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LONG TERM STRUCTURAL ASSESSMENT OF AN FSU SHIP BASED ON THE SPECTRAL FATIGUE METHOD

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ABSTRACT

For the safety operation of the offshore FSU floating storage units, the structural design must be assessed on the short-term yielding stress criterion and on the long-term fatigue strength criterion. This paper presents the fatigue strength assessment for a large FSU structure with length of 292 m, based on the wave loads from Western North Atlantic at zero speed in the operation area. Besides the waves loading cycles, the oil tanks loading and unloading low cycles are taken into account. The short-term stress analysis is based on a coupled hydrodynamic and structural 3D model. The spectral fatigue analysis is based on the long-term D damage cumulative factor method, considering 100 years as the design exploitation time reference. The numerical results from this study point out the structural details of the FSU hull which do not comply with the fatigue strength criteria.

Keywords: spectral fatigue method, 3D-FEM model, FSU floating storage unit.

1. INTRODUCTION

The offshore structures operate in extreme sea environments, on long time periods, making the fatigue strength assessment a mandatory analysis, according to the ship classification societies [2],[6].

The fatigue phenomenon is generated by the damage that can occur in ships and offshore structures during their long-term exploitation life, because of the waves-induced loads.

The spectral fatigue analysis method [6] includes the following steps: deterministic stress *RAO* functions computations [3],[5],[7]; short-term significant stress values computations for specific power density spectra of waves [4],[5],[7]; the fatigue damage computation for a long-term wave scattering diagram [1] corresponding to the operation area of the FSU floating structure.

The numerical analyses are carried out with Bureau Veritas programs [3],[4],[5], for a large offshore FSU floating storage unit [8].

2. THEORETICAL BASES

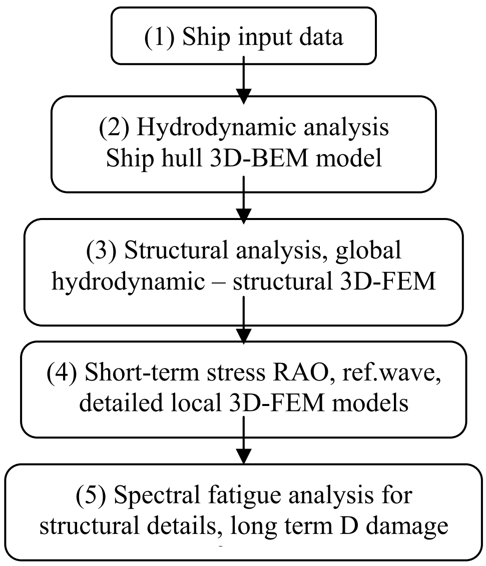


Fig.1. The main flowchart for spectral fatigue damage analysis of FSU.

Figure 1 presents the main flowchart of the spectral fatigue damage analysis method, with the following steps:

(1) *Ship input data.* The 3D-CAD ship offset-lines, structural plan, material characteristics, onboard masses are the required input data for the integrated fatigue analysis.

(2) *Hydrodynamic analysis*. The oscillations of the dynamic responses of the ship hull are computed. The hydrodynamic radiation and diffraction problems are solved in frequency domain, linear motions hypothesis, by the 3D-BEM boundary element method, using the BV HydroStar [3] program. A full set of regular waves heading angles and circular frequencies are considered [7],[10].

(3) *Global structural analysis.* Using a 3D-FEM global coarse mesh model developed by Femap [9] program, the structural analysis coupled to the hydrodynamic loads is solved by BV Homer [5] program. Because the ship motions are based on a linear model, which delivers larger amplitudes than a non-linear motion model [7], according to BV, fatigue rules [6] corrections are used for the wave load pressure applied on the hull external side shell.

(4) *Short-term stress RAO*. For selected structural elements, with significant hot-spots, several 3D-FEM detailed fatigue fine mesh models are developed. The fatigue models have the mesh size equal to the thickness of the plates [6]. As boundary conditions the displacements and rotations based on the global FEM coarse model results are considered. The stress *RAO* functions for the reference waves (module 2) and selected structural details are obtained.

(5) *Spectral fatigue analysis (long-term)*. For each selected structural detail, based on the material stress-cycle diagram *S-N* [6], stress *RAO* functions (module 4), specific wave short-term power density functions [7] and long-term scattering diagrams [1],[7], the long-term fatigue strength assessment is accomplished for a design exploitation time reference of R=100 years. The spectral analysis is carried out by BV StarSpec [4] program.

