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NUMERICAL APPROACH FOR GLOBAL SHIP STRENGTHS ANALYSIS BASED ON 1D-BEAM MODEL, UNDER OBLIQUE EQUIVALENT QUASI-STATIC WAVE LOADS

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ABSTRACT

This paper focuses on a new iterative approach for global ship strengths analysis, based on equivalent hull structure 1D-beam model, under oblique quasi-static wave design loads. As testing case, a maritime barge with a total length of 97m is considered. The barge has a prismatic rectangular hull shape and uniform mass distribution. The analyses are based on a non-linear iterative algorithm, implemented in own program code P_QSW. The results point out the maximum wave-induced loads into the ship's girder, which are assessed by statistical rule-based design values.

Keywords: non-linear iterative procedure, ship equivalent 1D-beam model, global strength, oblique waves.

1. INTRODUCTION

At the initial design of ships structure, the shipbuilding classification societies [1],[3],[5], [7] require that the global strength criteria be verified based on 1D-beam hull girder model.

This study is focused on developing an iterative non-linear algorithm for solving the equilibrium conditions of the ship hull under oblique equivalent quasi-static waves [8],[6]. This algorith is presented in section 2. The equilibrium iterative algorithm is implemented into own developed program code *P_QSW*.

The own program code is tested on an maritime barge (section 3), with total length of 97 m, with prismatic hull shape and uniform mass distribution over the ship girder. The numerical analyses deliver the barge-wave equilibrium parameters and the wave induced loads into the ship girder, function of the wave characteristics. The maximum wave induced loads, bending moments, shear forces and torsion moment, are assessed by statistical rule based design values.

2. THE NON-LINEAR ITERATIVE ALGORITHM FOR GLOBAL SHIP STRENGTHS ANALYSIS

This approach takes into account the global ship strengths analysis under the loads from oblique equivalent quasi-static wave with the following parameters (Fig.1): h_w wave height, λ wave length, μ ship - wave direction heading angle.

The relative wave length, considering the maxim wave design loads condition, results from the following expression (Fig.1):

$$\lambda_1 = \lambda/\cos\mu = L \ ; \ \lambda = \lambda_1 \cos\mu = L\cos\mu \quad (1)$$

where L is the ship length.

The long-term statistical maximum wave height h_w, with Smith correction, results from Bureau Veritas, Pt.B, Ch.5, Sec 2 [3]:

$$h_w = 10.75 - (3 - 0.01 \cdot L)^{3/2} \quad (2)$$

In order to simplify the integrals calculation with trapeze method, the significant ship hull transversal sections are considered disposed at the middle of „*n*" 1D elements [4].

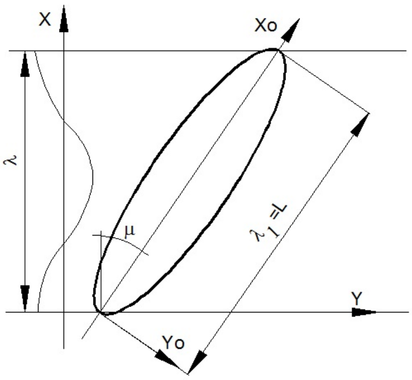

Fig.1 Relative position ship - oblique wave

$$x_1 = \frac{\delta x}{2} \quad x_i = x_{i-1} + \delta x \quad i = 2, n$$

$$\delta x = L/n \quad \int_0^L f(x)dx = \delta x \sum_{i=1}^{n} f(x_i) \tag{3}$$

The ship mass distribution is:

$$m_{xi}, i = 1, n \quad V = c_B LBT \quad y_G = 0$$

$$\Delta = \rho V = \delta x \sum_{i=1}^{n} m_{xi} \quad x_G = \frac{\delta x}{\Delta} \sum_{i=1}^{n} x_i m_{xi} \tag{4}$$

where: Δ, V - the ship displacement and volume; x_G, y_G - the gravity centre position; B, T - design ship breadth and draught; c_B - block coefficient.

In order to take into account the real ship offset lines ($C_i, i = 1, n$), a non-linear iterative procedure with three steps is used. An analysis case is defined by Δ, x_G, y_G and h_w, μ, λ_1, resulting the ship-wave equilibrium parameters d_m, θ, φ (draught, pitch and roll angles) which define the median plane position (x_F, y_F) of quasi-static wave into the reference to the ship base plane [2],[9]. For a roll angle $\varphi^{(p)}$ the following two steps are carried out:

Step I – the floating condition (5)

iter k=0 $d_m^{(0)} = 0 \quad \theta^{(0)} = 0 \rightarrow$

$x_F^{(0)}, y_F^{(0)}, A_{WL}^{(0)}$ and $A_T^{(0)}, y_{At}^{(0)}\big|_i^{sb,ps}$

iter k>1 $d_m^{(k)} = d_m^{(k-1)} + 0.001 \quad \theta^{(0)} = 0$

iterations on offset section lines $y, z \in C_i$

$$\delta y = \left(y_{Ci}^{\max} - y_{Ci}^{\min}\right)/1000 \quad \text{for} \quad i = 1, n$$

$$z^{(k)}, y^{(k)}\big|_i^{sb} \in C_i^{sb}; z^{(k)}, y^{(k)}\big|_i^{ps} \in C_i^{ps} \rightarrow x_F^{(k)}, y_F^{(k)}, A_{WL}^{(k)}$$

where: $z^{(k)}\big|_i^{sb,ps} = d_m^{(k)} + \left(x_i - x_F^{(k)}\right) \cdot \theta^{(0)} + \left(y^{(k)}\big|_i^{sb,ps} - y_F^{(k)}\right) \cdot tg\left(\varphi^{(p)}\right)$

