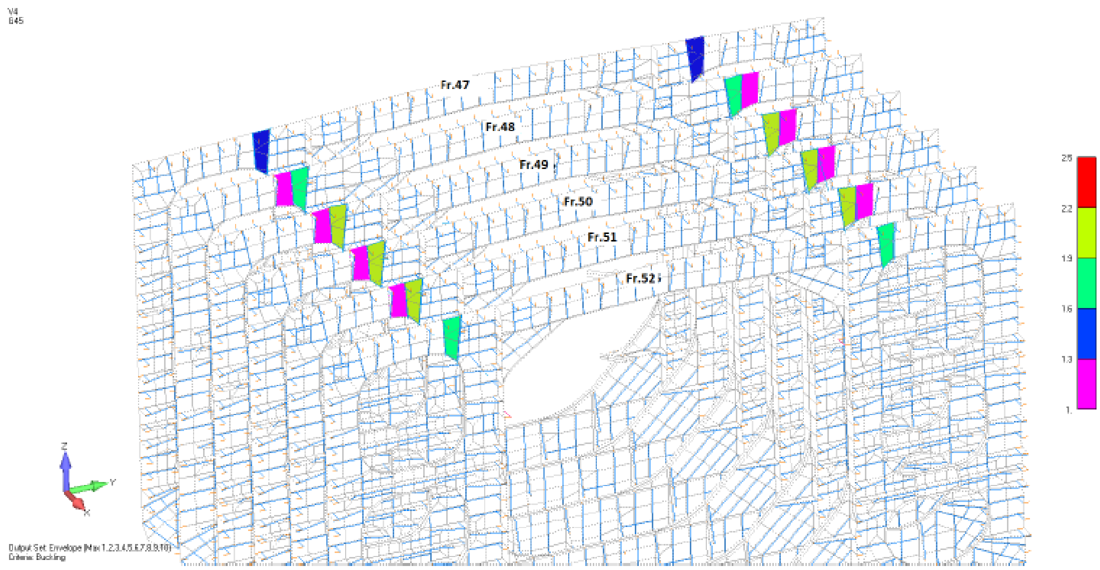


Figure 12 3D analysis buckling criteria result (sample)

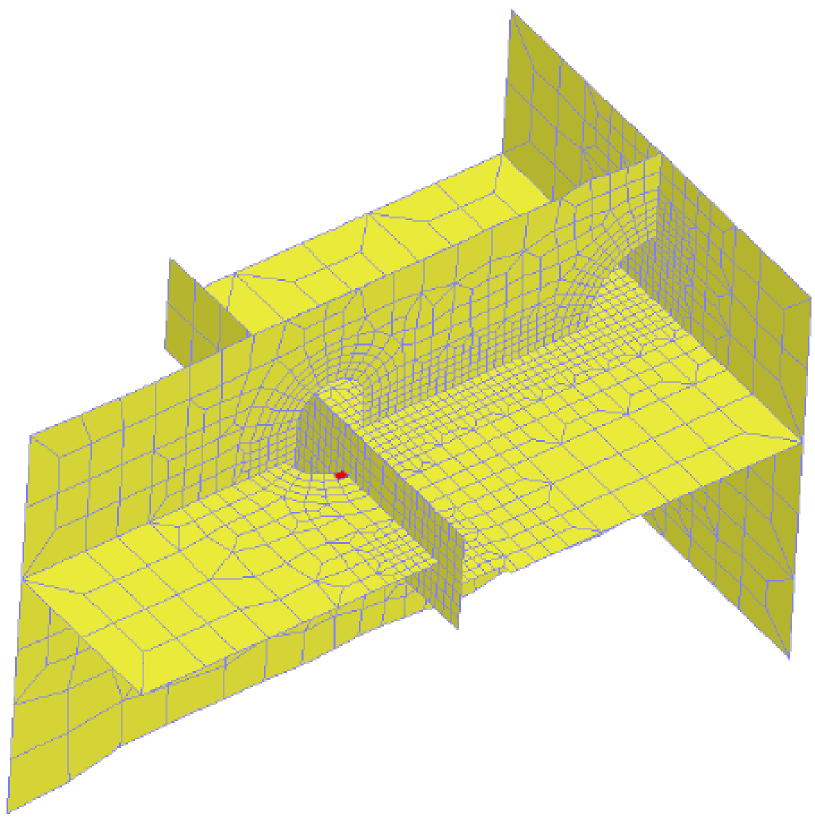


Figure 13 Hot spot at frame 49 – shell longitudinal #19 connection with side shell

The total steel renewal required after full model spectral analysis has been performed has shrunk to only **2.61 tons** which is much lower compared to the steel renewal requirement predicated from 3 hold analysis. There were 19 locations analysed for fatigue using local fine mesh models of which one location had a damage ratio greater than 1.

Table 6 shows the comparison between steel renewal estimation based on strength and fatigue checks for the life extension of FSO Dulang which were carried out using 3 methods i.e. 2D analysis, 3 cargo hold analysis and full ship spectral analysis.

Table 6 Steel renewal plan and fatigue concern based 3 different method

Failure Criteria	Steel Renewal (T)		
	2D analysis	3 cargo hold FE analysis	Full ship 3D model spectral analysis
Strength check	435.7	145.99	2.61
Fatigue check	No concern	2 locations [a]	1 location [a]

Notes

a. From 19 suspected locations investigated using local fatigue fine mesh models

5.0 CONCLUSION

The three levels of analysis discussed here offer some degree of flexibility to the designer depending on the requirements of different situations in a project life-cycle. The rule based two-dimensional verification of the mid-ship section is sufficient for steel quantity estimation or for screening between various design options or vessels for conversion at the initial stage of a project. A detailed three cargo hold finite element analysis need to be undertaken as a minimum for any new-build or conversion project in order to validate the design from the initial stage and to perform additional strength and fatigue checks on the hull structure design. A spectral analysis is called for only when the expected savings in steel justifies the modelling effort and computational time associated with the same. In fact, up until recent times a spectral analysis was not even possible owing to limitations in computational hardware capabilities. Typically 4 – 6 months time needs to be allocated for full ship modelling and analysis by spectral method. As such some of the situations which will justify the analysis based on spectral approach are:

- New build hull of non standard dimensions and design, to be located in relatively benign waters. In this case in addition to numerical analysis a physical model test might be required to calibrate some of the hydrodynamic properties such as roll damping.
- Conversion of a large tanker hull (Suezmax and above) to a offshore unit to be located in benign waters with a considerably long design life (20yrs +), where the expected optimisation in steel renewal quantities as a result of spectral analysis will be large
- Conversion or new build unit of considerable size (Aframax and above) to be located in a harsh environment where the spectral approach can ensure more accurate estimation of load parameters as against rule based empirical approach)
- In situ – life extension of an offshore unit where each ton of steel renewal saved offshore translates into substantial capital savings (as is in the case of the study example presented in this paper).

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