International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Vol. XV, No. 2 / 2023
https://doi.org/ 10.54684/ijmmt.2023.15.2.200

ON THE STRUCTURAL VALUATION IN OBLIQUE WAVES OF A LARGE LIQUEFIED NATURAL GAS CARRIER BY 3D-FEM MODEL APPROACH

Leonard Domnisoru

"Dunarea de Jos" University of Galati, Department of Naval Architecture, Domneasca Street 111, 800201, Galati, Romania

Corresponding author: Leonard Domnisoru, leonard.domnisoru@ugal.ro

Abstract: This structural valuation in oblique equivalent waves has as a study case a large LNG liquefied natural gas carrier, with an overall length of 289.3 m, structural gas membrane tanks, and a double hull. From the operation load cases, for the numerical study, a selection of the main cases is made, full cargo and ballast. The selected oblique design wave conditions are specific to unrestricted navigation areas, sagging and hogging wave-free surface, with the heading angle covering the oblique relevant cases. The computation of the LNG carrier equilibrium in oblique design waves is done by a three-parameter non-linear approach, with the own P_QSW software. The 3D-FEM large LNG carrier model is developed by Femap/NX Nastran software. The structural valuation in oblique design waves, by strength and freeboard criteria, of the large LNG carrier involves 3D and 1D models. For practical purposes, the strength valuation results are synthesized as polar diagrams, for the relevant heading angles of the oblique design waves, representing the wave height safety limits for preserving the large LNG carrier structural integrity.
Key words: large LNG carrier, oblique design waves, 3D-FEM model, maritime operations.

1. INTRODUCTION

The standard strength valuation of the maritime floating structures is done usually for still water and head design wave navigation conditions [1, 2], delivering the first assessment of the structural design according to the rules [3, 4]. Extended strength valuation of the ships must include oblique design wave conditions, resulting in a whole range of the structural ship's design evaluation [5, 6, 7]. Ship's strength valuation in oblique design waves requires an enhanced three parameters non-linear iterative approach, with optimized procedures to achieve the best solution convergence and less computational time for delivering the quasi-static equilibrium state, implemented by eigen *P_QSW* code [7], for the whole range of navigation conditions. The oblique waves' procedure requires 1D beam and 3D FEM structural models, with correlated input data as mass diagram and 3D ship's hull shape by user Femap/NX Nastran [8] subroutines, to ensure the accuracy for the computation of relative equilibrium position of the ship and also the necessary structural details for the local and global strength valuation. In brief, the 1D and 3D non-linear approach is in section 2 presented.
This study focuses on strength valuation in oblique waves of a large LNG 150000 cbm liquefied natural gas carrier [9], with gas membrane tanks, having a double hull and deck panels. The 1D and 3D numerical models are covering the entire large LNG carrier structure, including geometric non-linearities, with relevant data presented in section 3. For the large LNG 150000 cbm carrier, two main loading cases are selected, full load and heavy ballast. The study involves the structural valuation in oblique waves by strength and freeboard criteria, using 1D - 3D models, with relevant results in sections 4 and 5 included. Combined criteria deliver the oblique design wave height limits to ensure the large LNG safety navigation operation, with the comparison of the loading cases and structural models in section 6.

2. FUNDAMENTS FOR THE LARGE LNG CARRIER ENHANCED STRUCTURAL VALUATION IN OBLIQUE WAVES

For the computation of the equilibrium position of the large LNG carrier in oblique waves and the strength valuation, 1D linked to 3D models are necessary. The computation process leads to the implementation of an iterative algorithm [7], synthesized in figure 1, with the main next steps:
(1) *The large LNG carrier data and oblique EDW cases* step involves the idealization of the hull structure and onboard masses, selection of the loading condition (displacement, gravity center position), oblique wave height and heading angle analysis case.

(2) *The 3D-CAD/FEM modeling* step involves the development of the 3D-CAD hull model imported from the hull design, ensuring the geometrical accuracy inclusive of the external 3D hull shape. The 3D-FEM model is developed using Femap/NX procedures [8], with Mindlin-Reissner triangle and quad shell finite elements for the whole structure [10]. The 3D-FEM model is extended over the entire large LNG carrier hull, stern-to-bow and side-to-side (figures 2, 3, 4). The onboard masses are modeled as non-structural distributed masses associated with several shell elements and as lumped mass elements for cargo, ballast, equipment, and other local masses. The steel hull mass results by defining the proper density of the material for all the structural elements (table 1).
(3) *The 1D beam model development* step involves importing from the 3D-CAD model the 3D external hull shape for defining the ship's offset lines, and the equivalent mass diagram from the 3D-FEM including all onboard mass categories, by user subroutines implemented in Femap/NX Nastran [7, 8] modules for preprocessing.
(4) *The 1D strength analysis* step involves first the computation of the LNG equilibrium parameters (sinkage, heel, trim), in oblique waves by in-house non-linear iterative equilibrium subroutine, program *P_QSW* [7]. The oblique waves' parameters are in the range: of 0÷12 m (1m) h_w height and 0÷75 deg (15 deg) μ heading angle, hogging and sagging wave-free surface condition. The preliminary global strength valuation is done by 1D-beam criteria concerning the admissible vertical, horizontal, and torsional sectional efforts [3, 4].
(5) *The 3D-FEM strength analysis* step involves first loading on the LNG external shell with the equivalent pressure of oblique wave, according to the ship's equilibrium parameters from previous step (figures 5, 6). According to the rules [3, 4] a proper selection of the boundary conditions is made (see 3D-FEM mode, figure 2). As main results of the 3D analysis, the stresses and deformations for each combination of loading case and wave condition (h_w, μ). The 3D analysis involves standard Femap/NX Nastran modeling [8]. The 3D numerical results are used for the large LNG carrier strength valuation, involving stress and deflection criteria [3, 4].
(6) *The valuation of the LNG operation in the oblique EDW* step involves combining the strength criteria with the minimum free-board criterion to obtain the operation limit polar diagram by the ship's 3D model $h_{w\ limit}(\mu)_{3D}$ and by the ship's 1D model $h_{w\ limit}(\mu)_{1D.}$ Both loading cases and structural models are compared in terms of operation limit in an oblique wave state.

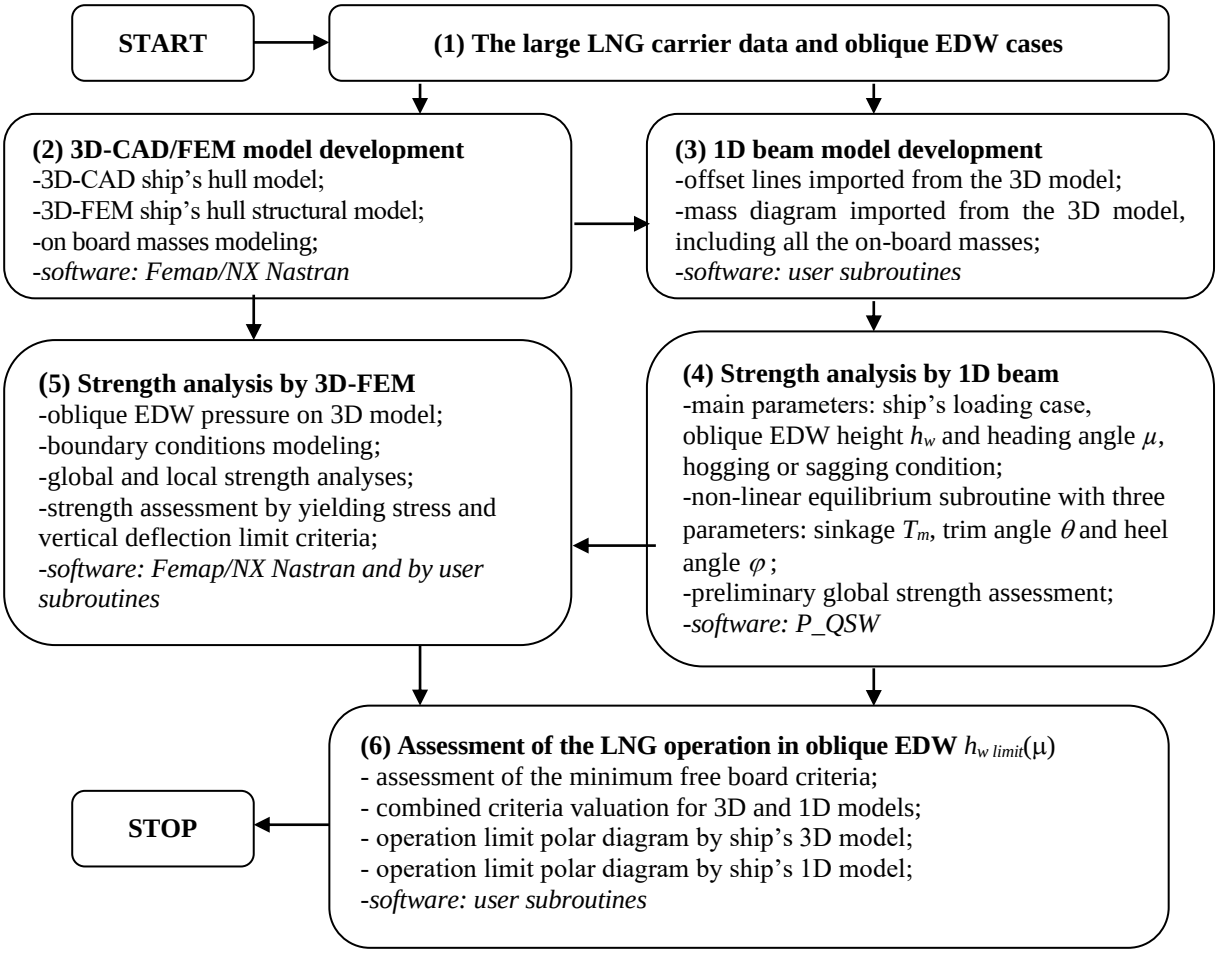

Fig. 1. The algorithm for large LNG carrier global and local strength assessment by 3D and 1D models

3. STRUCTURAL MODELS OF THE LARGE LNG 150000 CBM LIQUEFIED NATURAL GAS CARRIER

This research is focused on a large LNG 150000 cbm liquefied natural gas carrier [9] with a double hull and structural gas membrane tanks (figures 2, 3, 4). The large LNG carrier has at the stern, and bow, an external shape with significant geometric non-linearities (figure 2), so the approach from section 2 is suitable for computing the equilibrium position of the ship in oblique waves. For the LNG strength valuation according to the algorithm from section 2 (figure 1), two structural models 1D and 3D are developed, with the main characteristics in table 1. The 1D model is based on the LNG equivalent beam approach [6], with an average length of 1.6 m for the 1D-beam elements. The 3D-FEM model (figures 2, 3, 4) covers the whole structure of the large LNG carrier hull, mainly including the significant structural panels, without some of the local details. A coarse mesh size of 0.8 ÷ 3.2 m is used for the 3D model, planar shell type elements [8]. The whole LNG hull structure is made of high-tensile steel grade [3, 4]. The strength valuation is developed for two relevant loading cases for the large LNG carrier: full cargo and ballast (table 1).