The fatigue strength evaluation is based on the damage cumulative factor D by the Palmgren-Miner approach [2],[6].

For each structural detail, the welding type and corrosion coefficients are considered for the computation of the reference fatigue stress value [2],[6].

Besides the variable loads with high frequency (*HC* high cycles) induced by waves, the low frequency loads (*LC* low cycles), at still water condition, from loading and unloading the oil cargo of the offshore unit are considered for fatigue strength computation [2],[6]. The total D damage factor is:

$$D = D_{HC} + D_{LC}\,;\;\; D_{HC} = \sum_{j=1}^{m} k_j \cdot D_{HC\,j} \quad (1)$$

where D_{HC} is the high-cycle damage factor, exploitation scenario with cumulated m loading cases; D_{LC} is the low-cycle damage factor.

The expected fatigue life for one loading case has the following expression:

$$FL = R/D \text{ [years]} \quad (2)$$

where R [years] is the design exploitation time reference for the offshore unit.

For a well designed structural detail, the following fatigue criteria have to be met:

$$D \geq 1\;;\quad FL \geq R \text{ [years]} \quad (3)$$

3. THE 3D-FEM MODEL OF THE FSU UNIT AND THE LOADING CASES

In this study a large offshore FSU floating storage unit at zero speed is considered, with the main characteristics provided in Table 1.

Table 1. FSU main characteristics

Length between perpendiculars	*LBP*	292 *m*
Breadth	*B*	48 *m*
Depth	*D*	31.6 *m*
Maximum draft	T_{max}	20 *m*
Minimum draft	T_{min}	14 *m*

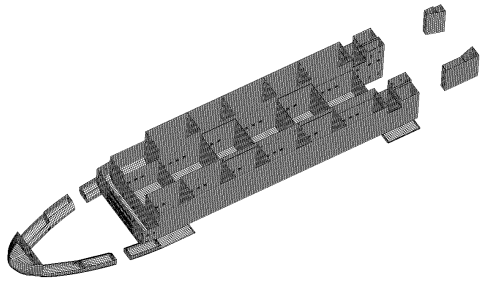


Fig.2 Full load loading case (T=20m), j=1

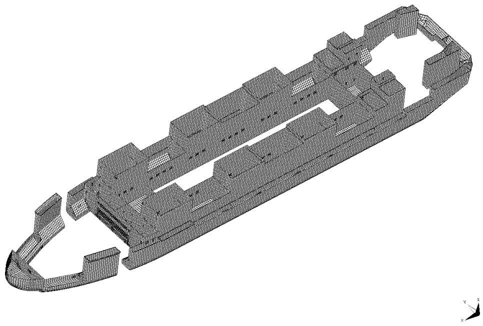


Fig.3 Intermediate 2 loading case (T=18m), j=2

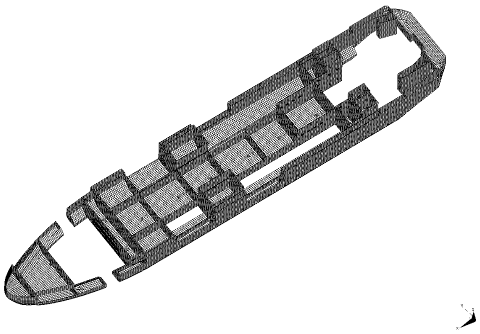


Fig.4 Intermediate 1 loading case (T=16m), j=3

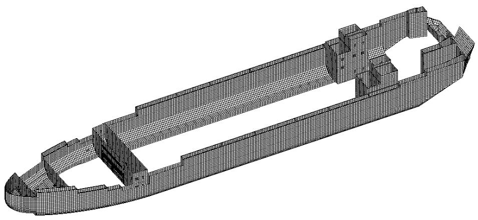


Fig.5 Ballast loading case (T=14m), j=4

Figures 2,3,4,5 present the j=1,4 loading cases for the FSU selected according to Bureau Veritas Rules [2] for the offshore units, with the associated onboard tankers layout and draft conditions.

The FSU hull structure is made of two types of steel, mild and high tensile, with the properties presented in Table 2.

