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FPSO Global Strength and Hull Optimization

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Abstract: Global strength is a significant item for floating production storage and offloading (FPSO) design, and steel weight plays an important role in the building costs of FPSO. It is the main task to consider and combine these two aspects by optimizing hull dimensions. There are many optional methods for the global strength analysis. A common method is to use the ABS FPSO Eagle software to analyze the global strength including the rule check and direct strength analysis. And the same method can be adopted for the FPSO hull optimization by changing the depth. After calculation and optimization, the results are compared and analyzed. The results can be used as a reference for the future design or quotation purpose.

Keywords: global strength; hull optimization; FPSO; steel weight; building costs; hull strength; ship design; hull design

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1 Introduction

With the high demand for oil and gas, the offshore installations are developing rapidly. FPSO as an important offshore unit, has been studied and built by a lot of universities, institutes, shipyards and classifications. And the class rules have been updated by societies along the development of technology. Many classification societies have their methods and software for the FPSO design (ABS, 2013; DNV, 2011; BV, 2013). And all these methods are mature by now. FPSO Eagle is one of the qualified software. It is chosen because of its strong ability to analyze the global strength and hull optimization. It is important to determine the design basis and analysis method at the beginning of the design procedure. And a clear design procedure is necessary to improve design efficiency. Based on the design basis, the design load, scantling check and three-dimensional(3D) FE is to be analyzed. As a primary offshore FPSO has its own design point, the environment loads and loading conditions are different from the ordinary vessels. And the low cycle fatigue load during the process of the loading and offloading conditions is to be considered. Based on a design procedure and FPI Guide, FPSO global strength is assessed. After the analysis of the whole design procedure, several other cases are calculated by changing the main dimensions of FPSO in the same way. Finally, the results are compared between the different FPSOs with different dimensions, then the optimized size is achieved. The design procedure can be used as a guide for the FPSO hull design. And the results may be used as a reference for the initial design under the similar loads.

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2 Design and optimization procedure

The design procedure is given as follows:

1) Determine the hull dimensions (preliminary stage);
2) Rule check (ISE stage);
3) Direct strength calculations (TSA stage).

At the preliminary stage, the general layout, which includes topside, mooring, riser and equipment layout, and so on, is to be confirmed initially. And the structural general arrangement including transverse bulkheads, longitudinal bulkheads and preliminary mid-ship shall be designed. The hull global loads provided in this stage can be used as an input for the calculations for the next stage (Molin *et al*., 2002;Deng *et al*.,2009). And the preliminary stability (IMO, 2008; IMO, 2004) and freeboard calculation (IMO, 2005) are to be completed in this stage. It is important to check the hull dimensions(L & B & D) and arrangement of the structures to ensure that they are in compliance with the main regulations (IMO, 2009).

Generally, the size of the hull of the FPSO is to be designed to take into consideration the following:

a) Space requirement of liquid storage, topsides facilities, living quarters, flare boom, pedestal cranes, moorings, risers, umbilical and other equipment;
b) Limitations of the construction shipyard;
c) Global hull strength and its fatigue life;
d) Intact and damage stability;
e) Global performance during operation;
f) Green water on deck and wave slamming;
g) Class rules and class notation requirements;
h) Safety in the design standard.

At the ISE (Initial Scantling Evaluation) stage, the hull section scantling will be checked to ensure that it meets the strength criteria of the class rules. The assessment of the main hull structures including mid-ship, transverse frame and transverse bulkheads etc. is to be carried out. The hull strength assessment includes yielding, buckling and fatigue (Zhao, 2002; Paik *et al*., 2008; Hu and Chen, 1996). It should also be noted that the hull girder ultimate strength will be finished in this stage. This stage is focused on ensuring that the basic hull design reflects the overall hull girder and local structural component strength. During this stage, it is suggested that the design of the hull structures complies with the standards.

The final stage is the TSA(total strength assessment) stage. The TSA stage is for the direct strength calculations using three-dimensional(3D) FE. In assessing the adequacy of the structural configuration and the initial scantlings, the strength of the hull girder and the individual structural member or element is to be in compliance with the failure criteria specified in the class rules. In this regard, the structural response is to be calculated by performing a structural analysis. In determination of the structural response, the combined load cases are to be considered together with sloshing loads, deck loads, bottom slamming and other loads.