Table 1. Large LNG 150000 cbm carrier [9] structural 3D FEM and 1D beam models characteristics

Main dimensions	L_{OA} (m)	289.3	3D	ND	53888		FB_{minim} (m)	0.3
	B (m)	43.3		EL (shell)	188902		x_{stern} (m)	0
	H_{afi} (m)	20.8		GR (data)	583		x_{mid} (m)	144.65
	H_{mid} (m)	25.6	1D	ND	201		x_{bow} (m)	289.3
	H_{fore} (m)	25.6		EL (beam)	200		y_{PS} (m)	21.65
Case 1 Full cargo	Δ (t)	105881.4	Case 2 Ballast	Δ (t)	73166.8	Limit criteria permissible values	y_{SB} (m)	-21.65
	x_G (m)	144.01		x_G (m)	138.513		VBM_{adm}(kNm)	8.68E+6
	y_G (m)	0		y_G (m)	0		VSF_{adm} (kN)	1.13E+5
	T_{stern} (m)	11.8		T_{stern} (m)	10.0		HBM_{adm}(kNm)	2.63E+6
	T_{mid} (m)	11.8		T_{mid} (m)	8.5		HSF_{adm}(kN)	5.43E+4
	T_{bow} (m)	11.8		T_{bow} (m)	7.0		MT_{adm}(kNm)	1.65E+06
High-tensile steel	E (N/m^2)	2.1E+11	Oblique EDW wave	h_w (m)	0÷12 (1)		σ_{adm} (MPa)	263
	R_{eH} (MPa)	355		μ (deg)	0÷75 (15)		w_{adm} (m)	0.723

The boundary conditions for the 3D-FEM model (figure 2) are specific for 3D strength valuation in oblique design wave conditions [3, 4, 7], being restraint the following displacement degrees of freedom: vertical (z) at both sides aft and center fore, transversal (y) at center aft and fore, longitudinal (x) at center fore.

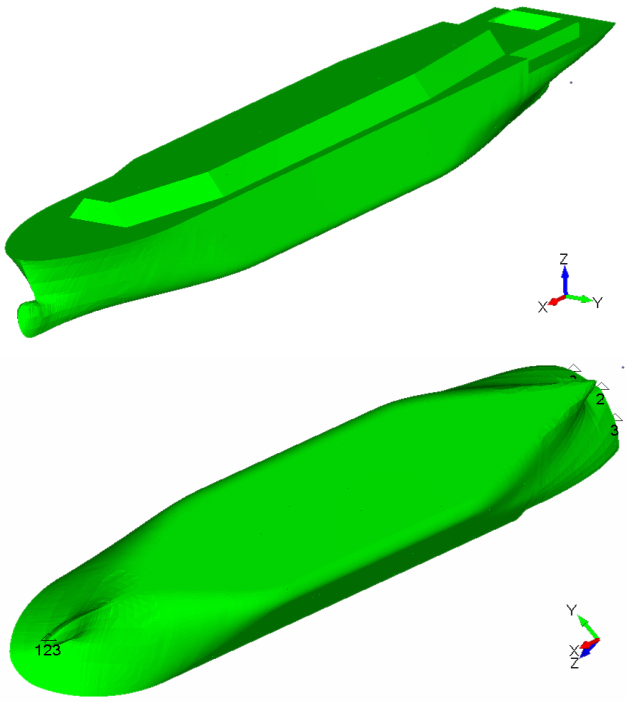

Fig. 2. Large LNG carrier 3D-FEM model, general view, bottom view and boundary conditions

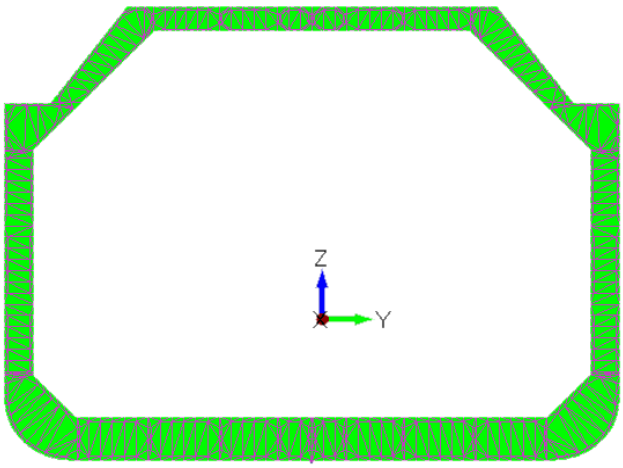

Fig. 3. Large LNG carrier 3D-FEM model, amidships section

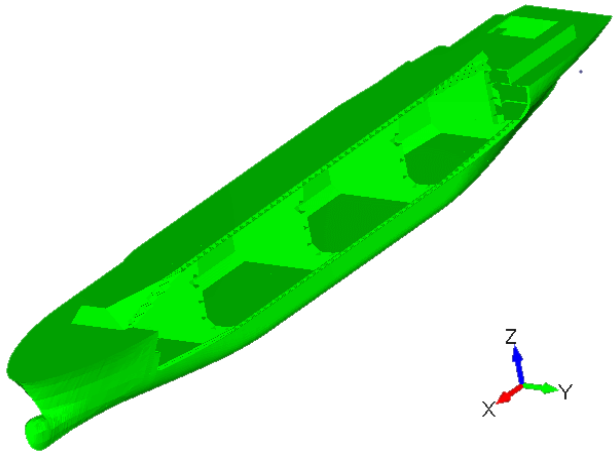

Fig. 4. Large LNG carrier 3D-FEM model, cargo holds view

The reference wave height is of 10.715 m [3, 4], going up to a maximum of 12 m design wave height. For each loading case and wave condition (h_w,μ) the LNG equilibrium position is obtained by *P_QSW* code, and user subroutines [7]. The equivalent quasi-static oblique EDW pressure is applied on the LNG 3D-FEM model, as presented in figures 5, 6 for μ=60 deg and h_w=10.715 conditions.
The next sections (4, 5, 6) include the analysis for strength valuation in EDW quasi-static oblique design waves of the large LNG 150000 cbm carrier, for both loading cases.

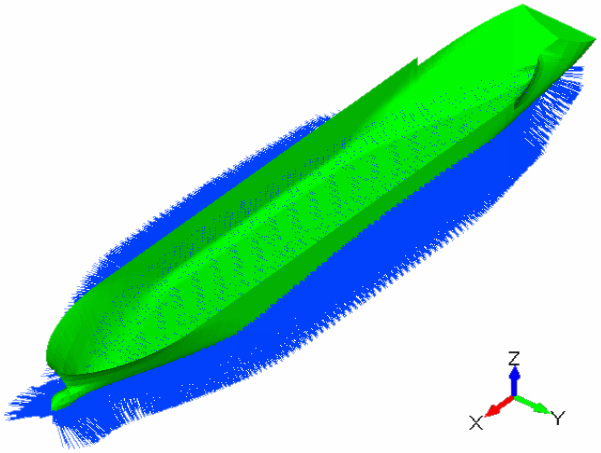

Fig. 5. Large LNG carrier, EDW wave pressure, hogging, μ=60 deg, h_w=10.715 m, full cargo

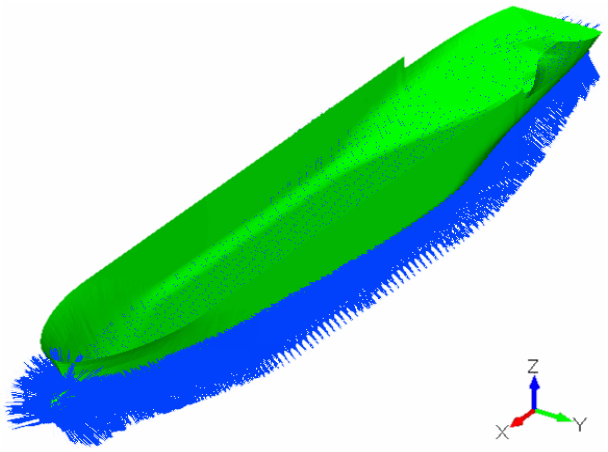

Fig. 6. Large LNG carrier, EDW wave pressure, sagging, μ=60 deg, h_w=10.715 m, ballast

4. THE STRUCTURAL VALUATION IN OBLIQUE WAVES OF THE LARGE LNG 150000CBM CARRIER - FULL CARGO

This section includes a synthesis of the large LNG ship structural valuation in oblique waves, 1D & 3D models (section 3), for full cargo condition.
First using the non-linear iterative algorithm (figure 1), program *P_QSW* [7], the 1D approach delivers the LNG equilibrium parameters (table 2), covering the whole range of oblique wave state (h_w,μ), h_w=0÷12 m and μ=0÷75 deg.

Table 2. Sinkage, trim and heel large LNG carrier eq. parameters in oblique EDW waves, full cargo.

1D-beam	μ (deg)	SW	EDW hogging oblique wave				EDW sagging oblique wave			
eq. param.	h_w(m)	0	5	8	10.715	12	5	8	10.715	12
sinkage (m)	0	**11.800**	11.197	10.789	10.395	**10.200**	12.278	12.514	12.704	**12.786**
	15		11.203	10.799	10.408	10.215	12.272	12.505	12.692	12.773
	30		11.226	10.835	10.455	10.267	12.250	12.471	12.649	12.725
	45		11.282	10.925	10.575	10.400	12.197	12.388	12.540	12.605
	60		11.443	11.181	10.916	10.782	12.044	12.150	12.227	12.257
	75		12.117	12.268	12.380	**12.425**	11.416	11.162	10.918	**10.798**
trim angle (rad)	0	**0.00000**	**-0.00097**	-0.00093	-0.00077	-0.00072	0.00338	0.00577	0.00792	**0.00890**
	15		-0.00096	-0.00092	-0.00076	-0.00070	0.00335	0.00572	0.00785	0.00882
	30		-0.00093	-0.00087	-0.00070	-0.00064	0.00326	0.00555	0.00760	0.00853
	45		-0.00084	-0.00075	-0.00055	-0.00047	0.00305	0.00515	0.00700	0.00784
	60		-0.00058	-0.00038	-0.00009	0.00004	0.00247	0.00410	0.00549	0.00610
	75		0.00063	0.00140	0.00227	**0.00272**	**0.00027**	0.00041	0.00046	0.00047
heel angle (rad)	0	**0.00000**	*no heel angle for μ = 0 deg*							
	15		-0.00020	-0.00018	-0.00012	-0.00009	0.00061	0.00106	0.00145	0.00162
	30		-0.00043	-0.00040	-0.00029	-0.00023	0.00129	0.00222	0.00302	0.00337
	45		-0.00078	-0.00077	-0.00063	-0.00057	0.00209	0.00356	0.00480	0.00534
	60		-0.00148	-0.00169	-0.00169	-0.00167	0.00300	0.00491	0.00648	**0.00714**
	75		-0.00366	-0.00569	-0.00728	**-0.00795**	0.00248	0.00314	0.00316	0.00279

The geometric non-linearities of the large LNG carrier external shape (figure 2) lead to significant changes in the equilibrium parameters: sinkage 10.200 ÷ 12.786 m that represents -1.600 ÷ +0.986 m around 11.8 m (still water sinkage); trim angle -0.00097 ÷ +0.00890 rad around 0 rad (still water trim angle); heel angle -0.00795 ÷ +0.00741 rad around 0 rad (still water heel angle).
Based on the equilibrium parameters (table 2), for the 1D-beam model of the large LNG carrier on full cargo load by *P_QSW* code [7], the vertical, horizontal, and torsional 1D sectional efforts are computed for the oblique wave state (h_w,μ) conditions. A selection of the sectional efforts by 1D LNG model on full cargo is presented in figures 7, 8, 9, and 10, for hogging oblique wave μ=60 deg.