Table 2. FSU hull material characteristics

Young's modulus	E	206000 MPa
Poisson's ratio	ν	0.3
Density	ρ	7.85 t/m^3
Yield stress (mild steel)	σ_Y	235 MPa
Yield stress (HTS32)	σ_Y	315 MPa

The 3D-FEM FSU hull numerical model is developed using Femap [9] program, according to CSR-IACS [11] rules, with the following types of finite elements :

- PLATE, membrane and Mindlin plate formulation, triangle and quadratic shape, low order formulation, with 6 d.o.f. in each node;
- BEAM, elastic 3D beam element, with 2 nodes and 6 d.o.f. in each node;
- RIGID, rigid bar with 2 nodes and 12 d.o.f.;
- MASS, lumped mass, one node and 6 d.o.f.

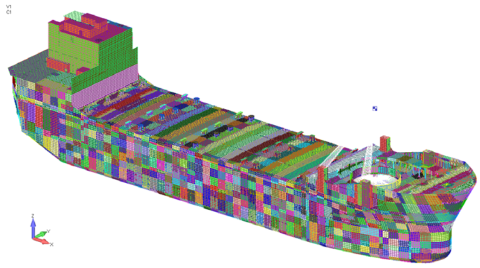


Fig.6 FSU 3D-FEM fully developed model

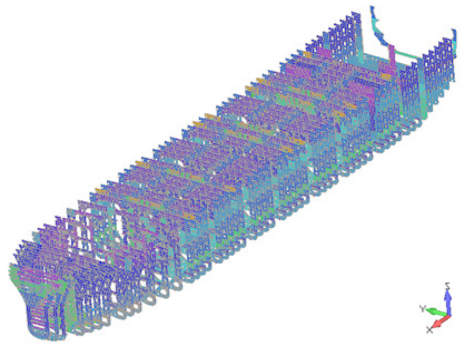


Fig.7 FSU 3D-FEM model – web frames

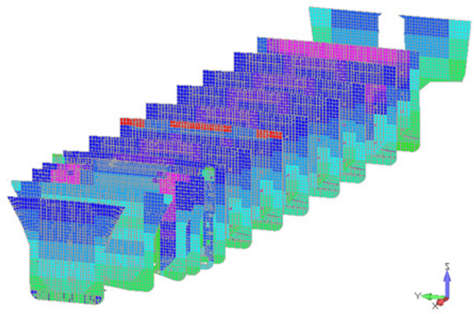


Fig.8 FSU 3D-FEM - transversal bulkheads

Figures 6 ÷ 13 present details of the 3D-FEM FSU hull numerical model, developed over the whole length and on both ship sides.

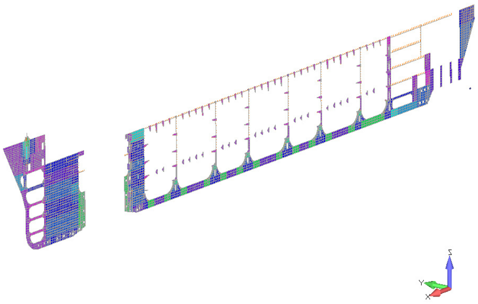


Fig.9 FSU 3D-FEM model – centre -line.