$$\ell_i^{(k)} = \left[\left(y^{(k)}\big|_i^{sb} - y^{(k)}\big|_i^{ps}\right)^2 + \left(z^{(k)}\big|_i^{sb} - z^{(k)}\big|_i^{ps}\right)^2\right]^{1/2}$$

$$\bar{y}_i^{(k)} = \left(y^{(k)}\big|_i^{sb} + y^{(k)}\big|_i^{ps}\right)/2 \quad A_{WL}^{(k)} = \delta x \sum_{i=1}^{n} \ell_i^{(k)}$$

$$x_F^{(k)} = \frac{\delta x}{A_{WL}^{(k)}} \sum_{i=1}^{n} x_i \ell_i^{(k)} \quad y_F^{(k)} = \frac{\delta x}{A_{WL}^{(k)}} \sum_{i=1}^{n} \bar{y}_i^{(k)} \ell_i^{(k)}$$

iterations on offset section lines $y, z \in C_i$

$$\delta y = \left(y_{Ci}^{\max} - y_{Ci}^{\min}\right)/1000 \quad \text{for} \quad i = 1, n$$

$$z_w^{(k)}, y_w^{(k)}\big|_i^{sb} \in C_i^{sb}; z_w^{(k)}, y_w^{(k)}\big|_i^{ps} \in C_i^{ps} \rightarrow A_T^{(k)}, y_{At}^{(k)}\big|_i^{sb,ps}$$

where: $z_w^{(k)}\big|_i^{sb,ps} = d_m^{(k)} + \left(x_i - x_F^{(k)}\right) \cdot \theta^{(0)} + \left(y_w^{(k)}\big|_i^{sb,ps} - y_F^{(k)}\right) \cdot tg\left(\varphi^{(p)}\right) \pm \pm \frac{h_w}{2} \cos\left(\frac{2\pi x_i}{\lambda_1} + 2\pi y_w^{(k)}\big|_i^{sb,ps} \frac{\sin\mu}{\lambda}\right)$

$$V^{(k)} = \delta x \sum_{i=1}^{n} \left(A_T^{(k)}\big|_i^{sb} + A_T^{(k)}\big|_i^{ps}\right)$$

$$x_B^{(k)} = \frac{\delta x}{V^{(k)}} \sum_{i=1}^{n} x_i \left(A_T^{(k)}\big|_i^{sb} + A_T^{(k)}\big|_i^{ps}\right)$$

$$y_B^{(k)} = \frac{\delta x}{V^{(k)}} \sum_{i=1}^{n} \left(y_{At}^{(k)}\big|_i^{sb} A_T^{(k)}\big|_i^{sb} + y_{At}^{(k)}\big|_i^{ps} A_T^{(k)}\big|_i^{ps}\right)$$

and the iterations are done until $V^{(k)} \geq V$.

The solution is refined, using the half domain method on d_m parameter, so that at the last iteration „k", the convergence criterion is achieved: $\left|V - V^{(k)}\right| \leq 0.001 \cdot V$

At the end of *Step I*, the following parameters are obtained:

$$d_m^I = d_m^{(k)} \quad \theta^I = 0 \quad x_F^I = x_F^{(k)} \quad y_F^I = y_F^{(k)}$$

$$A_{WL}^I = A_{WL}^{(k)} \quad x_B^I = x_B^{(k)} \quad y_B^I = y_B^{(k)}$$

$$A_T^I\big|_i^{sb} = A_T^{(k)}\big|_i^{sb} \quad A_T^I\big|_i^{ps} = A_T^{(k)}\big|_i^{ps}$$

$$y_{At}^I\big|_i^{sb} = y_{At}^{(k)}\big|_i^{sb} \quad y_{At}^I\big|_i^{ps} = y_{At}^{(k)}\big|_i^{ps} \quad \text{for} \quad i = 1, n$$

Step II – the pitch condition (6)

iter j=0 $\theta^{(0)} = 0$ $d_m^{(0)} = d_m^I$ $x_F^{(0)} = x_F^I$

$y_F^{(0)} = y_F^I$ $A_{WL}^{(0)} = A_{WL}^I$ $x_B^{(0)} = x_B^I$ $y_B^{(0)} = y_B^I$

if $x_G > x_B^{(0)}$ $\rightarrow$ $\delta\theta^{(0)} = 0.00001$ or

if $x_G < x_B^{(0)}$ $\rightarrow$ $\delta\theta^{(0)} = -0.00001$

$\left|x_G - x_B^{(0)}\right| \le 0.001L \rightarrow \delta\theta^{(0)} = 0 \rightarrow$ end of Step II

iter j>1 $\theta^{(j)} = \theta^{(j-1)} + \delta\theta^{(j-1)}$

$$d_m^{(j)} = d_m^{(j-1)} + \frac{V - V^{(j-1)}}{A_{wL}^{(j-1)}}$$

iterations on offset section lines $y, z \in C_i$

$\delta y = \left(y_{Ci}^{\max} - y_{Ci}^{\min}\right)/1000$ for $i = 1, n$

$$z^{(j)}, y^{(j)}\Big|_i^{sb} \in C_i^{sb}; z^{(j)}, y^{(j)}\Big|_i^{ps} \in C_i^{ps} \rightarrow x_F^{(j)}, y_F^{(j)}, A_{WL}^{(j)}$$

where: $z^{(j)}\Big|_i^{sb,ps} = d_m^{(j)} + \left(x_i - x_F^{(j)}\right)\cdot\theta^{(j)} +$