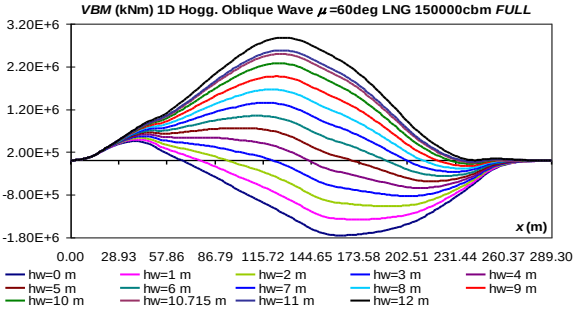

Fig. 7. LNG 1D, *VBM* (kNm), hogg., μ=60deg, full

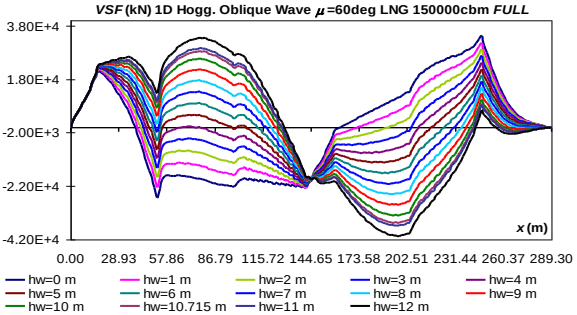

Fig. 8. LNG 1D, *VSF* (kN), hogg., μ=60deg, full

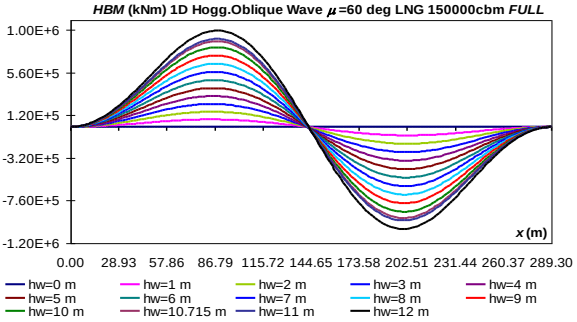

Fig. 9. LNG 1D, *HBM*(kNm), hogg., μ=60deg, full

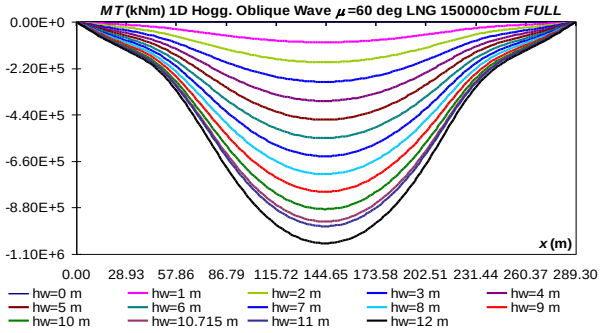

Fig. 10. LNG 1D, *MT*(kNm), hogg., μ=60deg, full

Table 3. Strength valuation of the large LNG carrier in oblique EDW by 1D beam model, full cargo

1D-beam strength	μ(deg)	SW		EDW hogging oblique wave					EDW sagging oblique wave				
	h_w(m)	0	%adm	10.715	%adm	12	%adm	h_{wlimit}	10.715	%adm	12	%adm	h_{wlimit}
Vertical bending moment (kNm)	0	1.75E+6	20.15%	3.75E+6	43.18%	**4.29E+6**	**49.40%**	12	7.74E+6	89.18%	**8.57E+6**	**98.71%**	12
	15			3.72E+6	42.81%	4.25E+6	48.99%	12	7.70E+6	88.73%	8.52E+6	98.19%	12
	30			3.60E+6	41.49%	4.12E+6	47.51%	12	7.56E+6	87.09%	8.36E+6	96.32%	12
	45			3.31E+6	38.19%	3.80E+6	43.80%	12	7.21E+6	83.03%	7.96E+6	91.68%	12
	60			2.49E+6	28.73%	2.88E+6	33.15%	12	6.22E+6	71.69%	6.83E+6	78.74%	12
	75			1.64E+6	18.89%	1.68E+6	19.32%	12	2.46E+6	28.39%	2.57E+6	29.61%	12
Vertical shear force (kN)	0	3.41E+4	30.30%	5.42E+4	48.16%	**6.14E+4**	**54.57%**	12	1.01E+5	90.13%	**1.12E+5**	**99.40%**	12
	15			5.38E+4	47.74%	6.09E+4	54.11%	12	1.01E+5	89.70%	1.11E+5	98.91%	12
	30			5.21E+4	46.24%	5.90E+4	52.42%	12	9.92E+4	88.13%	1.09E+5	97.13%	12
	45			4.78E+4	42.47%	5.42E+4	48.18%	12	9.48E+4	84.21%	1.04E+5	92.69%	12

	60			3.57E+4	31.72%	4.06E+4	36.09%	12	8.25E+4	73.27%	9.03E+4	80.19%	12
	75			2.61E+4	23.15%	2.69E+4	23.91%	12	4.64E+4	41.19%	4.79E+4	42.54%	12
Horizontal bending moment (kNm)	0	0	-	0	-	0	-	12	0	-	0	-	12
	15			1.59E+5	6.05%	1.78E+5	6.78%	12	1.51E+5	5.76%	1.68E+5	6.38%	12
	30			3.40E+5	12.93%	3.81E+5	14.49%	12	3.23E+5	12.29%	3.58E+5	13.61%	12
	45			5.77E+5	21.95%	6.47E+5	24.61%	12	5.45E+5	20.74%	6.04E+5	22.97%	12
	60			9.39E+5	35.72%	1.05E+6	40.05%	12	8.73E+5	33.21%	9.66E+5	36.77%	12
	75			1.38E+6	52.68%	**1.55E+6**	**59.17%**	12	1.20E+6	45.51%	**1.32E+6**	**50.23%**	12
Horizontal shear force (kN)	0	0	-	0	-	0	0	12	0	-	0	-	12
	15			4.55E+3	8.38%	5.16E+3	9.51%	12	3.14E+3	5.79%	3.40E+03	6.26%	12
	30			9.68E+3	17.84%	1.10E+4	20.24%	12	6.74E+3	12.43%	7.30E+03	13.45%	12
	45			1.63E+4	29.98%	1.84E+4	33.98%	12	1.16E+4	21.28%	1.25E+04	23.09%	12
	60			2.57E+4	47.36%	2.91E+4	53.58%	12	1.93E+4	35.47%	2.10E+04	38.71%	12
	75			3.25E+4	59.91%	**3.64E+4**	**67.13%**	12	3.03E+4	55.88%	**3.37E+04**	**62.16%**	12
Torsion moment (kNm)	0	0	-	0	-	0	-	12	0	-	0	-	12
	15			1.55E+5	9.36%	1.71E+5	10.33%	12	2.15E+5	13.03%	2.46E+5	14.86%	12
	30			3.32E+5	20.07%	3.66E+5	22.18%	12	4.57E+5	27.66%	5.21E+5	31.54%	12
	45			5.67E+5	34.34%	6.28E+5	38.00%	12	7.63E+5	46.19%	8.69E+5	52.58%	12
	60			9.46E+5	57.24%	1.05E+6	63.51%	12	1.19E+6	71.90%	1.35E+6	81.51%	12
	75			1.43E+6	86.30%	**1.60E+6**	**97.02%**	12	1.47E+6	89.03%	**1.65E+6**	**99.56%**	12

Preliminary global strength valuation by 1D-beam LNG model on full cargo is based on the rule's admissible sectional efforts criteria (table 1) [3, 4] applied for the maximum sectional efforts over the ship's length and wave state (h_w,μ) conditions (table 3, figures 11, 12, 13, 14).

Taking as reference the ratio between the maximum (table 3) and admissible (table 1) sectional efforts, *%adm* results in next limits: vertical sectional efforts 49,40%÷99.40% (figures 11, 12) with higher values on sagging than hogging waves and μ=0 deg; horizontal bending moment and shear force 50,23%÷67.13% (figure 13) with higher values on hogging than sagging waves and μ=75 (90) deg; torsional moment 97,02%÷99.56% (figure 14) with similar high values on sagging and hogging waves at μ=75 (90) deg. For the large LNG carrier on full cargo, the 1D global strength criteria are satisfied for all wave state (h_w,μ) conditions (table 3).