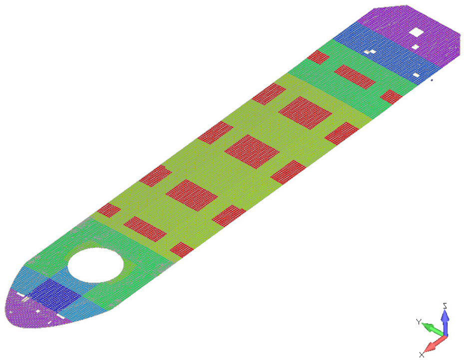


Fig.10 FSU 3D-FEM model – main deck

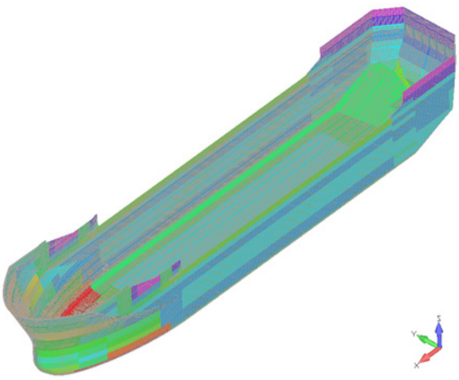


Fig.11 FSU 3D-FEM model – external shell

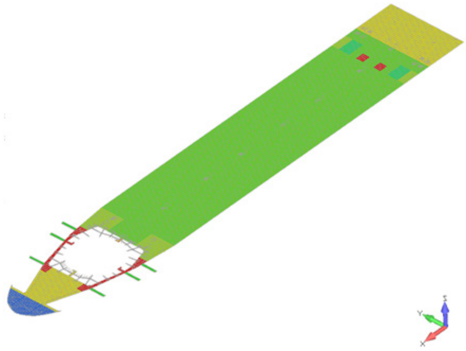


Fig.12 FSU 3D-FEM model – inner bottom

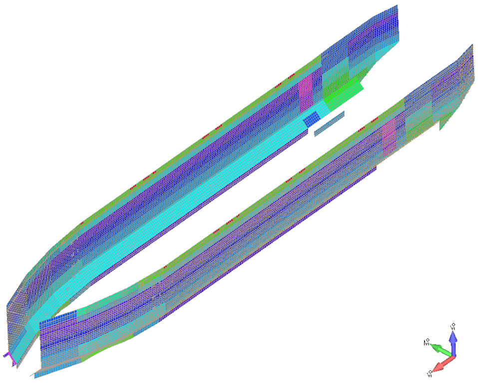


Fig.13 FSU 3D-FEM model – inner hull

The boundary conditions on the full FSU 3D-FEM model are applied according to the CSR-IACS [11] rules (Fig.14, Table 3).

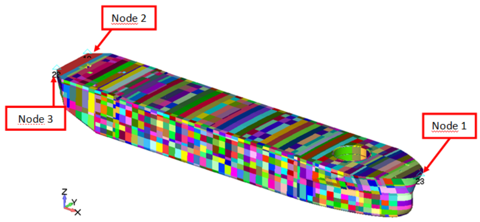


Fig.14 Global FSU 3D-FEM boundary cond.

Table 3. FSU 3D-FEM boundary conditions

Nodes	*D.O.F. degree of freedom on ref. Nodes*					
	TX	*TY*	*TZ*	*RX*	*RY*	*RZ*
Node 1	-	X	X	-	-	-
Node 2	X	-	X	-	-	-
Node 3	-	X	X	-	-	-

Table 4, Figures 15,18 include the selected structural details for fatigue analysis, with significant stress hot spots (HS), on both sides (PS, SB), amidships at a transversal bulkhead TBHD. Around the local geometric / stress hot spots, the 3D-FEM model mesh has been refined with element size equal to the plate thickness. In order to take into account the corrosion effect [2],[6], a 1.5 correction is considered for the inside oil tank elements and 1.1 for the inside ballast tanks.

Table 4. Selected details with hot-spots for fatigue analysis from the FSU 3D-FEM model

HS no.	*Description of structural details (Fig.15÷19)*
HS1 (PS,SB)	outward joint brackets BB stringer 4 connections in way of TBHD
HS2 (PS,SB)	inward joint brackets BB stringer 4 connections in way of TBHD
HS3 (PS,SB)	outward joint brackets BB stringer 3 connections in way of TBHD
HS4 (PS,SB)	inward joint brackets BB stringer 3 connections in way of TBHD
HS5 (PS,SB)	outward joint brackets BB stringer 2 connections in way of TBHD
HS6 (PS,SB)	inward joint brackets BB stringer 2 connections in way of TBHD
HS7 (PS,SB)	outward joint brackets BB stringer 1 connections in way of TBHD
HS8 (PS,SB)	inward joint brackets stringer 1 connections in way of TBHD