The procedure above is an iterative process. A lot of work is to be done in the process, especially in the optimization stage. The detailed design procedure, which can be followed for development of the hull structure design and hull optimization, can be found in the flowchart shown in Fig.1.

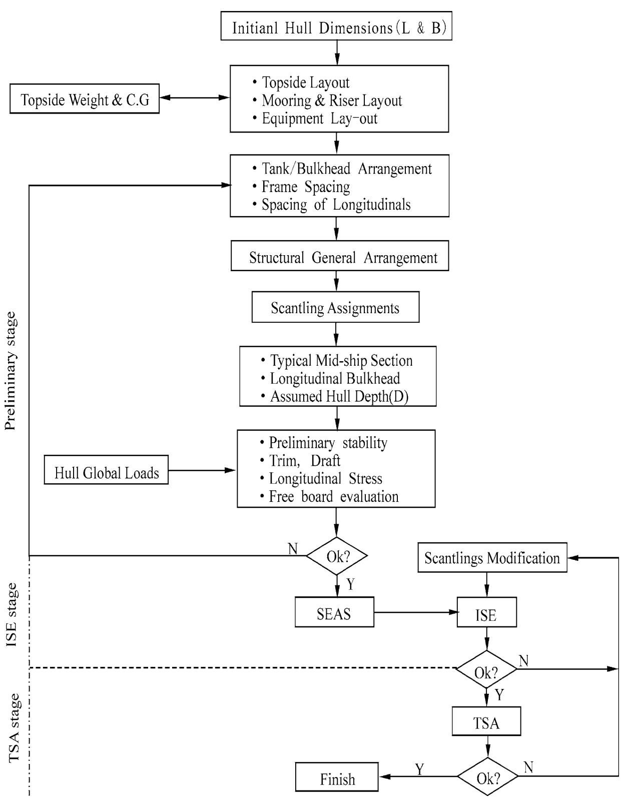

Fig.1 Flowchart of design procedure

3 The goal and criteria of optimization design

The design and optimization is based on the ABS FPI rules (Zhao, 2002; ABS, 2009; Ferro and Cervetto Soares (1984); ABS, 2012). And the software FPSO Eagle is used for analysis of strength. The goal of optimization is to try to reduce the steel weight based on the owner's specifications and then save the cost of shipbuilding and increase the competitiveness of the yard.

3.1 Initial design

Consider all the items listed at the preliminary stage in Part 2. Compare the building capacity of the shipyard and input data of the client. We decided to choose the barge-shaped hull with the dimensions of 200m×50m×15.5m as the initial design. Based on the initial information, the design and optimization are carried out, respectively. The initial general arrangement is shown in Fig.2 and Fig.3.

3.2 Design basis

According to the owner's specifications and class requirements, the following basic design concept for the hull structural strength evaluation is considered.

The notation of the project is as follows:

+A1 Floating Production, Storage and Offloading System.

The notation gives the main class requirements. The vessel will be designed to receive, store and offload gas and gas condensate as well as sulfur product. The vessel will be designed for continuous loading, and to offload simultaneously without interruption to loading. The details of the requirements are specified in the ABS FPI GUIDE. The design fatigue life of this project is 20 years and this FPSO will operate near the sea of Makasar. And her transit route is from Dalian to Batam and from Batam to Makasar.

3.3 Design loads

In the design of the hull structure of FPSO, all of the load components with respect to the hull girder and local structure were taken into account. These included static loads in still water, wave-induced motions and loads, sloshing, slamming, dynamic loads, *etc*. The loading conditions at transit, operation, inspection and repair conditions were analyzed respectively based on the loading patterns specified in ABS, 2013. Then the maximum permissible still water bending moment and still water shear force can be achieved during the process of stability analysis (IMO, 2008). The environmental loads are calculated by PRECAL using Eagle software based on the environmental severity factors (ESFs).