$+\left(y^{(j)}\Big|_i^{sb,ps} - y_F^{(j)}\right)\cdot tg\left(\varphi^{(p)}\right)$

$$\ell_i^{(j)} = \left[\left(y^{(j)}\Big|_i^{sb} - y^{(j)}\Big|_i^{ps}\right)^2 + \left(z^{(j)}\Big|_i^{sb} - z^{(j)}\Big|_i^{ps}\right)^2\right]^{1/2}$$

$$\bar{y}_i^{(j)} = \left(y^{(j)}\Big|_i^{sb} + y^{(j)}\Big|_i^{ps}\right)\Big/2 \quad A_{WL}^{(j)} = \delta x \sum_{i=1}^{n} \ell_i^{(j)}$$

$$x_F^{(j)} = \frac{\delta x}{A_{WL}^{(j)}} \sum_{i=1}^{n} x_i \ell_i^{(j)} \quad y_F^{(j)} = \frac{\delta x}{A_{WL}^{(j)}} \sum_{i=1}^{n} \bar{y}_i^{(j)} \ell_i^{(j)}$$

iterations on offset section lines $y, z \in C_i$

$\delta y = \left(y_{Ci}^{\max} - y_{Ci}^{\min}\right)/1000$ for $i = 1, n$

$$z_w^{(j)}, y_w^{(j)}\Big|_i^{sb} \in C_i^{sb}; z_w^{(j)}, y_w^{(j)}\Big|_i^{ps} \in C_i^{ps} \rightarrow A_T^{(j)}, y_{At}^{(j)}\Big|_i^{sb,ps}$$

where: $z_w^{(j)}\Big|_i^{sb,ps} = d_m^{(j)} + \left(x_i - x_F^{(j)}\right)\cdot\theta^{(j)} +$

$+\left(y_w^{(j)}\Big|_i^{sb,ps} - y_F^{(j)}\right)\cdot tg\left(\varphi^{(p)}\right)\pm$

$$\pm\frac{h_w}{2}\cos\left(\frac{2\pi x_i}{\lambda_1} + 2\pi y_w^{(j)}\Big|_i^{sb,ps}\frac{\sin\mu}{\lambda}\right)$$

$$V^{(j)} = \delta x \sum_{i=1}^{n}\left(A_T^{(j)}\Big|_i^{sb} + A_T^{(j)}\Big|_i^{ps}\right)$$

$$x_B^{(j)} = \frac{\delta x}{V^{(j)}} \sum_{i=1}^{n} x_i \left(A_T^{(j)}\Big|_i^{sb} + A_T^{(j)}\Big|_i^{ps}\right)$$

$$y_B^{(j)} = \frac{\delta x}{V^{(j)}} \sum_{i=1}^{n}\left(y_{At}^{(j)}\Big|_i^{sb} A_T^{(j)}\Big|_i^{sb} + y_{At}^{(j)}\Big|_i^{ps} A_T^{(j)}\Big|_i^{ps}\right)$$

if $x_G > x_B^{(j)}$ $\rightarrow$ $\delta\theta^{(j)} = 0.00001$ or

if $x_G < x_B^{(j)}$ $\rightarrow$ $\delta\theta^{(j)} = -0.00001$

$\left|x_G - x_B^{(j)}\right| \le 0.001L \rightarrow \delta\theta^{(j)} = 0 \rightarrow$ end of Step II

iterations until $\operatorname{sgn}\left\{\delta\theta^{(j-1)}\cdot\delta\theta^{(j)}\right\} = -1$

The solution is refined with the half domain method on θ parameter, so that at the last iteration „j", the following convergence criteria are met:

$\left|V - V^{(j)}\right| \le 0.001\cdot V$; $\left|x_G - x_B^{(j)}\right| \le 0.001\cdot L$

At the end of Step II, the following data is obtained:

$d_m^{II} = d_m^{(j)}$ $\theta^{II} = \theta^{(j)}$ $x_F^{II} = x_F^{(j)}$ $y_F^{II} = y_F^{(j)}$

$A_{WL}^{II} = A_{WL}^{(j)}$ $x_B^{II} = x_B^{(j)}$ $y_B^{II} = y_B^{(j)}$

$A_T^{II}\Big|_i^{sb} = A_T^{(j)}\Big|_i^{sb}$ $A_T^{II}\Big|_i^{ps} = A_T^{(j)}\Big|_i^{ps}$

$y_{At}^{II}\Big|_i^{sb} = y_{At}^{(j)}\Big|_i^{sb}$ $y_{At}^{II}\Big|_i^{ps} = y_{At}^{(j)}\Big|_i^{ps}$ for $i = 1, n$

Step III – the roll condition (7)

iter p=0 $\varphi^{(0)} = 0$

Step I – the floating condition

Step II – the pitch condition

if $y_G > y_B^{(0)}$ $\rightarrow$ $\delta\varphi^{(0)} = 0.00001$ or

if $y_G < y_B^{(0)}$ $\rightarrow$ $\delta\varphi^{(0)} = -0.00001$

$\left|y_G - y_B^{(0)}\right| \le 0.001B \rightarrow \delta\varphi^{(0)} = 0 \rightarrow$ end of Step III

iter p>1 $\varphi^{(p)} = \varphi^{(p-1)} + \delta\varphi^{(p-1)}$

Step I – the floating condition

$d_m^I\Big|^{(p)}, \theta^I\Big|^{(p)} = 0$,

$x_F^I\Big|^{(p)}, y_F^I\Big|^{(p)}, A_{WL}^I\Big|^{(p)}, x_B^I\Big|^{(p)}, y_B^I\Big|^{(p)}$