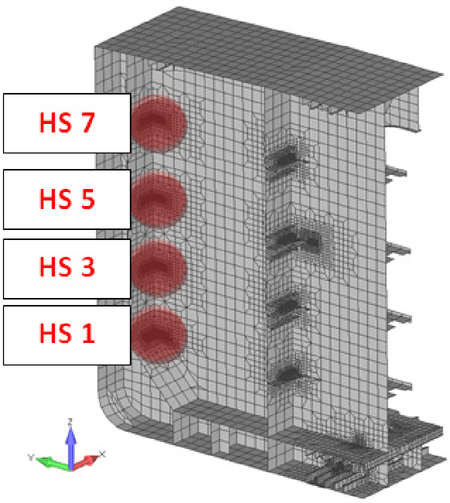


Fig.15 Structural details HS1,HS3,HS5,HS7

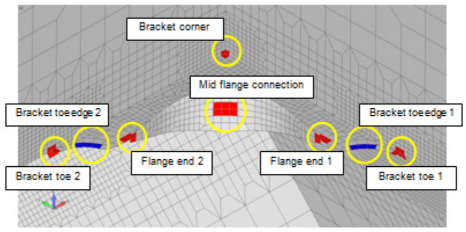


Fig.16 Details of HS1

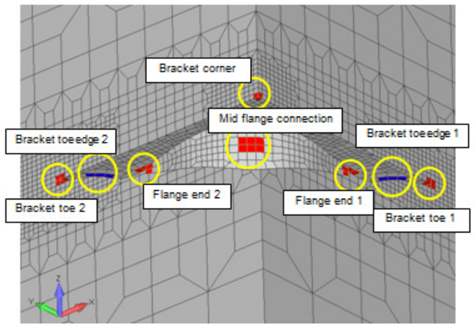


Fig.17 Details of HS3, HS5, HS7

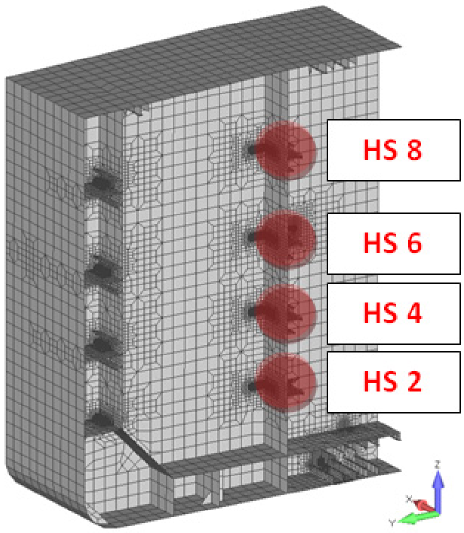


Fig.18 Structural details HS2,HS4,HS6,HS8

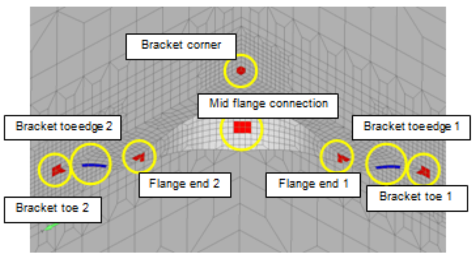
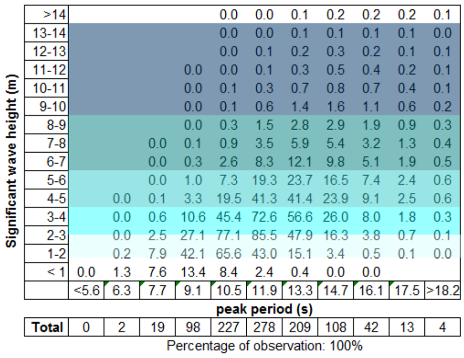


Fig.19 Details of HS2,HS4,HS6,HS8

4. FATIGUE ANALYSIS RESULTS

The numerical hydrodynamic analysis (Fig.1 module 2) is done for 79 circular frequencies 0.05 to 2.0 rad/s (with 0.025 rad/s step) and 24 wave heading angles from 0° to 345° (with 15° step). Details of the hydrodynamic analyses are presented in reference [10].

The offshore FSU floating storage unit is operating in the WNA – Western North Atlantic, with the long-term wave scatter diagrams from Figs. 20, 21, from the Global Wave Statistics database [1].



Significant wave height (m)	<5.6	6.3	7.7	9.1	10.5	11.9	13.3	14.7	16.1	17.5	>18.2
>14					0.0	0.0	0.1	0.2	0.2	0.2	0.1
13-14					0.0	0.0	0.1	0.1	0.1	0.1	0.0
12-13					0.0	0.1	0.2	0.3	0.2	0.1	0.1
11-12				0.0	0.0	0.1	0.3	0.5	0.4	0.2	0.1
10-11				0.0	0.1	0.3	0.7	0.8	0.7	0.4	0.1
9-10				0.0	0.1	0.6	1.4	1.6	1.1	0.6	0.2
8-9				0.0	0.3	1.5	2.8	2.9	1.9	0.9	0.3
7-8			0.0	0.1	0.9	3.5	5.9	5.4	3.2	1.3	0.4
6-7			0.0	0.3	2.6	8.3	12.1	9.8	5.1	1.9	0.5
5-6			0.0	1.0	7.3	19.3	23.7	16.5	7.4	2.4	0.6
4-5		0.0	0.1	3.3	19.5	41.3	41.4	23.9	9.1	2.5	0.6
3-4		0.0	0.6	10.6	45.4	72.6	56.6	26.0	8.0	1.8	0.3
2-3		0.0	2.5	27.1	77.1	85.5	47.9	16.3	3.8	0.7	0.1
1-2		0.2	7.9	42.1	65.6	43.0	15.1	3.4	0.5	0.1	0.0
< 1	0.0	1.3	7.6	13.4	8.4	2.4	0.4	0.0	0.0		
Total	0	2	19	98	227	278	209	108	42	13	4

peak period (s)

Percentage of observation: 100%

Fig.20 WNA wave scattering diagram [1].