The definition of the severity measure β is as follows:

$$\beta = \frac{Ls}{Lu} \qquad (1)$$

where, Ls = most probable extreme value based on the intended site (100 years return period), transit (10 years return period), and the repair/inspection(1 year return period) environments for the dynamic load parameters. Lu = most probable extreme value based on the North Atlantic environment for the dynamic load parameters.

The wave bending moment is obtained from the following equations:

$$M_{ws} = -k_1 \beta_{VBM} C_1 L^2 B (C_b + 0.7) \times 10^{-3} \quad \text{Sagging Moment (2)}$$

$$M_{wh} = +k_2 \beta_{VBM} C_1 L^2 B C_b \times 10^{-3} \quad \text{Hogging Moment (3)}$$

where, $k_1 = 110$; $k_2 = 190$; β_{VBM} = ESF for vertical bending moment.

$$C_1 = 10.75 - \left(\frac{300 - L}{100}\right)^{1.5} \tag{4}$$

where, $L =$ length of vessel; $B =$ breadth of vessel; $C_b =$ block coefficient.

The wave shear force is obtained from the following equations:

$$F_{wp} = +k\beta_{VSF}F_1C_1LB(C_b + 0.7)\times 10^{-2} \tag{5}$$

$$F_{wn} = -k\beta_{VSF}F_2C_1LB(C_b + 0.7)\times 10^{-2} \tag{6}$$

where, $F_{wp}, F_{wn} =$ maximum shearing force induced by the wave, in kN; $\beta_{VSF} =$ ESF for vertical shear force; $k = 30$; $F_1, F_2 =$ distribution factor.