$A_T^I\Big|_i^{sb(p)}, A_T^I\Big|_i^{ps(p)}, y_{At}^I\Big|_i^{sb(p)}, y_{At}^I\Big|_i^{ps(p)}$, $i = 1, n$

Step II – the pitch condition

$d_m^{II}\Big|^{(p)}, \theta^{II}\Big|^{(p)}$,

$x_F^{II}\Big|^{(p)}, y_F^{II}\Big|^{(p)}, A_{WL}^{II}\Big|^{(p)}, x_B^{II}\Big|^{(p)}, y_B^{II}\Big|^{(p)}$

$A_T^{II}\Big|_i^{sb(p)}, A_T^{II}\Big|_i^{ps(p)}, y_{At}^{II}\Big|_i^{sb(p)}, y_{At}^{II}\Big|_i^{ps(p)}$, $i = 1, n$

if $y_G > y_B^{(p)}$ $\rightarrow$ $\delta\varphi^{(p)} = 0.00001$ or

if $y_G < y_B^{(p)}$ $\rightarrow$ $\delta\varphi^{(p)} = -0.00001$

$\left|y_G - y_B^{(p)}\right| \le 0.001B \to \delta\varphi^{(p)} = 0 \to$ end of Step III

iterations until $\operatorname{sgn}\left\{\delta\varphi^{(k-1)} \cdot \delta\varphi^{(k)}\right\} = -1$

The solution is refined with the half domain method on φ parameter, so that at the last iteration „*p*" the convergence criteria are satisfied: $\left|V - V^{(p)}\right| \le 0.001 \cdot V$

$\left|x_G - x_B^{(p)}\right| \le 0.001 \cdot L$; $\left|y_G - y_B^{(p)}\right| \le 0.001 \cdot B$

At the end of Step III, the following data is obtained:

$$d_m = d_m^{II}\Big|^{(p)} \quad \theta = \theta^{II}\Big|^{(p)} \quad \varphi = \varphi^{(p)}$$

$$x_F = x_F^{II}\Big|^{(p)} \quad y_F = y_F^{II}\Big|^{(p)} \quad A_{WL} = A_{WL}^{II}\Big|^{(p)}$$

$$x_B = x_B^{II}\Big|^{(p)} \quad y_B = y_B^{II}\Big|^{(p)}$$

$$A_T\Big|_i^{sb} = A_T^{II}\Big|_i^{sb(p)} \quad A_T\Big|_i^{ps} = A_T^{II}\Big|_i^{ps(p)}$$

$$y_{At}\Big|_i^{sb} = y_{At}^{II}\Big|_i^{sb(p)} \quad y_{At}\Big|_i^{ps} = y_{At}^{II}\Big|_i^{ps(p)} \text{ for } i = 1,n$$

iterations on offset section lines $y, z \in C_i$

$$\delta y = \left(y_{Ci}^{\max} - y_{Ci}^{\min}\right)/1000 \quad \text{for} \quad i = 1,n$$

$$z_w, y_w\Big|_i^{sb} \in C_i^{sb};\, z_w, y_w\Big|_i^{ps} \in C_i^{ps} \to A_H, z_{Ah}\Big|_i^{sb,ps}$$

where : $z_w\Big|_i^{sb,ps} = d_m + \left(x_i - x_F\right)\cdot\theta +$

$$+\left(y_w\Big|_i^{sb,ps} - y_F\right)\cdot tg(\varphi)\pm$$

$$\pm\frac{h_w}{2}\cos\left(\frac{2\pi x_i}{\lambda_1} + 2\pi y_w\Big|_i^{sb,ps}\frac{\sin\mu}{\lambda}\right)$$

$$z_H = \frac{\delta x}{V}\sum_{i=1}^{n}\left(z_{Ah}\Big|_i^{sb} A_H\Big|_i^{sb} + z_{Ah}\Big|_i^{ps} A_H\Big|_i^{ps}\right)$$

$$\alpha_1 = \delta x\sum_{i=1}^{n}\rho g\left(A_H\Big|_i^{ps} - A_H\Big|_i^{sb}\right)$$

$$\alpha_2 = \delta x\sum_{i=1}^{n}\rho g x_i\left(A_H\Big|_i^{ps} - A_H\Big|_i^{sb}\right)$$

sway and yaw influence terms (horizontal):

$$q_2 = 12/L^3\left(L/2\cdot\alpha_1 - \alpha_2\right);\, q_1 = -\alpha_1/L - L/2\cdot q_2$$

The total loads from equivalent quasi-static oblique wave result from the following expressions: (8)

$$x_{s1} = 0 \quad x_{si} = x_{si-1} + \delta x \quad i = 2,n+1 \quad \delta x = L/n$$

- vertical load per unit length, rule positive up to down

$$q_{vi} = g\cdot m_{xi} - \rho g\left(A_T\Big|_i^{sb} + A_T\Big|_i^{ps}\right) \quad i = 1,n$$

-vertical shear force

$$T_{v1} = 0 \quad T_{vi} = T_{vi-1} + q_{vi-1}\cdot\delta x \quad i = 2,n+1$$

-vertical bending moment $i = 2,n+1$

$$M_{v1} = 0 \quad M_{vi} = M_{vi-1} + \left(T_{vi-1} + T_{vi}\right)/2\cdot\delta x$$