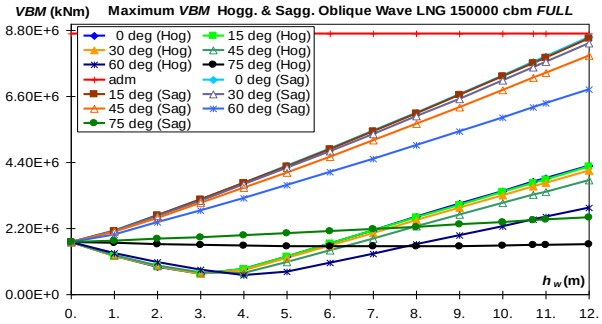

Fig. 11. LNG 1D, max.*VBM* (kNm), *h* & *s*, full

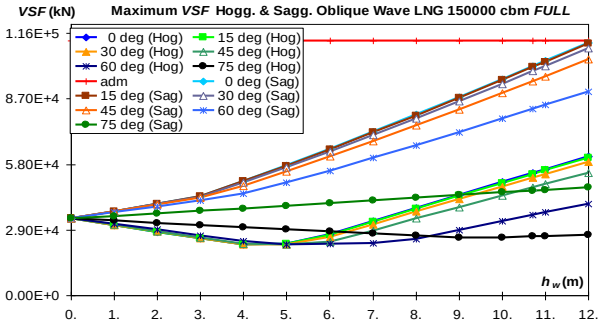

Fig. 12. LNG 1D, max. *VSF* (kN), *h* & *s*, full

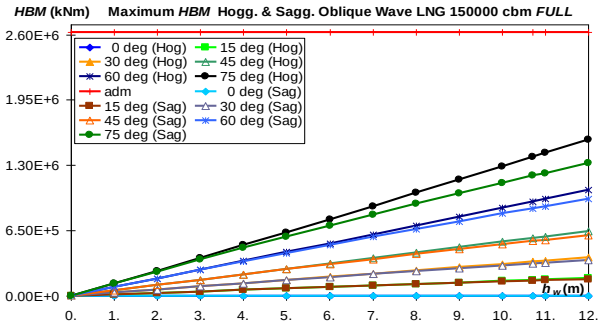

Fig. 13. LNG 1D, max. *HBM* (kNm), *h & s*, full

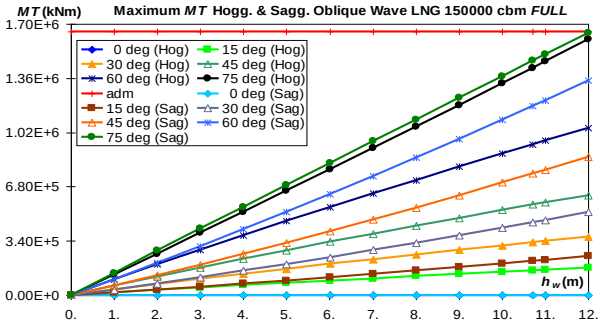

Fig. 14. LNG 1D, max. *MT* (kNm), *h & s*, full

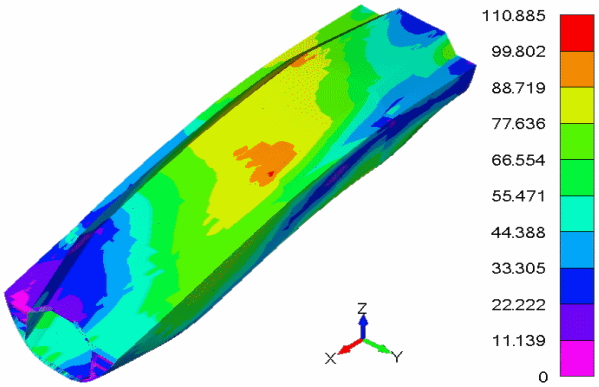

Fig. 15. LNG 3D, stress σ_{vonM} (MPa), *hogg. oblique wave*, μ=60 deg, ref. h_w=10.715 m, full

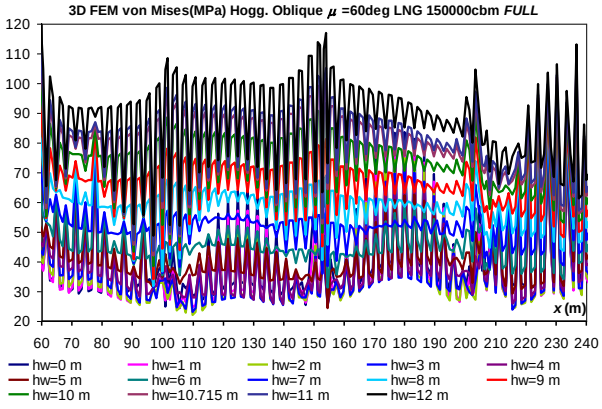

Fig. 16. LNG 3D, stress σ_{vonM} (MPa), *hogg. oblique wave* , μ=60 deg, full

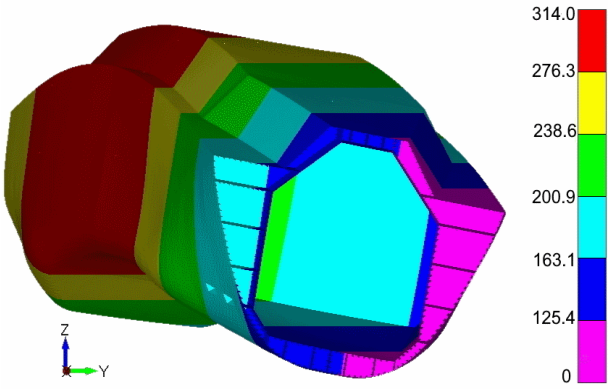

Fig. 17. LNG 3D, deflection w(mm), *hogg. oblique wave* , μ=60 deg, ref. h_w=10.715 m, full

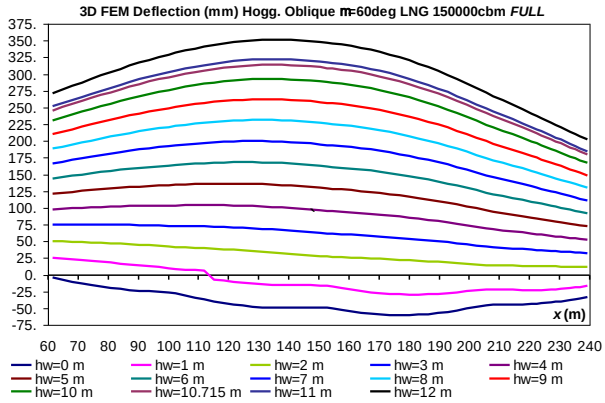

Fig. 18. LNG 3D, deflection w(mm), *hogg. oblique wave*, μ=60 deg, full

For the equilibrium parameters (table 2), based on specific user subroutines [7] implemented in the Femap/NX Nastran [8] program, according to the 1D/3D algorithm in section 2 (figure 1), the equivalent oblique wave pressure is applied on the 3D-FEM large LNG carrier model on the full cargo load and the strength 3D analysis is performed.

In figures 15, 17 (h_w=10.715 m) stresses and figures 16, 18 (h_w=0-12 m) deflections are presented, for hogging oblique wave μ=60 deg. Significant stress spots at the cargo hold bulkheads (figure 4) are recorded (figure 16). At the central stations of the large LNG carrier, the vertical deflection has maximum values (figure 18).

Enhanced strength valuation by 3D-FEM LNG model on full cargo is based on the yielding stress and admissible deflection criteria (table 1) [3, 4] applied for the maximum von Mises stresses over the ship's 3D structure and vertical deflection in oblique waves state (h_w,μ) conditions (table 4, figures 19, 20).

Table 4. Strength valuation of the large LNG carrier in oblique EDW by 3D-FEM model, full cargo

3D-FEM strength	μ(deg)	SW		EDW hogging oblique wave					EDW sagging oblique wave				
	h_w(m)	0	*%adm*	10.715	*%adm*	12	*%adm*	h_{wlimit}	10.715	*%adm*	12	*%adm*	h_{wlimit}
Equiv. von Mises stress (MPa)	0	83.475	31.76%	93.196	35.46%	97.395	37.06%	12	183.958	69.99%	203.194	77.31%	12
	15			96.080	36.56%	100.669	38.30%	12	185.944	70.75%	205.420	78.16%	12
	30			99.127	37.72%	104.129	39.62%	12	189.213	71.99%	209.155	79.58%	12
	45			102.726	39.09%	108.204	41.17%	12	196.023	74.58%	216.754	82.47%	12
	60			110.885	42.19%	124.005	47.18%	12	211.005	80.28%	233.218	88.74%	12
	75			206.564	78.60%	**231.913**	**88.24%**	12	**265.330**	**100.95%**	**294.888**	**112.2%**	**10.603**
Vertical deflection (m)	0	-0.0604	8.36%	0.1738	24.03%	0.1967	27.20%	12	-0.3727	51.53%	-0.4176	57.74%	12
	15			0.1810	25.03%	0.2036	28.15%	12	-0.3754	51.90%	-0.4207	58.16%	12
	30			0.1971	27.26%	0.2214	30.62%	12	-0.3854	53.29%	-0.4319	59.72%	12
	45			0.2302	31.83%	0.2582	35.70%	12	-0.4126	57.05%	-0.4639	64.14%	12
	60			0.3140	43.42%	0.3515	48.60%	12	-0.4898	67.72%	-0.5490	75.91%	12
	75			0.6215	85.93%	**0.6982**	**96.54%**	12	**-0.7235**	**100.03%**	-0.8046	**111.24%**	**10.712**

Taking as reference the ratio between the maximum (table 4) and admissible (table 1) von Mises stresses, results that on hogging oblique waves, the %*adm* limit is 88.24% at μ=75 (90) deg so the yielding stress criterion is satisfied. On

sagging oblique waves, the %*adm* is 112.2% at μ=75 (90) deg and to satisfy the yielding stress criterion the EDW height must be limited to h_{wlimit}= 10.603 m < 12 m at beam sea conditions, without restrictions for μ=0÷60 deg (figure 19).

Taking as reference the ratio between the maximum (table 4) and admissible (table 1) vertical deflection results that on hogging oblique waves, the %*adm* limit is 96.54% at μ=75 (90) deg so the vertical deflection criterion is satisfied. On sagging oblique waves, the %*adm* is 111.24% at μ=75 (90) deg, and to satisfy the vertical deflection criterion the wave height must be limited to h_{wlimit}= 10.712 m < 12 m at beam sea conditions, without restrictions for μ=0÷ 60 deg (figure 20).

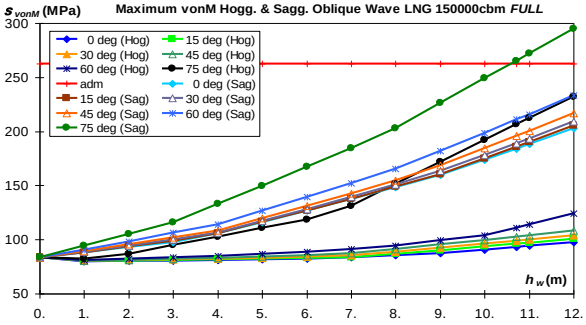

Fig. 19. LNG 3D, max. σ_{vonM} (MPa), *h & s*, full

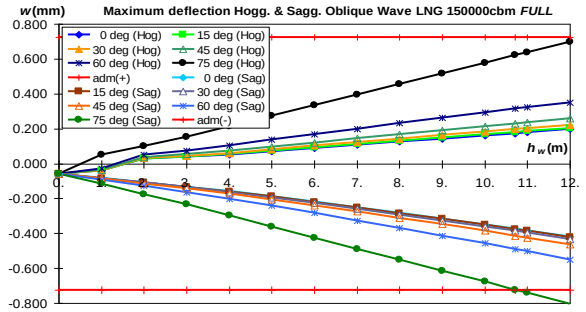

Fig. 20. LNG 3D, max. *w* (mm), *h & s*, full

For the large LNG carrier on full cargo, the 3D global strength criteria are satisfied for μ=0÷60 deg and with restrictions from both 3D criteria for beam sea state μ=75 (90), sagging wave (table 4). The minimum freeboard criterion leads to the same values for both LNG structural models, based on the oblique waves' free surface [7] computed by the equilibrium parameters on the full cargo loading case (table 2). The freeboard values are evaluated at the stern, amidships and bow of the LNG carrier, with some differences between the two sides due to the trim angle (table 5, figures 21, 22).

The freeboard for the large LNG carrier, taking as reference the wave height h_w=12m, has the minimum values: at the stern 3.275÷7.485 m, amidships 9.401÷13.642 m, and at bow 5.500÷11.498 m, all larger than 0.3 m (table 1), so the freeboard criterion is satisfied for all oblique waves state (h_w,μ) in the LNG full cargo case. The minim freeboard is obtained at the stern, due to the smaller side height of the large LNG carrier (figure 2, table 1).