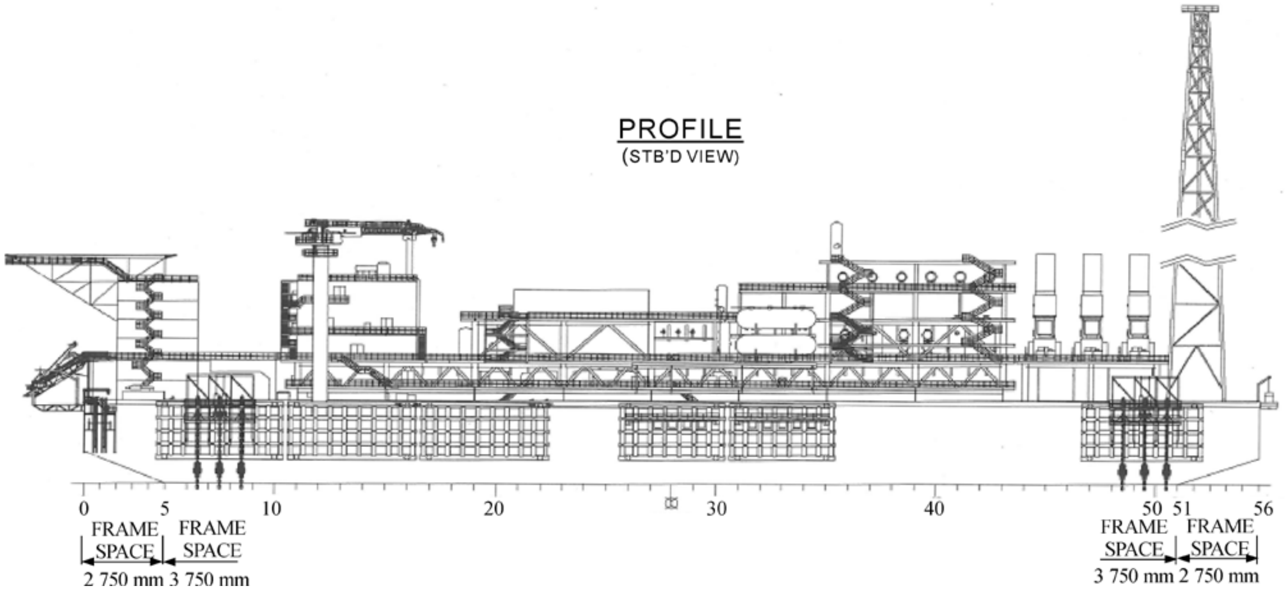

Fig.2 Elevation of general arrangement

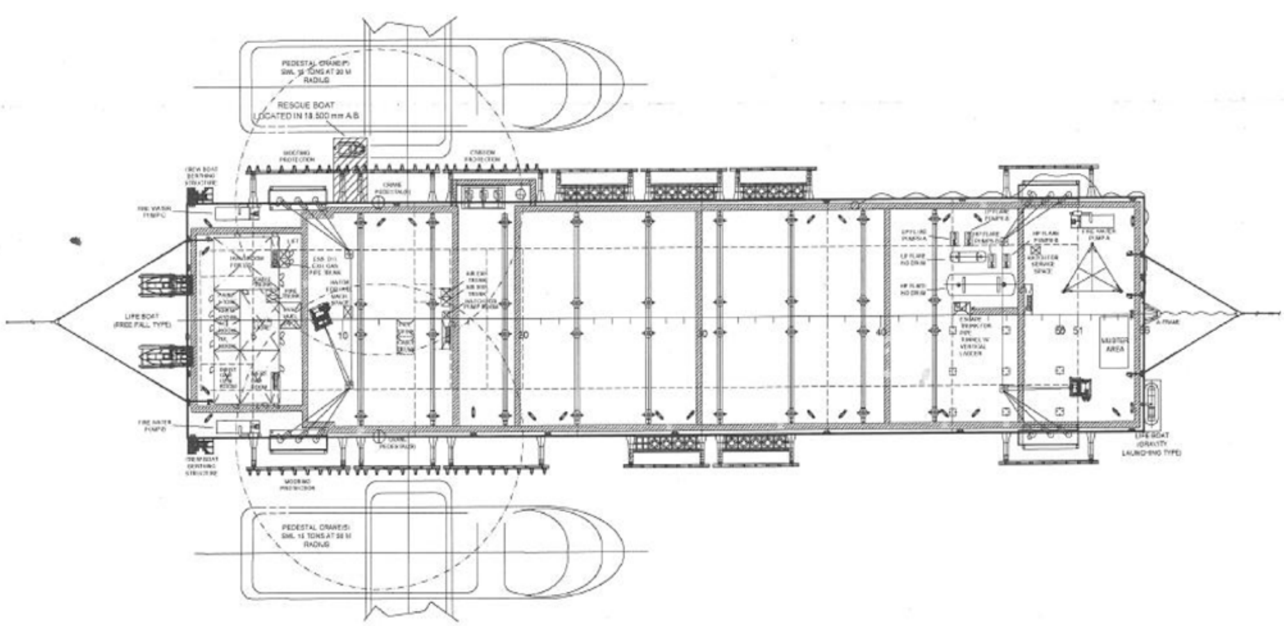

Fig.3 Deck plan of general arrangement

3.4 Rule check (ISE stage)

In the design of this stage, the hull girder strength including hull girder section modulus, hull girder moment of inertia, hull girder ultimate strength, yielding, buckling and fatigue strength etc. is evaluated (ABS, 2009; Miner, 1945; ABS, 2012).

3.4.1 Section modulus check results

The section modulus results are shown in Table 1 and Table 2.

Table 1 Design loads and required section modulus (mild)

Item	Onsite	Inspection	Repair	Transit
Beta, vbm	0.33	0.26	0.26	0.32
M_{sws}/ (tf·m)	−520000	−520000	−520000	−520000
M_{swh} /(tf·m)	520000	520000	520000	520000
M_{ws} /(tf·m)	−150061	−120049	−120049	−143695
M_{wh} /(tf·m)	150798	120638	120638	144400
M_{tvbm} /(tf·m)	670798	640638	640638	664401
SM_{Gross} /(m·cm^2)	376007	359102	359102	372422
SM_SVR /(m·cm^2)	405286	405286	405286	405286
BM Ratio at Beta	0.85	0.85	0.85	0.85
SM_{min} /(m·cm^2)	34494	34494	34494	34494
$SM_{required}$ /(m·cm^2)	376008	359102	359102	372422

In Table 1, M_{sws}: Still water sagging BM; M_{swh}: Still water hogging BM; M_{ws}: ABS vertical wave sagging BM; M_{wh}: ABS vertical wave hogging BM; M_{tvbm}: Total vertical bending moment; SM_{Gross}: Gross nominal sectional modulus; SM_{min}: Minimum required gross SM; $SM_{required}$: Gross required SM; vbm: vertical bending moment.