-horizontal load per unit length, rule positive from left to right

$$q_{hi} = \rho g\left(A_H\Big|_i^{ps} - A_H\Big|_i^{sb}\right) + q_1 + q_2\cdot x_i \quad i = 1,n$$

-horizontal shear force

$$T_{h1} = 0 \quad T_{hi} = T_{hi-1} + q_{hi-1}\cdot\delta x \quad i = 2,n+1$$

-horizontal bending moment $i = 2,n+1$

$$M_{h1} = 0 \quad M_{hi} = M_{hi-1} + \left(T_{hi-1} + T_{hi}\right)/2\cdot\delta x$$

- torsion moment, rule positive as roll angle around the *R* torsion centre $e_R = z_H - z_R$

$$m_{thi} = e_R\cdot q_{hi} \quad i = 1,n$$

$$M_{th1} = 0 \quad M_{thi} = M_{thi-1} + m_{thi-1}\cdot\delta x \quad i = 2,n+1$$

$$m_{tvi} = -\rho g\left(A_T\Big|_i^{sb}\cdot y_{At}\Big|_i^{sb} + A_T\Big|_i^{ps}\cdot y_{At}\Big|_i^{ps}\right) \quad i = 1,n$$

$$M_{tv1} = 0 \quad M_{tvi} = M_{tvi-1} + m_{tvi-1}\cdot\delta x \quad i = 2,n+1$$

$$M_{ti} = M_{thi} + M_{tvi} \quad i = 1,n+1$$

Obs. In the above equations the sign $\pm$ makes possible to select the hogging and sagging wave loading conditions.

Based on the above algorithm, the own program code *P_QSW*, using *Free Pascal* programming language [4], has been developed, for solving the equilibrium between the ship and the design oblique equivalent quasi-static waves.

The parameters $d_m, \theta, \varphi, x_F, y_F, h_w, \mu, \lambda$, which characterize the median plane of quasi-static wave and the wave free surface (9), into the reference to the ship base plane, can be further used for setting up the equilibrium of a 3D-FEM model, fully extended over the ship's length and both sides, for the ship hull under oblique quasi-static wave loads.

$$z_w(x,y) = d_m + \left(x - x_F\right)\cdot\theta + \left(y - y_F\right)\cdot tg(\varphi)$$

$$\pm\frac{h_w}{2}\cos\left[\frac{2\pi}{\lambda}\left(x\cos\mu + y\sin\mu\right)\right];\, x\in[0,L] \quad (9)$$

3. NUMERICAL GLOBAL STRENGHT ANALYSIS OF A BARGE, BASED ON THE 1D-BEAM MODEL

The main characteristics of the barge test ship are presented in Table 1, with uniform mass distribution and prismatic hull shape.

Table 1. The barge characteristics

L = 97 m	g = 9.81 m/s^2	h_w= 0 ÷ 10 m
B = 33 m	F_s = 0 m	δh_w=0.5 (1) m
H = 4 m	x_G = 48.5 m	h_{wmax}=7.858m
T = 2 m	y_G = 0 m	μ=0÷75(90) deg
c_B = 1	z_G = 4.3 m	$\delta\mu$ = 15 deg.
Δ =6562.05 t	z_R = 2 m	$\lambda=\lambda_1\cos\mu$
V = 6402 m^3	N_e = 40	$\lambda_1=L$ (0÷75 deg)
u_s = 0 m/s	δx = 2.425 m	$\lambda_1=B$ (90 deg)
ρ =1.025 t/m^3	m_x =67.650 t/m	quasi-static wave

Table 2. Equilibrium parameters μ=0 deg.

0 deg.	sagging			Hogging		
h_w[m]	0	4	7.858	0	4	7.858
x_F[m]	48.500	48.500	48.500	48.500	48.500	48.500
y_F[m]	0.000	0.000	0.000	0.000	0.000	0.000
d_m[m]	2.000	2.000	2.000	2.000	2.000	2.000
θ[rad]	0.000	0.000	0.000	0.000	0.000	0.000
φ[rad]	0.000	0.000	0.000	0.000	0.000	0.000
z_H[m]	0.667	1.111	1.489	0.667	1.111	1.489
e_R[m]	-1.333	-0.889	-0.511	-1.333	-0.889	-0.511

Table 3. Equilibrium parameters μ=45 deg.

45deg.	sagging			hogging		
h_w[m]	0	4	7.585	0	4	7.858
x_F[m]	48.500	48.500	48.500	48.500	48.500	48.500
y_F[m]	0.000	0.000	0.000	0.000	0.000	0.000
d_m[m]	2.000	2.000	2.988	2.000	2.000	2.988
θ[rad]	0.000	0.000	0.000	0.000	0.000	0.000
φ[rad]	0.000	0.000	0.000	0.000	0.000	0.000
z_H[m]	0.667	1.111	1.616	0.667	1.111	1.616
e_R[m]	-1.333	-0.889	-0.384	-1.333	-0.889	-0.384

Table 4. Equilibrium parameters μ=75 deg.