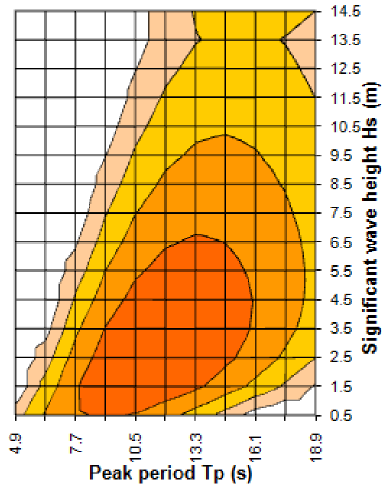


Fig.21 WNA wave scattering diagram [1].

Tables 5÷20 include the numerical results (1), (2) from the fatigue spectral analysis (Fig.1) of the offshore FSU floating storage unit, for the structural details presented in Table 4, taking into account the hot-spot elements with the highest probability of cracking.

Table 5. Fatigue life (*FL*) for PS hot-spot 1

Location	D_{HC}	D_{LC}	*FL [years]*
Bracket toe 1	0.330	0.226	> 100
Bracket toe edge 1	0.066	0.004	> 100
Flange end 1	0.194	0.009	> 100
Midflange connection	0.339	0.012	> 100
Flange end 2	0.052	0.003	> 100
Bracket toe edge 2	0.010	0.001	> 100
Bracket toe 2	0.081	0.002	> 100
Bracket corner	0.048	0.008	> 100

Table 6. Fatigue life (*FL*) for PS hot-spot 2

Location	D_{HC}	D_{LC}	*FL [years]*
Bracket toe 1	0.242	0.091	> 100
Bracket toe edge 1	0.037	0.005	> 100
Flange end 1	0.151	0.011	> 100
Midflange connection	0.166	0.028	> 100
Flange end 2	0.030	0.003	> 100
Bracket toe edge 2	0.005	0.001	> 100
Bracket toe 2	0.035	0.005	> 100
Bracket corner	0.018	0.008	> 100

Table 7. Fatigue life (*FL*) for SB hot-spot 1

Location	D_{HC}	D_{LC}	*[FL years]*
Bracket toe 1	0.201	0.267	> 100
Bracket toe edge 1	0.035	0.004	> 100
Flange end 1	0.083	0.008	> 100
Midflange connection	0.043	0.008	> 100
Flange end 2	0.000	0.001	> 100
Bracket toe edge 2	0.000	0.000	> 100
Bracket toe 2	0.003	0.002	> 100
Bracket corner	0.029	0.016	> 100

Table 8. Fatigue life (*FL*) forSB hot-spot 2.

Location	D_{HC}	D_{LC}	*[FL years]*
Bracket toe 1	0.176	0.091	> 100
Bracket toe edge 1	0.026	0.006	> 100
Flange end 1	0.102	0.014	> 100
Midflange connection	0.079	0.030	> 100
Flange end 2	0.005	0.003	> 100
Bracket toe edge 2	0.001	0.001	> 100
Bracket toe 2	0.004	0.005	> 100
Bracket corner	0.014	0.009	> 100

Table 9. Fatigue life (*FL*) for PS hot-spot 3

Location	D_{HC}	D_{LC}	*[FL years]*
Bracket toe 1	2.295	0.047	**42.7**
Bracket toe edge 1	0.289	0.011	> 100
Flange end 1	1.373	0.032	**71.2**
Midflange connection	6.586	0.126	**14.9**
Flange end 2	1.155	0.026	**84.7**
Bracket toe edge 2	0.208	0.009	> 100
Bracket toe 2	2.944	0.041	**33.5**
Bracket corner	0.231	0.008	> 100

Table 10. Fatigue life (*FL*) for PS hot-spot 4.

Location	D_{HC}	D_{LC}	*[FL years]*
Bracket toe 1	0.068	0.050	> 100
Bracket toe edge 1	0.012	0.003	> 100
Flange end 1	0.080	0.009	> 100
Midflange connection	0.239	0.028	> 100
Flange end 2	0.097	0.010	> 100
Bracket toe edge 2	0.023	0.003	> 100
Bracket toe 2	0.357	0.013	> 100
Bracket corner	0.008	0.002	> 100

Table 11. Fatigue life (*FL*) for SB hot-spot 3.