Table 2 Comparison ratio between required SM and design SM

Condition	Position	SM_{GR} /(m·cm^2)	Material	SM_{GD} /(m·cm^2)	SMA/ SMR
Onsite	Deck	293286	HT32	347479	1.185
	Bottom	293286	HT32	362367	1.236
Inspection	Deck	280100	HT32	347479	1.241
	Bottom	280100	HT32	362367	1.294
Repair	Deck	280100	HT32	347479	1.241
	Bottom	280100	HT32	362367	1.294
Transit	Deck	290489	HT32	347479	1.196
	Bottom	290489	HT32	362367	1.247

In Table 2, SM_{GR} is gross required section modulus; SM_{GD}, gross design section modulus; SMA/SMR, section modulus(SM) ratio between actual SM and required SM.

3.4.2 Ultimate strength check results

The ultimate strength results are shown in Table 3.

Table 3 Ultimate strength check

Condition	γ_s*M_s+γ_w*M_w /(tf·m)	M_u/γ_u /(tf·m)	Load/Resistance Ratio
Sagging	−715079.8	−837369.7	0.85
Hogging	716037.4	955737.1	0.75

Table 4 Factor for ultimate strength check

Condition	γ_s	γ_w	γ_u
Sagging	1.00	1.30	1.15
Hogging	1.00	1.30	1.15

In Table 3 and 4, γ_s: load factor for the maximum permissible still-water bending moment; γ_w: load factor for wave-induced bending moment; γ_u : safety factor for the vertical hull girder bending capacity; M_u : hull girder ultimate strength; M_u : permissible still-water bending moment, in kN·m; M_w : Vertical wave-induced bending moment, in kN·m.

3.4.3 Fatigue strength check results

The fatigue strength results are shown in Table 5.

Table 5 Simplified fatigue strength check

ID	Alpha factors intended Site	Fatigue damage Dcmb	Fatigue life
BTM01A	19.895	0.126	>99.0
BTM01F	19.895	0.152	>99.0
BTM02A	19.502	0.126	>99.0
BTM02F	19.502	0.152	>99.0
BTM03A	19.219	0.126	>99.0
BTM03F	19.219	0.152	>99.0
BTM04A	18.851	0.125	>99.0
BTM04F	18.851	0.151	>99.0
BTM05A	18.542	0.125	>99.0
BTM05F	18.542	0.151	>99.0
BTM06A	18.234	0.125	>99.0
BTM06F	18.234	0.150	>99.0
BTM07A	17.895	0.125	>99.0
BTM07F	17.895	0.150	>99.0
BTM08A	17.666	0.125	>99.0
BTM08F	17.666	0.150	>99.0
BTM09A	17.335	0.124	>99.0
BTM09F	17.335	0.150	>99.0

The fatigue damage parameter, DM, will be presented and calculated by comparing the fatigue strength of the structure (capacity) and the fatigue inducing loads (demands). The calculation method is as follows:

$$\mathrm{DM} = 0.15\mathrm{DM}_1 + 0.35\mathrm{DM}_2 + 0.35\mathrm{DM}_3 + 0.15\mathrm{DM}_4 \quad (7)$$

$$\mathrm{DM}_i = f_{i,1-2}\mathrm{DM}_{i,1-2} + f_{i,3-4}\mathrm{DM}_{i,3-4} + f_{i,5-6}\mathrm{DM}_{i,5-6} + f_{i,7-8}\mathrm{DM}_{i,7-8} \quad (8)$$

where, DM_i = cumulative DM_i fatigue damage ratio for the applicable loading condition *I*; $f_{i,j-k}$ = factors.

$$\mathrm{DM}_{i,j-k} = \frac{N_L}{K_2}\frac{(0.01 f_{Ri})^m}{(\ln N_R)^{m/\gamma}}\mu_i\Gamma\left(1+\frac{m}{\gamma}\right) \quad (9)$$

where, $N_L = \frac{U}{4\log_{10} L}$, number of cycles for the expected design life; U = design life, in seconds; L = rule length, in m; m = S-N curve parameter; K_2 = S-N curve parameter; f_{Ri} = stress range at the representative probability level of 10^{-4}; γ = long term stress distribution parameter; Γ =

Gamma function; μ_i = stress coefficient taking into account the change in slope of the S-N curve.