75deg.	sagging			hogging		
h_w[m]	0	4	7.585	0	4	7.858
x_F[m]	48.500	48.500	48.500	48.500	48.500	48.500
y_F[m]	0.000	0.000	0.000	0.000	0.000	0.000
d_m[m]	2.000	2.000	3.630	2.000	2.000	3.630
θ[rad]	0.000	0.000	0.000	0.000	0.000	0.000
φ[rad]	0.000	0.000	0.000	0.000	0.000	0.000
z_H[m]	0.667	1.111	1.594	0.667	1.111	1.594
e_R[m]	-1.333	-0.889	-0.406	-1.333	-0.889	-0.406

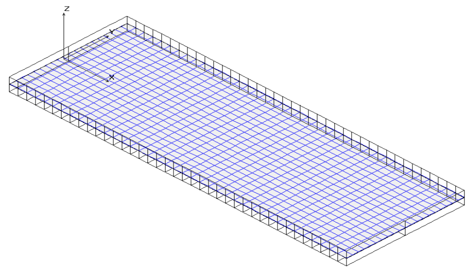

Fig.2. Barge-Wave position: h_w=0 still water

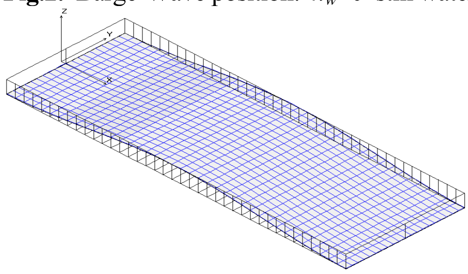

Fig.3. B-W: h_w=4 m, μ=0 deg., $\lambda=L$, hogg.

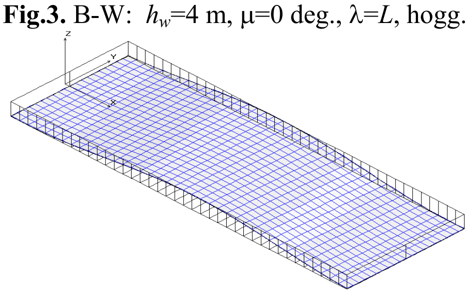

Fig.4. B-W: h_w=4m, μ=15 deg., $\lambda=0.966L$,hogg.

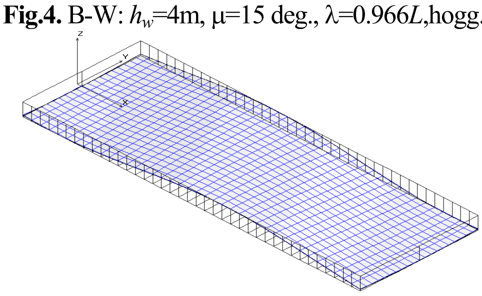

Fig.5. B-W: h_w=4m, μ=30 deg.,$\lambda=0.866L$,hogg.

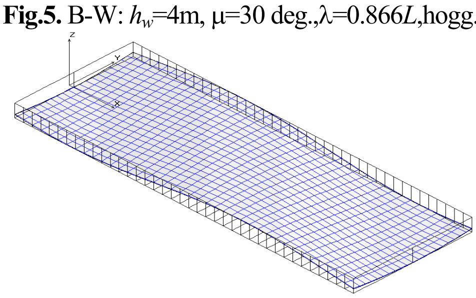

Fig.6. B-W: h_w=4m, μ=45 deg., $\lambda=0.707L$,hogg.

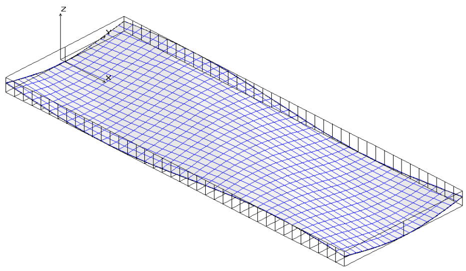

Fig.7. B-W: h_w=4m, μ=60 deg.,λ=0.500*L*,hogg.

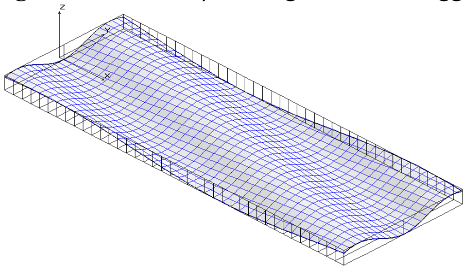

Fig.8. B-W: h_w=4m, μ=75 deg., λ=0.259*L*,hogg.

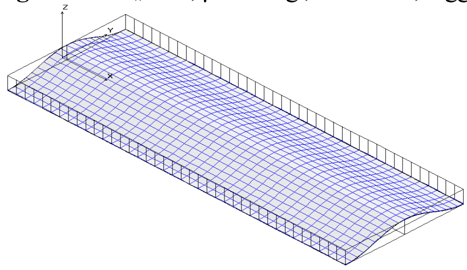

Fig.9. B-W: h_w=4m, μ=90 deg., λ=*B*, hogg.

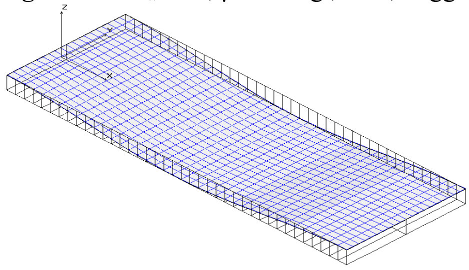

Fig.10. B-W: h_w=4m, μ=0 deg., λ=*L*, sagg.

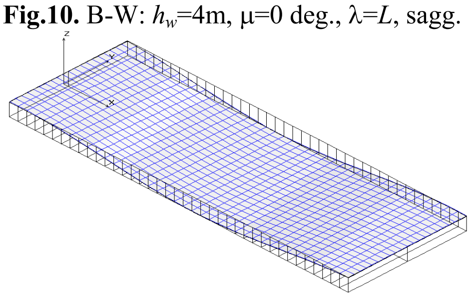

Fig.11. B-W: h_w=4m, μ=15 deg.,λ=0.966*L*,sagg.