Table 5. Freeboard criteria valuation of the large LNG carrier in oblique EDW, full cargo

Free board (m)	μ(deg)	SW	EDW hogging oblique wave					EDW sagging oblique wave				
	h_w(m)	0	10.715		12		h_{wlimit}	10.715		12		h_{wlimit}
	PS-SB		PS	SB	PS	SB		PS	SB	PS	SB	
Stern	0	9.000	15.653	15.653	16.497	16.497	12	3.859	3.859	**3.275**	**3.275**	12
	15		15.601	15.596	16.440	16.436	12	3.872	3.935	3.290	3.360	12
	30		15.412	15.400	16.226	16.216	12	4.000	4.131	3.430	3.576	12
	45		14.937	14.909	15.693	15.669	12	4.371	4.579	3.842	4.073	12
	60		13.584	13.511	14.178	14.106	12	5.534	5.815	5.136	5.445	12
	75		7.914	7.599	**7.830**	**7.485**	12	10.860	10.996	11.105	11.226	12
Amidships	0	13.800	9.849	9.849	**9.401**	**9.401**	12	18.229	18.229	18.788	18.788	12
	15		9.881	9.876	9.436	9.432	12	18.167	18.230	18.719	18.789	12
	30		9.991	9.978	9.558	9.548	12	18.023	18.154	18.557	18.703	12
	45		10.264	10.237	9.864	9.839	12	17.710	17.918	18.206	18.437	12
	60		11.044	10.970	10.737	10.664	12	16.894	17.174	17.289	17.598	12
	75		14.347	14.031	14.432	14.088	12	13.632	13.768	**13.642**	**13.763**	12

Bow	0	13.800	20.675	20.675	21.505	21.505	12	6.368	6.368	**5.500**	**5.500**	12
	15		20.621	20.616	21.442	21.438	12	6.401	6.464	5.538	5.608	12
	30		20.415	20.402	21.211	21.201	12	6.601	6.732	5.763	5.909	12
	45		19.896	19.868	20.629	20.605	12	7.146	7.354	6.374	6.605	12
	60		18.410	18.337	18.966	18.894	12	8.746	9.027	8.171	8.480	12
	75		12.057	11.742	**11.843**	**11.498**	12	15.527	15.663	15.772	15.893	12

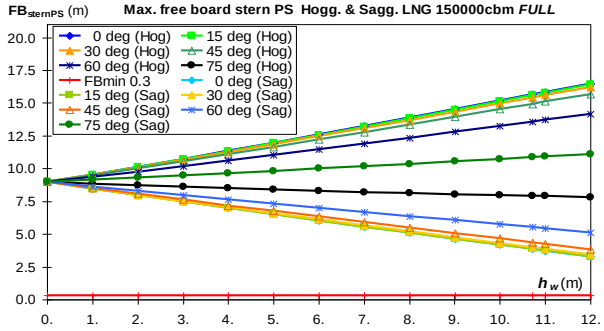

Fig. 21. LNG 1D & 3D, max. *FB*(m) stern PS, *h* & *s*, full

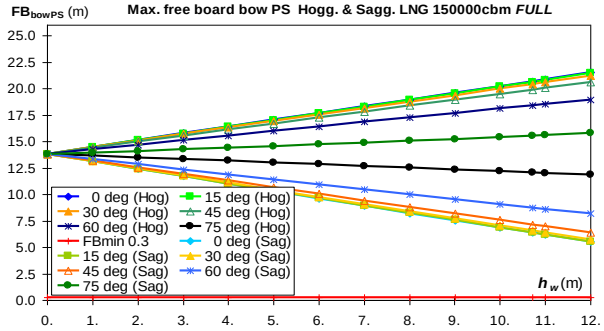

Fig. 22. LNG 1D & 3D, max. *FB*(m) bow PS, *h* & *s*, full

5. THE STRUCTURAL VALUATION IN OBLIQUE WAVES OF THE LARGE LNG 150000 CBM CARRIER - BALLAST

This section includes a synthesis of the large LNG ship structural valuation in oblique waves, 1D & 3D models (section 3), for ballast condition.

Analogous to the previous loading case by 1D approach (figure 1), with *P_QSW* program [7] for the 1D-beam model on ballast load, the three equilibrium parameters of the LNG-wave system (table 6) are obtained, for the oblique wave state (h_w,μ).

The smaller ballast draught in comparison to the first loading case (table 1), leads to more geometric non-linearities of the immerged LNG hull shape (figure 2), and considerable changes in the equilibrium parameters: sinkage 6.602 ÷ 9.791 m that represents -1.898 ÷ +1.291 m around 8.5 m (still water sinkage); trim angle -0.01386 ÷ -0.00218 rad around -0.01037 rad (still water trim angle); heel angle -0.00976 ÷ +0.00777 rad around 0 rad (still water heel angle). For any oblique wave state, the large LNG carrier on ballast load is angled aft.

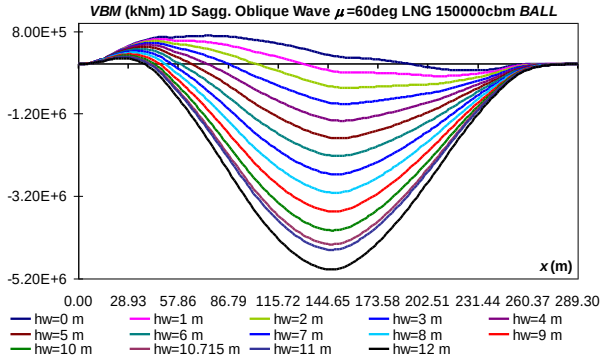

Fig. 23. LNG 1D, *VBM* (kNm), sagg., μ=60deg, ball

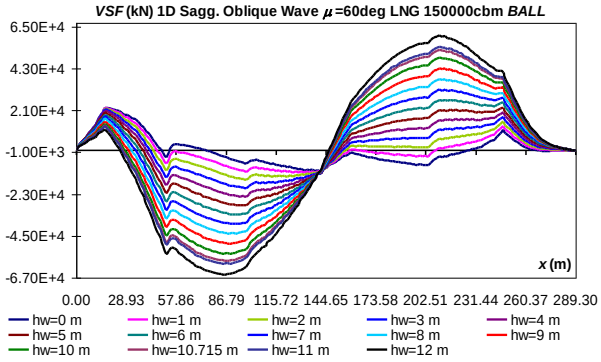

Fig. 24. LNG 1D, *VSF* (kN), sagg., μ=60deg, ball

Table 6. Sinkage, trim and heel large LNG carrier parameters in oblique EDW waves, ballast

1D-beam	μ (deg)	SW	EDW hogging oblique wave				EDW sagging oblique wave			
eq.param.	h_w(m)	0	5	8	10.715	12	5	8	10.715	12
sinkage (m)	0	**8.500**	7.796	7.311	6.839	**6.602**	9.133	9.436	9.683	**9.791**
	15		7.803	7.322	6.853	6.618	9.126	9.425	9.667	9.774
	30		7.829	7.363	6.906	6.676	9.099	9.383	9.612	9.712
	45		7.893	7.463	7.038	6.822	9.033	9.278	9.474	9.559
	60		8.077	7.753	7.418	7.244	8.847	8.984	9.085	9.125
	75		8.861	9.011	9.106	**9.136**	8.097	7.810	7.537	**7.403**
trim angle (rad)	0	**-0.01037**	-0.01118	-0.01186	-0.01302	**-0.01386**	-0.00840	-0.00592	-0.00340	**-0.00218**
	15		-0.01117	-0.01185	-0.01300	-0.01384	-0.00841	-0.00596	-0.00345	-0.00225
	30		-0.01114	-0.01180	-0.01293	-0.01375	-0.00847	-0.00609	-0.00367	-0.00251
	45		-0.01107	-0.01167	-0.01274	-0.01352	-0.00861	-0.00641	-0.00418	-0.00313
	60		-0.01084	-0.01128	-0.01213	-0.01278	-0.00903	-0.00732	-0.00562	-0.00484
	75		-0.00971	-0.00915	-0.00873	**-0.00864**	**-0.01075**	-0.00106	-0.00107	-0.00108
heel angle (rad)	0	**0.00000**	*no heel angle for μ = 0 deg*							
	15		-0.00023	-0.00038	-0.00058	-0.00072	0.00050	0.00099	0.00149	0.00173
	30		-0.00050	-0.00081	-0.00125	-0.00154	0.00104	0.00207	0.00310	0.00359
	45		-0.00087	-0.00143	-0.00219	-0.00270	0.00171	0.00333	0.00492	0.00568
	60		-0.00153	-0.00256	-0.00393	-0.00481	0.00252	0.00468	0.00675	**0.00777**
	75		-0.00311	-0.00555	-0.00822	**-0.00976**	0.00263	0.00349	0.00314	0.00279

Table 7. Strength valuation of the large LNG carrier in oblique EDW by 1D beam model, ballast

1D-beam	μ(deg)	SW		EDW hogging oblique wave					EDW sagging oblique wave				
strength	h_w(m)	0	*%adm*	10.715	*%adm*	12	*%adm*	h_{wlimit}	10.715	*%adm*	12	*%adm*	h_{wlimit}
Vertical bending moment (kNm)	0	6.91E+5	7.96%	4.75E+6	54.78%	**5.19E+6**	**59.82%**	12	5.75E+6	66.23%	**6.56E+6**	**75.57%**	12
	15			4.73E+6	54.45%	5.16E+6	59.46%	12	5.71E+6	65.82%	6.52E+6	75.10%	12
	30			4.62E+6	53.27%	5.05E+6	58.15%	12	5.58E+6	64.34%	6.37E+6	73.40%	12
	45			4.37E+6	50.31%	4.76E+6	54.85%	12	5.26E+6	60.66%	6.00E+6	69.16%	12
	60			3.63E+6	41.84%	3.94E+6	45.39%	12	4.37E+6	50.32%	4.98E+6	57.36%	12
	75			9.33E+5	10.75%	9.30E+5	10.71%	12	6.37E+5	7.34%	7.62E+5	8.78%	12
Vertical shear force (kN)	0	2.24E+4	19.90%	6.71E+4	59.64%	**7.34E+4**	**65.22%**	12	7.44E+4	66.07%	**8.35E+4**	**74.16%**	12
	15			6.67E+4	59.24%	7.29E+4	64.77%	12	7.40E+4	65.71%	8.31E+4	73.77%	12
	30			6.51E+4	57.82%	7.11E+4	63.16%	12	7.25E+4	64.42%	8.14E+4	72.31%	12
	45			6.11E+4	54.26%	6.66E+4	59.12%	12	6.88E+4	61.15%	7.73E+4	68.63%	12
	60			4.98E+4	44.20%	5.38E+4	47.77%	12	5.81E+4	51.61%	6.52E+4	57.92%	12
	75			2.51E+4	22.32%	2.58E+4	22.95%	12	2.81E+4	24.92%	2.95E+4	26.17%	12
Horizontal bending moment (kNm)	0	0	-	0	-	0	-	12	0	-	0	-	12
	15			1.10E+5	4.17%	1.23E+5	4.66%	12	1.05E+5	3.98%	1.16E+5	4.43%	12
	30			2.34E+5	8.92%	2.62E+5	9.97%	12	2.23E+5	8.49%	2.48E+5	9.43%	12
	45			3.99E+5	15.17%	4.46E+5	16.95%	12	3.76E+5	14.29%	4.17E+5	15.87%	12
	60			6.52E+5	24.83%	7.30E+5	27.78%	12	5.99E+5	22.81%	6.64E+5	25.27%	12
	75			1.00E+6	38.21%	**1.13E+6**	**42.97%**	12	8.35E+5	31.78%	**9.17E+5**	**34.90%**	12
Horizontal shear force (kN)	0	0	-	0	-	0	-	12	0	-	0	-	12
	15			3.29E+3	6.07%	3.73E+3	6.88%	12	2.11E+03	3.88%	2.33E+03	4.29%	12
	30			7.01E+3	12.91%	7.94E+3	14.64%	12	4.52E+03	8.33%	4.94E+03	9.11%	12
	45			1.18E+4	21.69%	1.33E+4	24.56%	12	7.77E+03	14.31%	8.33E+03	15.34%	12