For fatigue assessment of the structures of FPSO, the low cycle fatigue (LCF) is concerned due to the stress magnitudes exceeding the yield strength of the material during some operation conditions. The low cycle damage is:

$$\mathrm{DM}_{\mathrm{LCF}} = \frac{N_{\mathrm{LCF}} S_L^q}{B} \tag{10}$$

where, q=2.4; B= 3.51×10^{10} (MPa units); N_{LCF} = total cycles of loading/offloading.

The total fatigue damage due to both low cycle and high cycle stress is calculated by:

$$\mathrm{DM}_{\mathrm{comb}} = \frac{(\mathrm{DM}_{LCF}^2 + 2\delta \mathrm{DM}_{LCF}\mathrm{DM}_{HCF} + \mathrm{DM}_{HCF}^2)}{\sqrt{\mathrm{DM}_{LCF}^2 + \mathrm{DM}_{HCF}^2}} \tag{11}$$

where, δ = 0.02; DM_{LCF} = low cycle fatigue damage; DM_{HCF} = high cycle fatigue damage.

3.4.4 Sloshing check

The purpose of the sloshing analysis is to determine if the sloshing natural periods of the anticipated filling levels in each tank are close to the installation's pitch and roll motion periods. The effectiveness of the impulsive sloshing pressure on the design of the main supporting structures of the tank transverse and longitudinal bulkheads is subject to special consideration (Rognebakke and Faltinsen, 2001). The typical results are shown in Figs.4-6.

Ship Motions

					PITCH			ROLL		
LOAD CASE	DRAFT m	WAVE HEADING (deg.)	GM m	ROLL Kr	Amp. (deg.)	Eff. (deg.)	Period (sec.)	Amp. (deg.)	Eff. (deg.)	Period (Sec.)
1	6.00(0.67)	60.0	9.00	19.49	0.99	-0.70	8.41	1.49	1.06	13.00
2	6.00(0.67)	60.0	9.00	19.49	0.99	0.70	8.41	1.49	-1.06	13.00

Note:
Pitch (+) bow up
Roll (+) STBD down

Fig.4 Ship motions

<< LOAD CASE 01 >>

[TANK 01]

TANK LENGTH = 18.288 (m) (TANK LENGTH)/(SHIP LENGTH) = 0.095
TANK WIDTH = 21.031 (m) (TANK WIDTH) / (SHIP WIDTH) = 0.421
NO. OF TRAN. SWASH BULKHEADS = 0 NO. OF LONG. SWASH BULKHEADS = 0

FLVL	FLVL(m)	Le*Beta_T(m)	Be*Beta_L(m)	Tx(sec)	Ty(sec)	Tx/Tpicth	Ty/Troll
1	3.120	18.288	21.031	8.473	9.567	1.008	0.736
2	3.900	18.288	21.031	7.294	8.240	0.867	0.634
3	4.680	18.288	21.031	6.576	7.414	0.782	0.570
4	5.460	18.288	21.031	6.101	6.854	0.726	0.527
5	6.240	18.288	21.031	5.770	6.456	0.686	0.497
6	7.020	18.288	21.031	5.534	6.163	0.658	0.474
7	7.800	18.288	21.031	5.361	5.944	0.638	0.457
8	8.581	18.288	21.031	5.233	5.778	0.622	0.445
9	9.361	18.288	21.031	5.138	5.650	0.611	0.435
10	10.141	18.288	21.031	5.066	5.551	0.603	0.427
11	10.921	18.288	21.031	5.012	5.474	0.596	0.421
12	11.701	18.288	21.031	4.972	5.414	0.591	0.417
13	12.481	18.288	21.031	4.940	5.367	0.588	0.413
14	13.261	13.696	21.031	4.205	5.330	0.500	0.410
15	14.041	18.288	21.031	4.899	5.301	0.583	0.408