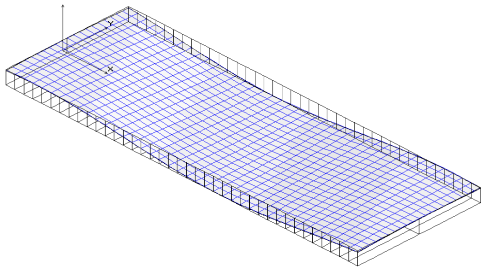

Fig.12. B-W: h_w=4m, μ=30 deg.,λ=0.866*L*,sagg.

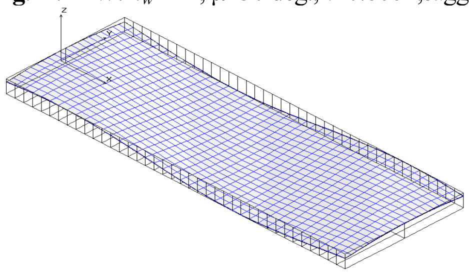

Fig.13. B-W: h_w=4m, μ=45 deg.,λ=0.707*L*,sagg.

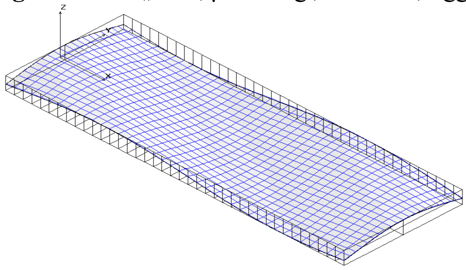

Fig.14. B-W: h_w=4m, μ=60 deg.,λ=0.500*L*,sagg.

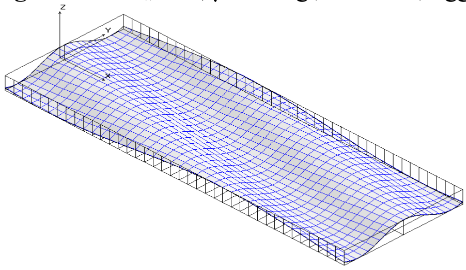

Fig.15. B-W: h_w=4m, μ=75 deg.,λ=0.259*L*,sagg.

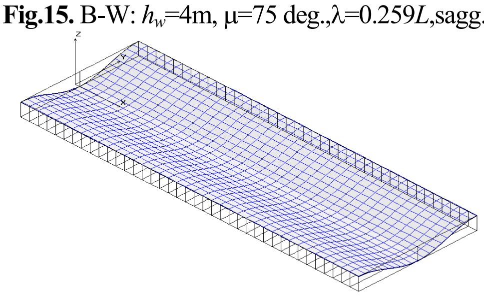

Fig.16. B-W: h_w=4m, μ=90 deg., λ=*B*, sagg.

Tables 2-4 present the equilibrium ship-wave parameters obtained by the iterative procedure from section 2.

Figs.2-16 present the barge-wave position for still water and h_w=4 m, on sagging and hogging conditions, μ=0-75 and 90 deg.

Figs.17-20.a,b present the vertical bending moment and shear force diagrams, on sagging and hogging conditions, μ=0,45 deg.

Figs.21-26.a,b present the horizontal bending moment and shear force diagrams, on sagging and hogging conditions, μ=45-75 deg.

Figs.27-30 present the torsion moment diagrams, on sagging and hogging conditions, μ=60,75 deg.

Figs.31,32.a,b present the transversal bending moment and shear force diagrams, on sagging and hogging conditions, μ=90 deg.

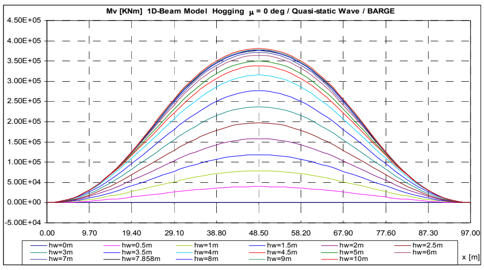

Fig.17.a Barge, M_v [kNm], μ=0 deg., hogg.

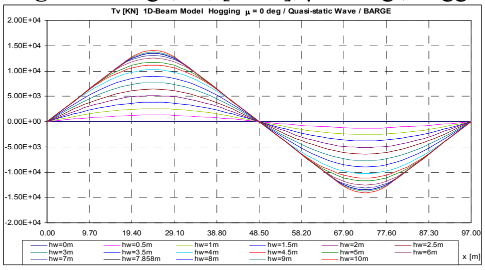

Fig.17.b Barge, T_v [kN], μ=0 deg., hogg.

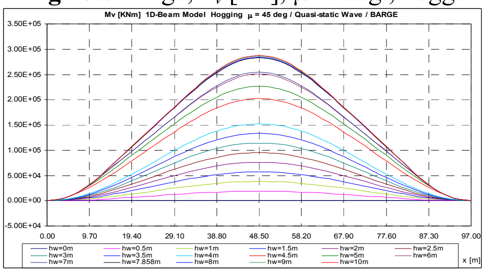

Fig.18.a Barge, M_v [kNm], μ=45 deg., hogg.

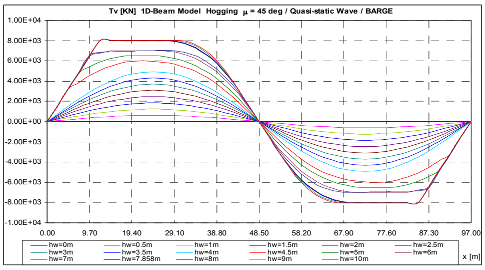

Fig.18.b Barge, T_v [kN], μ=45 deg., hogg.