Location	D_{HC}	D_{LC}	*[FL years]*
Bracket toe 1	1.837	0.039	**53.3**
Bracket toe edge 1	0.135	0.008	> 100
Flange end 1	0.720	0.024	> 100
Midflange connection	4.085	0.117	**23.8**
Flange end 2	0.834	0.025	> 100
Bracket toe edge 2	0.177	0.010	> 100
Bracket toe 2	1.403	0.042	**69.2**
Bracket corner	0.141	0.008	> 100

Table 12. Fatigue life (*FL*) for SB hot-spot 4.

Location	D_{HC}	D_{LC}	*[FL years]*
Bracket toe 1	0.257	0.012	> 100
Bracket toe edge 1	0.017	0.003	> 100
Flange end 1	0.070	0.009	> 100
Midflange connection	0.172	0.028	> 100
Flange end 2	0.060	0.009	> 100
Bracket toe edge 2	0.010	0.003	> 100
Bracket toe 2	0.054	0.050	> 100
Bracket corner	0.006	0.002	> 100

Table 13. Fatigue life (*FL*) for PS hot-spot 5.

Location	D_{HC}	D_{LC}	*[FL years]*
Bracket toe 1	1.697	0.039	**57.6**
Bracket toe edge 1	0.207	0.008	> 100
Flange end 1	0.923	0.024	> 100
Midflange connection	3.875	0.078	**25.3**
Flange end 2	0.584	0.019	> 100
Bracket toe edge 2	0.096	0.006	> 100
Bracket toe 2	1.686	0.030	**58.3**
Bracket corner	0.198	0.004	> 100

Table 14. Fatigue life (*FL*) for 6 PS hot-spot.

Location	D_{HC}	D_{LC}	*[FL years]*
Bracket toe 1	0.045	0.026	> 100
Bracket toe edge 1	0.003	0.005	> 100
Flange end 1	0.017	0.014	> 100
Midflange connection	0.052	0.020	> 100
Flange end 2	0.033	0.010	> 100
Bracket toe edge 2	0.010	0.003	> 100
Bracket toe 2	0.226	0.013	> 100
Bracket corner	0.007	0.001	> 100

Table 15. Fatigue life (*FL*) for SB hot-spot 5.

Location	D_{HC}	D_{LC}	*[FL years]*
Bracket toe 1	1.198	0.031	**81.4**
Bracket toe edge 1	0.070	0.006	> 100
Flange end 1	0.407	0.020	> 100
Midflange connection	2.777	0.081	**35.0**
Flange end 2	0.680	0.025	> 100
Bracket toe edge 2	0.158	0.008	> 100
Bracket toe 2	1.268	0.040	**76.5**
Bracket corner	0.143	0.005	> 100

Table 16. Fatigue life (*FL*) for SB hot-spot 6.

Location	D_{HC}	D_{LC}	*[FL years]*
Bracket toe 1	0.136	0.013	> 100
Bracket toe edge 1	0.008	0.004	> 100
Flange end 1	0.025	0.010	> 100
Midflange connection	0.037	0.020	> 100
Flange end 2	0.014	0.014	> 100
Bracket toe edge 2	0.003	0.005	> 100
Bracket toe 2	0.176	0.013	> 100
Bracket corner	0.008	0.001	> 100

Table 17. Fatigue life (*FL*) for PS hot-spot 7.

Location	D_{HC}	D_{LC}	*[FL years]*
Bracket toe 1	0.025	0.007	> 100
Bracket toe edge 1	0.000	0.001	> 100
Flange end 1	0.002	0.002	> 100
Midflange connection	0.040	0.005	> 100
Flange end 2	0.043	0.004	> 100
Bracket toe edge 2	0.026	0.003	> 100
Bracket toe 2	0.619	0.025	> 100
Bracket corner	0.042	0.005	> 100

Table 18. Fatigue life (*FL*) for PS hot-spot 8.