	60		1.86E+4	34.25%	2.10E+4	38.69%	12	1.31E+04	24.06%	1.41E+04	25.99%	12
	75		2.38E+4	43.76%	**2.66E+4**	**48.92%**	12	2.13E+04	39.30%	**2.36E+04**	**43.46%**	12
Torsion moment (kNm)	0	0 -	0	-	0	-	12	0	-	0	-	12
	15		1.44E+5	8.72%	1.59E+5	9.61%	12	2.02E+5	12.24%	2.31E+5	13.98%	12
	30		3.09E+5	18.69%	3.40E+5	20.61%	12	4.29E+5	25.99%	4.90E+5	29.66%	12
	45		5.28E+5	31.97%	5.83E+5	35.27%	12	7.17E+5	43.39%	8.17E+5	49.43%	12
	60		8.79E+5	53.19%	9.72E+5	58.84%	12	1.12E+6	67.53%	1.27E+6	76.57%	12
	75		1.43E+6	86.83%	**1.61E+6**	**97.37%**	12	1.39E+6	83.89%	**1.55E+6**	**93.87%**	12

For the computed equilibrium parameters (table 2) by *P_QSW* code [7], and the 1D-beam model of the large LNG carrier on ballast load, the 1D equivalent beam sectional efforts are computed in the oblique waves (h_w,μ). A selection of the 1D LNG model results on ballast in figures 23, 24, 25, and 26, for sagging oblique wave μ=60 deg, is presented.

Based on the 1D approach, the preliminary global strength valuation of the large LNG 15000cbm carrier on ballast load is done. The maximum sectional efforts over the ship's length and waves state (h_w,μ) conditions are checked against the rule's admissible sectional efforts criteria (table 1) [3, 4] (table 7, figures 27, 28, 29, 30).

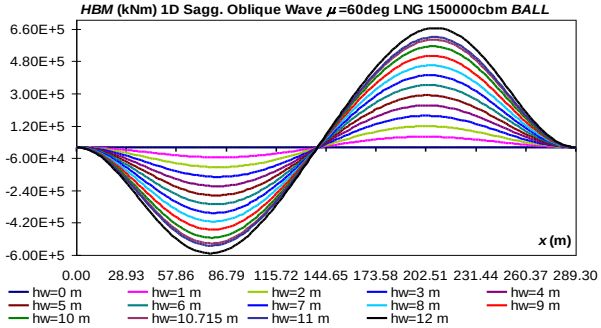

Fig. 25. LNG 1D, *HBM*(kNm), sagg., μ=60deg, ball

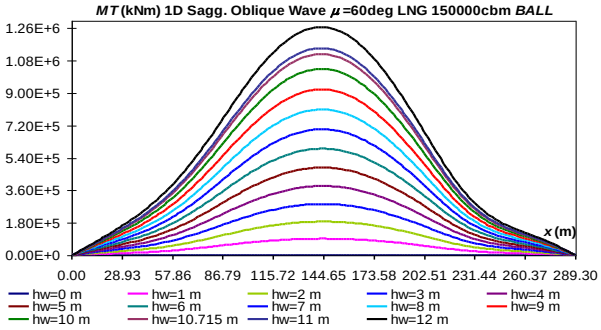

Fig. 26. LNG 1D, *MT*(kNm), sagg., μ=60deg, ball

Taking as reference the ratio between the maximum (table 7) and admissible (table 1) sectional efforts, *%adm* results in next limits: vertical sectional efforts 59,82%÷75.57% (figures 28, 30) with higher values on sagging waves μ=0 deg; horizontal bending moment and shear force 34,90%÷48.92% (figure 31) with higher values on hogging μ=75(90) deg; torsional moment 93,87%÷97.37% (figure 32) with high values on sagging and hogging waves μ=75 (90) deg.

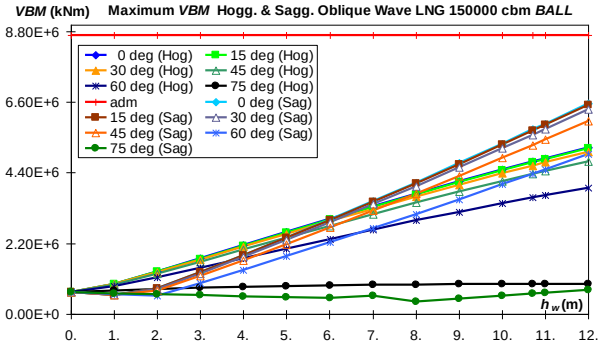

Fig. 27. LNG 1D, max. *VBM* (kNm), *h* & *s*, ball

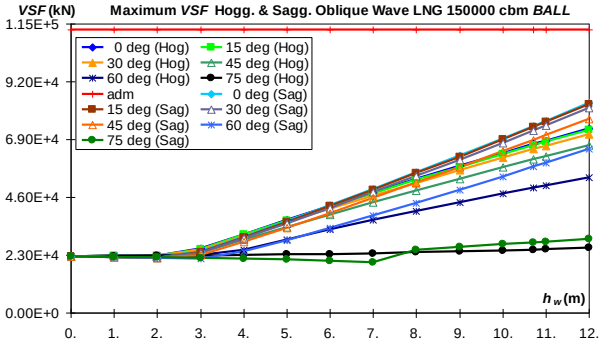

Fig. 28. LNG 1D, max. *VSF* (kN), *h & s*, ball

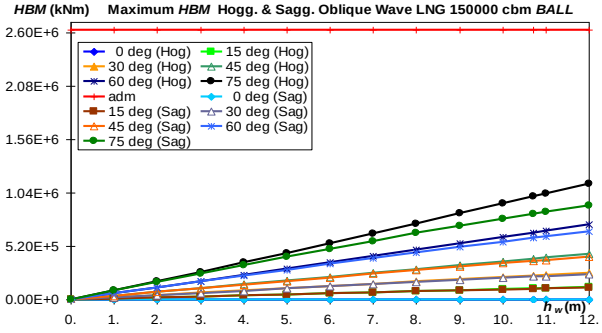

Fig. 29. LNG 1D, max. *HBM* (kNm), *h & s*, ball

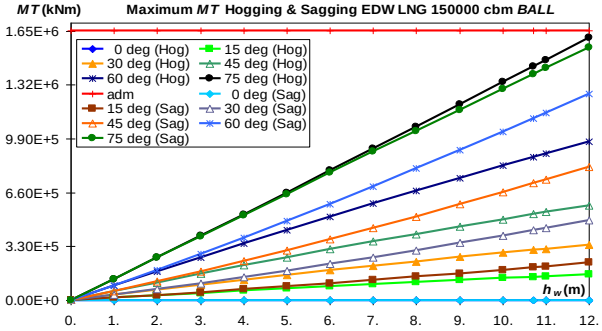

Fig. 30. LNG 1D, max. *MT* (kNm), *h & s*, ball

The vertical and horizontal sectional efforts are smaller in the ballast case in comparison to the full cargo case, but the torsional moments have similar maximum values in both loading cases. The 1D global strength criteria are satisfied on all wave conditions (h_w,μ) (table 7) for the large LNG carrier in the ballast case.

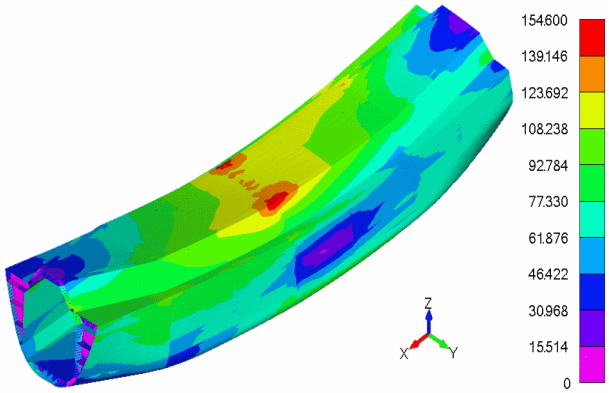

Fig. 31. LNG 3D, stress σ_{vonM} (MPa), *sagg. oblique wave*, μ=60 deg, ref. h_w=10.715 m ballast

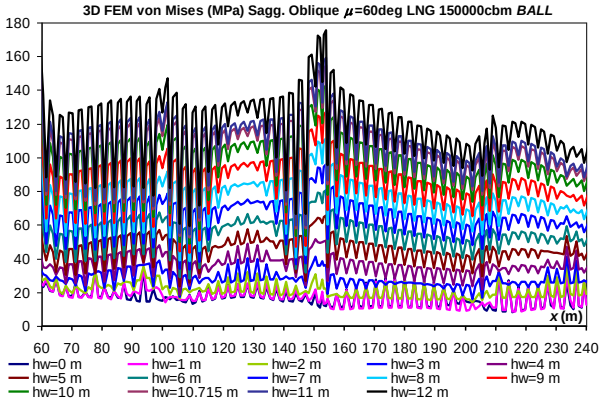

Fig. 32. LNG 3D, stress σ_{vonM} (MPa), *sagg. oblique wave*, μ=60 deg, ballast.

According to the iterative algorithm in figure 1, based on specific user subroutines [7], for the equilibrium parameters (table 6), the oblique waves equivalent pressure is applied on the 3D-FEM large LNG carrier model on the ballast load, followed by the global and local strength 3D analysis. A selection of the von Mises stress distribution and vertical deflection by 3D-FEM LNG model on ballast case are presented in figures 31, 33 (h_w=10.715 m) and figures 32, 34, for sagging wave (μ=60deg). Similar to the first loading case, at the cargo hold bulkheads (figure 4) considerable stress hot spots (figure 32) are recorded. In addition, the vertical deflection has its maximum values at the central part of the large LNG carrier (figure 34).
The global and local strength valuation by 3D-FEM LNG model on ballast case is done by the yielding stress and admissible deflection criteria (table 1) [3, 4], in order to assess the von Mises stresses and vertical deflection in oblique waves (table 8, figures 35, 36).