Fig.5 Wing cargo tank sloshing check

Net Thickness Calculation for Plating at X= 19.000

** C.L. Longitudinal Bulkhead Plating (5A-3-3/13.1) **

MEMR	ZP m	YP m	s mm	p kgf/cm2	MAT'L	tn_SH mm	Ps kgf/cm2	t1s mm	t2s mm	tns mm	trq mm	trd mm	toff mm
CTR-01	0.00	0.00	711.	1.673	(HT32)	11.91	1.17	7.92	7.21	9.50	11.91	12.00	15.00
CTR-02	0.00	2.85	712.	1.379	(HT32)	9.50	0.85	5.95	6.15	9.50	9.50	9.50	15.00
CTR-03	0.00	3.15	712.	1.347	(HT32)	9.50	0.81	5.73	6.00	9.50	9.50	9.50	15.00
CTR-04	0.00	5.99	713.	1.052	(HT32)	9.50	0.42	3.75	4.34	9.50	9.50	9.50	15.00
CTR-05	0.00	9.45	713.	0.692	(HT32)	9.50	0.08	1.64	1.87	9.50	9.50	9.50	15.00
CTR-06	0.00	12.29	712.	0.395	(HT32)	10.36	0.11	2.15	2.24	9.50	10.36	10.50	18.00
CTR-07	0.00	14.94	458.	0.210	(HT32)	9.50	0.14	1.74	1.63	9.50	9.50	9.50	18.00

** Other Longitudinal Bulkhead Plating (5A-3-3/13.1) **

Fig.6 Sloshing results of longitudinal @FR49+19m

3.5 Direct strength evaluation(TSA stage)

The TSA provides a calculation the structural response by performing a finite element analysis. This is based on a "net" ship approach. The reassessed net scantlings are obtained by deducting the nominal design corrosion margins from the reassessed scantlings.

Generally, the strength assessment of the hull structure can be based on one of two approaches. One approach is based on a three cargo tank length finite element model about mid-ships where the strength assessment is focused on the results obtained from structures in the middle tank. Another approach is based on a complete hull length or full cargo block length finite element model including all cargo and ballast tanks in the hull structure. Since there is a large amount of work required during the optimization process, the first method is applied to the hull optimization.

In the analysis, the three-hold length 3D model within 0.4L amidships is made. And two frames fore and aft of the two end bulkheads were modeled. All primary load-carrying members were modeled. Secondary structural members which may affect the overall load distribution are made. And structural idealization is made and based on the stiffness and anticipated response of the structures.

The overall response of the hull girder under the imposed sea loading is obtained. The analysis of the global model is used not only to assess the hull girder plating of the deck, side shell, bottom, inner bottom, longitudinal bulkheads, and transverse bulkheads but also to assess the main supporting members. And the local fine-mesh models are used to determine the additional requirements for the critical areas. The typical FE model is shown in Fig.7.

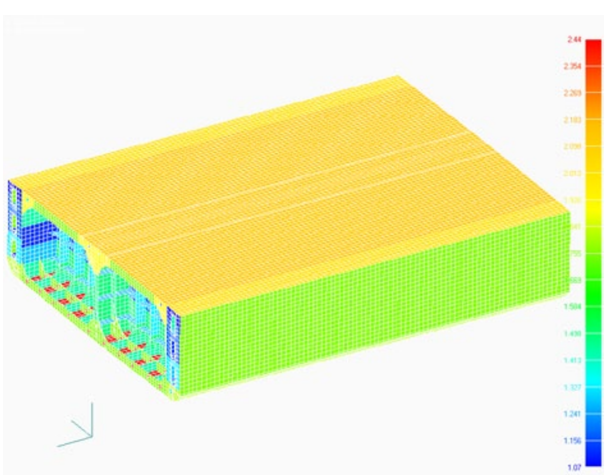

Fig.7 FE Model of FPSO

The standard combined load cases with the corresponding loading patterns are used in the FE analysis. And in assessing the strength of the tank boundary supporting structures, the additional combined load cases of the sloshing load cases are considered. The hull girder shear force and bending moment are adjusted automatically by the Eagle. And the boundary conditions, which are in compliance with the rules, are applied at the ends of the cargo tank FE model. A typical result for one of the loading cases is shown in Fig.8.