Location	D_{HC}	D_{LC}	*[FL years]*
Bracket toe 1	0.657	0.022	> 100
Bracket toe edge 1	0.058	0.006	> 100
Flange end 1	0.143	0.014	> 100
Midflange connection	0.078	0.011	> 100
Flange end 2	0.002	0.002	> 100
Bracket toe edge 2	0.000	0.001	> 100
Bracket toe 2	0.036	0.006	> 100
Bracket corner	0.052	0.006	> 100

Table 19. Fatigue life (*FL*) for SB hot-spot 7

Location	D_{HC}	D_{LC}	*[FL years]*
Bracket toe 1	0.648	0.024	> 100
Bracket toe edge 1	0.026	0.003	> 100
Flange end 1	0.044	0.004	> 100
Midflange connection	0.042	0.005	> 100
Flange end 2	0.002	0.002	> 100
Bracket toe edge 2	0.001	0.001	> 100
Bracket toe 2	0.028	0.007	> 100
Bracket corner	0.041	0.005	> 100

Table 20. Fatigue life (FL) for SB hot-spot 8

Location	D_{HC}	D_{LC}	*[FL years]*
Bracket toe 1	0.028	0.006	> 100
Bracket toe edge 1	0.000	0.001	> 100
Flange end 1	0.001	0.002	> 100
Midflange connection	0.080	0.011	> 100
Flange end 2	0.151	0.013	> 100
Bracket toe edge 2	0.061	0.006	> 100
Bracket toe 2	0.713	0.024	> 100
Bracket corner	0.056	0.006	> 100

5. CONCLUSIONS

For the reference exploitation life of R=100 years, using the fatigue analysis results from Tables 15÷20, in Table 21 are selected the details with fatigue life less than the reference of 100 years (2) which do not meet the fatigue strength criteria (3) [6].

Table 21. Structural details which do not meet the fatigue limit criteria (3)

HS no.	*Location*	*FL [years]*
HS 3 PS	Bracket toe 1	42.7
	Flange end 1	71.2
	Midflange connection	14.9
	Flange end 2	84.7
	Bracket toe 2	33.5
HS 3 SB	Bracket toe 1	53.3
	Midflange connection	23.8
	Bracket toe 2	58.3
HS 5 PS	Bracket toe 1	57.6
	Midflange connection	25.3
	Bracket toe 2	58.3
HS 5 SB	Bracket toe 1	81.4
	Midflange connection	35.0
	Bracket toe 2	76.5

For backing brackets BB of two horizontal stringers, the potential crack path is presented in Figure 22.

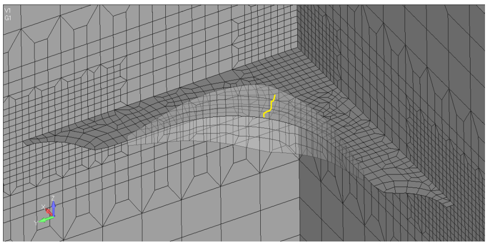


Fig.22 Potential crack path for BB brackets

The fatigue damage factor D_{LC} of low-cycle loading and unloading processes is in most cases smaller compared to the wave induced high-cycle fatigue damage factor D_{HC} (Tables 15-20).

Based on the results from Table 21, the design of some of brackets has to be improved in order to satisfy the fatigue strength criteria (3) [6].

Further studies will be focused on other ships and offshore unit structures. In some cases the hydroelastic dynamic loads will also have to be considered for the very flexible hull girder floating structures.

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REFERENCES

[1]. **BMT**,*"Global Wave Statistic", 2014, BMT Fluid Mechanics,ww.globalwavestatisticsonline.com.*

[2]. **BV,** "*Rules for the Classification of Offshore Units"*, Bureau Veritas, Paris, 2014.

[3]. **BV**,*"HydroStar for experts user's manual",* Bureau Veritas, Paris, 2014.

[4]. **BV**, *"StarSpec user's guide",* Bureau Veritas Paris, 2014.

[5]. **BV**, *"Homer user's manual"*, Bureau Veritas, Paris, 2010.

[6]. **BV**, *"Fatigue strength of welded ship structures", NI 393,* Bureau Veritas, Paris, 1998.

[7]. **Domnisoru, L**,*"Ship Dynamics. Oscillations and Vibrations",* Technical Publishing House, Bucharest, 2001.

[8]. **FleetMon**, *"Vessel Database all over world", 2014, https://www.fleetmon.com/en/vessels.*

[9]. **FNN**, *"Femap NX Nastran user's manual"*, Siemens PLM Software, 2007.

[10]. **Jagate, G., Domnisoru, L.**, *"Advanced sea-keeping computation for an FSU ship under given environmental conditions", 9 Oct.* Galati ASTR Conference,pp.164-169, AGIR, 2015.

[11]. **CSR,***"Common Structural Rules for Bulk Carriers and Oil Tankers"*, IACS, January 2015.

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