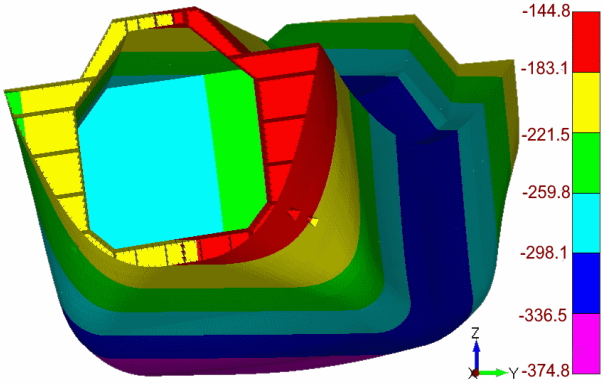

Fig. 33. LNG 3D, deflection *w*(mm), *sagg. oblique wave*, μ=60 deg, ref. h_w=10.715 m, ballast

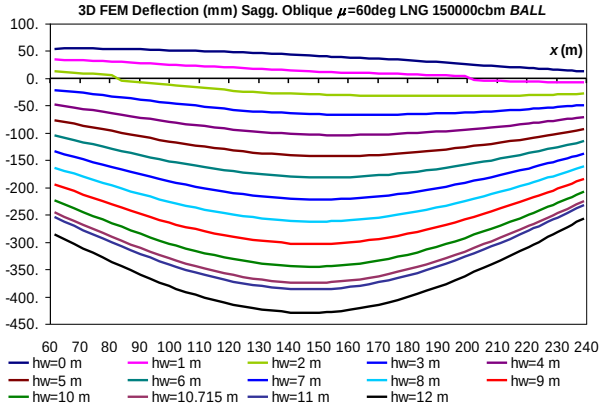

Fig. 34. LNG 3D, deflection *w*(mm), *sagg. oblique wave*, μ=60 deg, ballast

The ratio max. / adm. stresses (tables 1, 8), has the maximum values 95.27 ÷ 98.53% at μ=75 (90) deg, so results no restrictions for the analyzed oblique waves (figure 35).

The ratio of the max. / adm. (tables 1, 8) deflections is 107.57% ÷ 106.15% at μ=75 (90) deg, so in order to satisfy the vertical deflection criterion the wave height must be limited to h_{wlimit}= 10.999 ÷ 11.298 m < 12 m at beam sea conditions, without restrictions for heading angles μ=0÷60 deg (figure 36).
For the large LNG carrier on ballast case, the 3D global strength criteria are satisfied for μ=0÷60 deg and with restrictions only from the vertical deflection criteria for beam sea state μ=75(90) deg (table 8).

Table 8. Strength valuation of the large LNG carrier in oblique EDW by 3D-FEM model, ballast.

3D-FEM	μ(deg)	SW		EDW hogging oblique wave					EDW sagging oblique wave				
strength	h_w(m)	0	*%adm*	10.715	*%adm*	12	*%adm*	h_{wlimit}	10.715	*%adm*	12	*%adm*	h_{wlimit}
Equiv. von Mises stress (MPa)	0	34.192	13.01%	103.503	39.38%	113.151	43.05%	12	125.350	47.69%	142.913	54.38%	12
	15			104.643	39.82%	114.421	43.54%	12	126.733	48.22%	144.486	54.98%	12
	30			107.462	40.89%	117.544	44.72%	12	130.100	49.50%	148.343	56.44%	12
	45			113.781	43.29%	124.535	47.38%	12	137.309	52.24%	156.378	59.50%	12
	60			130.573	49.68%	143.121	54.46%	12	154.600	58.82%	175.540	66.79%	12
	75			227.153	86.43%	**250.400**	**95.27%**	12	231.723	88.17%	**258.944**	**98.53%**	12
Vertical deflection (m)	0	0.0544	7.53%	0.2297	31.76%	0.2476	34.24%	12	-0.2387	33.00%	-0.2788	38.54%	12
	15			0.2333	32.25%	0.2515	34.77%	12	-0.2422	33.49%	-0.2826	39.07%	12
	30			0.2455	33.95%	0.2649	36.62%	12	-0.2546	35.20%	-0.2964	40.98%	12
	45			0.2787	38.53%	0.3011	41.63%	12	-0.2852	39.43%	-0.3302	45.66%	12
	60			0.3663	50.65%	0.3977	54.99%	12	-0.3748	51.82%	-0.4297	59.41%	12
	75			0.7071	97.77%	**0.7793**	**107.75%**	**10.999**	-0.6865	94.92%	-0.7677	**106.15%**	**11.298**

The 3D and 1D LNG models have the same values for the freeboard, based on the oblique waves' free surface [7], being computed by the equilibrium parameters on the ballast loading case (table 6). Similar to the full cargo case, the freeboard values are evaluated at the stern, amidships, and bow, on both sides of the large LNG carrier (table 9, figures 37, 38). The freeboard for the large LNG carrier on ballast case, taking as reference the wave height h_w=12m, has the minimum values: at the stern 4.696÷9.123 m, amidships 13.027÷17.038 m, and at bow 10.127 ÷16.422 m, all being larger than 0.3 m (table 1). The freeboard criterion is satisfied for all the oblique wave states (h_w,μ) in the LNG ballast case. Similar to full cargo case, the minim freeboard is obtained at the stern. The LNG freeboard values are larger in the case of ballast than first loading case, due to the ballast smaller draught (table 1).

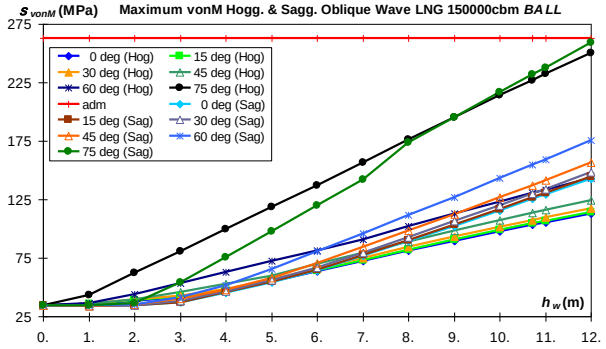

Fig. 35. LNG 3D, max. σ_{vonM} (MPa), *h & s*, ball

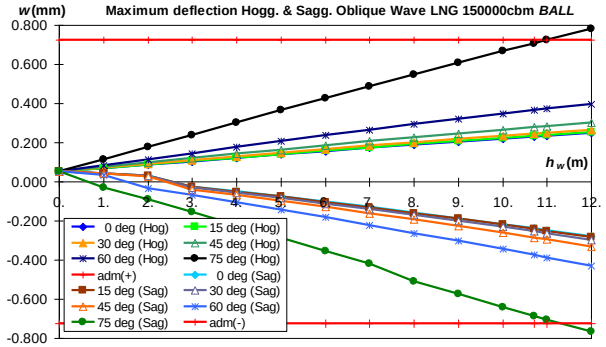

Fig. 36. LNG 3D, max. *w* (mm), *h & s*, ball

Table 9. Free board criteria valuation of the large LNG carrier in oblique EDW, ballast

Free board (m)	μ(deg)	SW	EDW hogging oblique wave					EDW sagging oblique wave				
	h_w(m)	0	10.715		12		h_{wlimit}	10.715		12		h_{wlimit}
	PS-SB		PS	SB	PS	SB		PS	SB	PS	SB	
Stern	0	10.800	17.460	17.460	18.222	18.222	12	5.272	5.272	**4.696**	**4.696**	12
	15		17.419	17.394	18.177	18.146	12	5.291	5.355	4.713	4.788	12
	30		17.237	17.183	17.977	17.910	12	5.433	5.568	4.869	5.025	12
	45		16.767	16.672	17.457	17.340	12	5.844	6.057	5.320	5.566	12
	60		15.411	15.241	15.954	15.746	12	7.086	7.379	6.694	7.031	12
	75		9.646	9.290	**9.545**	**9.123**	12	14.020	14.156	14.278	14.398	12
Amidships	0	17.100	13.429	13.429	**13.027**	**13.027**	12	21.279	21.279	21.812	21.812	12
	15		13.469	13.444	13.074	13.043	12	21.220	21.284	21.744	21.819	12
	30		13.584	13.530	13.206	13.139	12	21.087	21.221	21.593	21.749	12
	45		13.857	13.762	13.515	13.398	12	20.801	21.014	21.270	21.516	12
	60		14.612	14.442	14.367	14.159	12	20.053	20.345	20.430	20.766	12
	75		17.669	17.313	17.791	17.368	12	17.014	17.150	**17.038**	**17.159**	12
Bow	0	18.600	25.600	25.600	25.600	25.600	12	11.056	11.056	**10.127**	**10.127**	12
	15		25.600	25.600	25.600	25.600	12	11.089	11.153	10.164	10.239	12
	30		25.600	25.600	25.600	25.600	12	11.295	11.429	10.396	10.551	12
	45		25.252	25.157	25.600	25.600	12	11.853	12.066	11.025	11.271	12
	60		23.720	23.550	24.451	24.243	12	13.512	13.804	12.895	13.231	12
	75		16.971	16.615	**16.845**	**16.422**	12	19.130	19.266	19.390	19.511	12

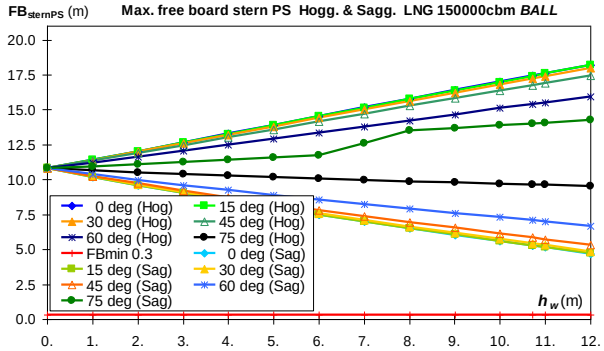

Fig. 37. LNG 1D & 3D, max. *FB*(m) stern PS, *h* & *s*, ball

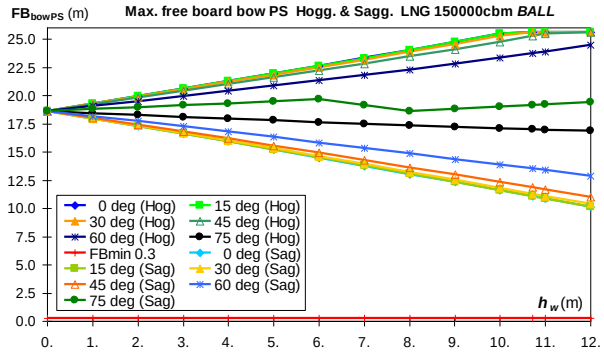

Fig. 38. LNG 1D & 3D, max. *FB*(m) bow PS, *h* & *s*, ball

6. COMPARISON OF STRENGTH OPERATION LIMITS FOR THE LARGE LNG CARRIER

The structural valuation of the large LNG 150000 cbm carrier (table 1, figures 2, 3, 4) by 1D & 3D approached, has been evaluated by stress and deformation criteria, involving the two loading cases: full load and heavy ballast.