With consideration to the huge workload, the VonMises stress and the deflection is the key point in the optimization. The buckling strength is calculated using a simple method for a typical area. And the fatigue strength is based on the simplified method in the ISE stage.

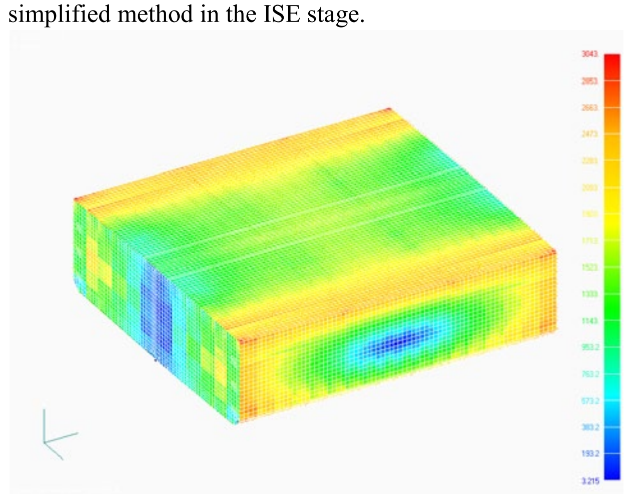

Fig.8 VonMises stress plot for one of the load cases

4 Consequence assessment for the hull optimization

Optimization design is made according to the same design procedure and method. Several ships with different dimensions and the same loads are analyzed. And the consequence comparison is shown in Table 6 and Table 7.

Based on the design basis, the results from Table 6 and Table 7 can be found as follows:

1) The total weight of the barge-shaped and ship-shaped hull is nearly same.

2) For barge-shaped hull, increasing depth appropriately can reduce the weight of structures.

4.1 Comparison between ship-shaped and barge-shaped

The comparison is based on the assumptions below:

a)The load cases are the same.

b)The ratio between actual and rule is the same.

Table 6 Steel weights of longitudinal structures for ship-shaped and barge-shaped

Main dimension (m) L×B×D	Total weight of all longitudinal structures (tons)
200×50×15.5 (Barge shaped)	9885
230×45×19 (ship shaped)	9900

4.2 Barge-shaped with different depths

The comparison is based on the assumptions below:

a) The load cases are the same.

b)The ratio between SMA and SMR is the same.

Table 7 Steel weights of longitudinal structures in the hull with different depths

Main dimension L×B×D (m)	Weight (tons)	SMA/SMR (deck)	SMA/SMR (bottom)
200×50×15.5	9885	1.043	1.016
200×50×17	9430	1.045	1.023
200×50×17.7	9185	1.041	1.026
200×50×18.4	8995	1.040	1.026

In Table 7， Weight = Total weight of all longitudinal structures.

After finishing the comparison above, the barge-shaped FPSO with the main dimensions of 200m×50m×17.7m is chosen as the optimization hull. This design can meet the specifications of the owner, and reduce the steel weight by approximately 500 tons.

5 Conclusions

Based on the design procedure, this paper analyzes the scantling of several mid-ship section, through analyzing the calculation results, the following conclusions have been obtained:

1) The design procedure can be applied to the FPSO hull design and hull optimization. Especially for the optimization, because a lot of work is to be done, the design procedure can help improve design efficiency.

2) Under this design basis, the FPSO of the barge-shaped design is better than the ship-shaped design, because the depth of the barge-shaped design can be changed with flexibility. And increasing the depth not only reduces the steel weight but also benefits the longitudinal strength. Under determined loads, a better main dimension can be found through the design procedure in this paper.

3) The arrangement and operation conditions are different for every FPSO. Then the still water bending moment and wave bending moment is different. Based on the different loads, the mid-ship section scantlings are different. The achieved assessment results can provide a reference for the determination of FPSO design.

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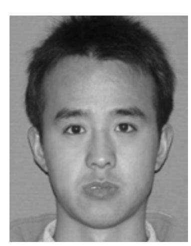
Author biography



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