The preliminary strength valuation of the large LNG carrier is done by 1D-beam model results and the admissible sectional efforts criteria (table 1), for the full cargo case (table 3, figures 11, 12, 13, 14) and ballast case (table 7, figures 27, 28, 29, 30). The vertical bending moments and shear forces have maximum values for both loading cases at head wave condition μ=0 deg. Those are higher for ballast, at hogging, and for full load, at sagging. The horizontal sectional efforts are maximum at μ=75 (90) deg, being higher for the full load. The torsional moment

has maximum values for both loading cases at beam wave condition μ=75 (90) deg, with similar values. All five sectional efforts criteria by the 1D-beam model are satisfied for both loading conditions, so no operation restrictions occur from the 1D strength criteria in any oblique wave state (h_w=12 m).

The enhanced strength valuation of the large LNG carrier is done by the 3D approach, stresses and deflections criteria (table 1), for full load case (table 4, figures 19, 20) and ballast case (table 8, figures 35, 36).

The von Mises stresses have the maximum values for both loading cases at beam wave condition μ=75(90) deg. For the hogging wave, the von Mises stresses are larger for ballast in comparison to full cargo, being satisfied the yielding stress criterion for both loading cases. For sagging waves, the von Mises stresses are larger for full cargo in comparison to the ballast. The yielding stress criterion is satisfied for the ballast case, so no operation restriction occurs (h_w=12m). For the full cargo case, on the sagging wave, operational restrictions are imposed by the yielding stress criterion, h_w=10.609< 10.715 m at beam waves μ=75(90) deg, and without restrictions for the other heading angles.

The vertical displacements have the maximum values for both loading cases at μ=75(90) deg.

For the hogging wave, the vertical deflections are larger for ballast in comparison to full cargo, leading to operational restrictions for ballast case h_w=10.999 m at beam waves, the deflection criterion being satisfied for full cargo case. For sagging waves, the vertical deflections are larger for full cargo in comparison to the ballast. On the sagging wave, for both loading cases operational restrictions are imposed by the vertical deflection criterion, h_w=10.712< 10.715 m on full cargo case and h_w=11.298 m on ballast case, at beam waves, μ=75(90) deg, without restrictions for the other heading angles.

For both structural models, the minimum freeboard is a common criterion that is satisfied in both loading cases (h_w=12m), full cargo (table 5, figure 21, 22), and ballast (table 9, figure 37, 38), due to higher sides specific for this large LNG 150000 cbm carrier (table 1).

Table 10 combines the criteria for strength valuation of the large LNG carrier in oblique waves, resulting that by the 1D-beam model no restrictions occur, and by the 3D-FEM model at beam waves, restrictions occur on both loading cases. As the synthesis of the strength valuation of the large LNG carrier, the cumulative polar diagrams $h_{wlimit}(\mu)$ for both loading cases are drawn up, for the prediction of the safety operation limits by 3D-FEM (figure 39) and 1D-beam (figure 40) structural models.

Table 10. Large LNG carrier h_{wlimit} (m) by strength and free board criteria, both loading cases

Load	Full cargo				Ballast			
Model	3D model		1D model		3D model		1D model	
μ (deg)	hogging	sagging	hogging	sagging	hogging	sagging	hogging	sagging
0 ÷ 60	12	12	12	12	12	12	12	12
75 (90)	12	**10.603**	12	12	**10.999**	**11.298**	12	12

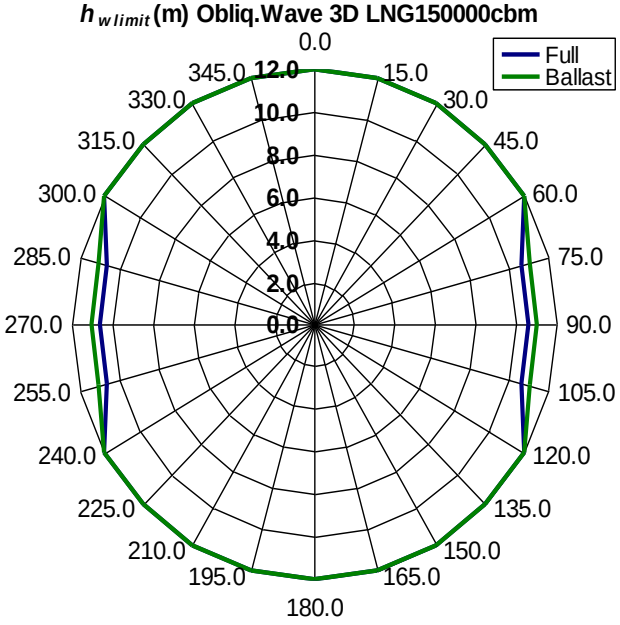

Fig. 39. Large LNG carrier, $h_{wlimit}(\mu)$ *oblique wave*, 3D model, both loading cases

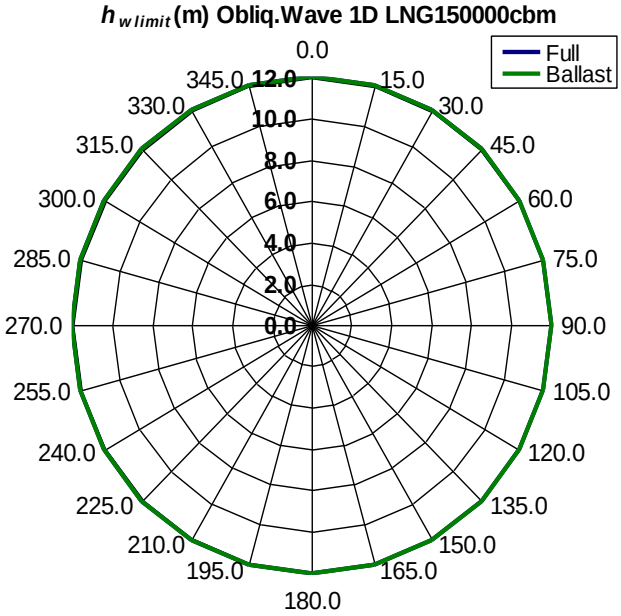

Fig. 40. Large LNG carrier, h_{wlimit} (μ) *oblique wave*, 1D model, both loading cases

7. CONCLUSIONS

In this research an enhanced numerical approach is applied for the strength valuation of a large LNG 150000 cbm carrier in oblique waves (section 3), having extended geometric non-linearities at stern and bow that can lead to slow down the convergence of the usual iterative procedures for the ship's-wave equilibrium position computation [6].

The request for improvement of the equilibrium procedure convergence, lead to the development of the eigen developed three parameters iterative code (figure 1), program *P_QSW* [7] with new updates, that uses for optimized computational time an equivalent 1D-beam LNG hull model. To provide the structural accuracy for strength valuation in oblique waves, a 3D-FEM LNG hull model has been developed, ensuring by user subroutines the data exchange of the external ship's 3D shape and mass distribution for a correlated 1D-beam model. The numerical analysis is applied in the relevant loading cases of the large LNG carrier: full cargo and ballast cases (sections 4, 5, 6). Due to the geometric non-linearities of the LNG external shell, influencing the hull hydrostatics, lead to consistent changes in the three equilibrium parameters of the ship according to the oblique wave state (tables 2, 6).

The 1D-beam large LNG carrier model, besides the step for equilibrium parameters computation, delivers the preliminary global strength valuation by admissible sectional efforts criteria (table 1). Although the maximum sectional efforts are obtained at head (follow) waves, μ=0 deg, for vertical sectional efforts, and beam waves, μ=75(90) deg, for horizontal and torsional sectional efforts, for both loading cases, in any oblique wave state the 1D strength criteria are satisfied and no operation restriction is provided (tables 3, 7).

The 3D-FEM large LNG carrier model, which includes the relevant structural details (figure 4), delivers the enhanced strength valuation by yielding stress and vertical deflection criteria (table 1). For both loading cases, the maximum stress von Mises and vertical deflection values are obtained at beam waves, μ=75(90) deg. For the full cargo case, the operation restrictions occur from both 3D strength criteria only at beam waves (table 4), sagging condition. For the ballast case, fewer operational restrictions occur, only from vertical deflection criteria, and only at beam waves (table 8), sagging and hogging conditions. Better modeling of the LNG hull structure by 3D-FEM, in terms of hot spots and elasticity, makes it possible to reveal the restrictions in comparison to the 1D-beam model.

Besides the strength valuation, also for the operational assessment of the large LNG carrier, the minimum freeboard criterion is applied for both loading cases, and no restrictions occur (table 5, 9).

In conclusion, the strength valuation of the large LNG carrier is proving the advantages of the enhanced analysis in oblique waves in comparison to the standard analysis in head waves [1, 2], revealing for this ship that only the beam wave condition is leading to operational restrictions (table 10).

Further development of this study, shall include other intermediate loading cases for a whole design range of operational conditions assessment. Also, this study shall continue with the analysis of other ship types that will make it possible to add further improvements to the numerical code, for ensuring the accuracy and the convergence of the iterative non-linear approach (fig.1).

Acknowledgements
Special thanks for ICEPRONAV Galati that has provided the LNG initial design data. Also, thanks for the UDJG Naval Architecture Research Centre that has ensured the support for this research.

8. REFERENCES

1. Stoicescu, L., Domnisoru, L., (2007). *Global Strength Analysis in Head Waves, for a Tanker with Longitudinal Uniform Structure*, Proceedings of Marstruct 2007, Advancements in Marine Structures, C.G. Soares (Ed.), pp. 283-294, A.A. Balkema Publishers, Taylor & Francis Group, Glasgow.
2. Tekgoz, M., Almany, N., Garbatov, Y., (2019). *Quasi-static Direct Strength Assessment of Offshore Multipurpose Support Vessel in Head Sea*, Proceedings of IMAM 2019, Sustainable Development and Innovations in Marine Technologies, C.G. Soares (Ed.), 3(415-422), CRC Press-Balkema, Varna.
3. BV (2022). *Hull Girder Strength. Direct Strength Analysis. Rules for the Classification of Steel Ships*, Bureau Veritas, Paris.
4. DNV (2022). *Hull Girder Strength. Finite Element Analysis. Rules for Classification Ships*, Det Norske Veritas. Novik.
5. ISSC (2022). *Proceeding of the 21th International Ship and Offshore Structures. Quasi-Static Response. Design Principles and Criteria*, ISSC, Vancouver.
6. Hughes, O.F., (2005). *A Rationally Based, Computer Aided Optimization Approach. Ship Structural Design*, SNAME Publishing House, New Jersey.
7. Domnisoru, L., (2017). *Applications. Special Chapters on Ships' Structures Analysis*, UDJG Publishing House, Galati.
8. FNN (2022). *Femap/NX Nastran. Academic License*, Siemens PLM Software.
9. Domnisoru, L., Dragomir, D., Stoicescu, L., Domnisoru, D., (2009). *Numerical Methods for Structural Analysis and Hydroelasticity of the Ship*, UDJG Publishing House, Galati.
10. Reddy, J.N. (2006). *An Introduction to the Finite Element Method. Third Edition*, McGraw Hill Publishing House, New York.

Received: April 30, 2023 / Accepted: December 15, 2023 / Paper available online: December 20, 2023 © International Journal of Modern Manufacturing Technologies