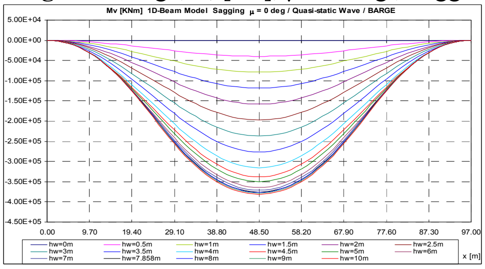

Fig.19.a Barge, M_v [kNm], μ=0 deg., sagg.

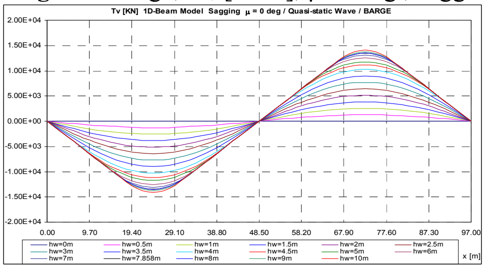

Fig.19.b Barge, T_v [kN], μ=0 deg., sagg.

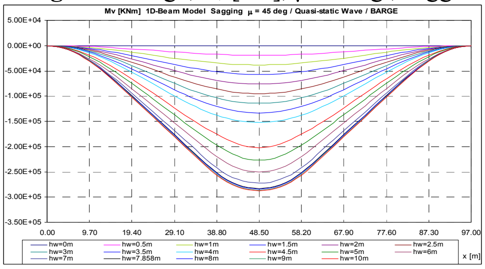

Fig.20.a Barge, M_v [kNm], μ=45 deg., sagg.

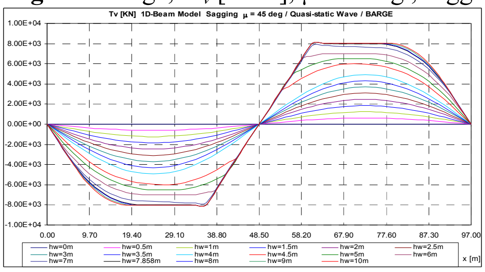

Fig.20.b Barge, T_v [kN], μ=45 deg., sagg.

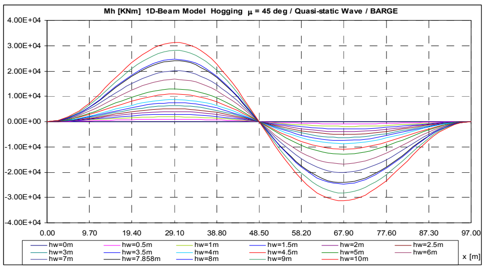

Fig.21.a Barge, M_h [kNm], μ=45 deg., hogg.

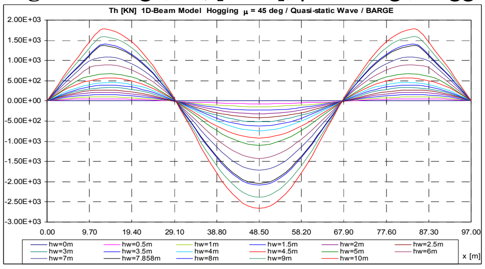

Fig.21.b Barge, T_h [kN], μ=45 deg., hogg.

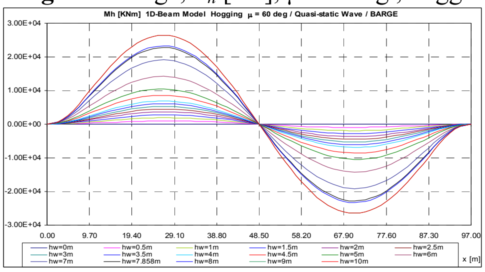

Fig.22.a Barge, M_h [kNm], μ=60 deg., hogg.

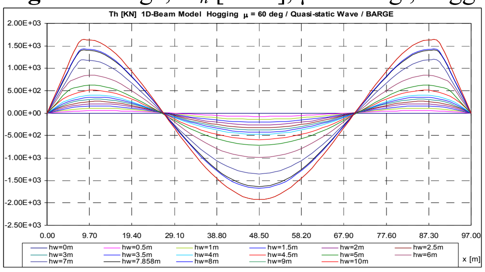

Fig.22.b Barge, T_h [kN], μ=60 deg., hogg.

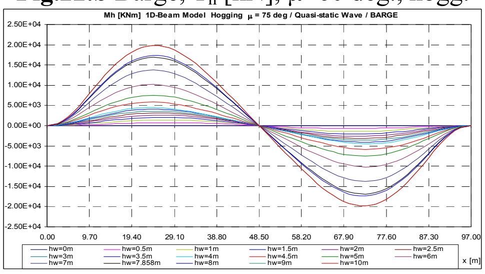

Fig.23.a Barge, M_h [kNm], μ=75 deg., hogg.

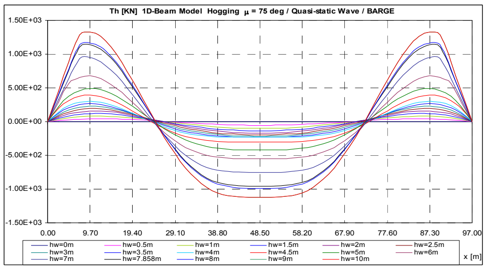

Fig.23.b Barge, T_h [kN], μ=75 deg., hogg.

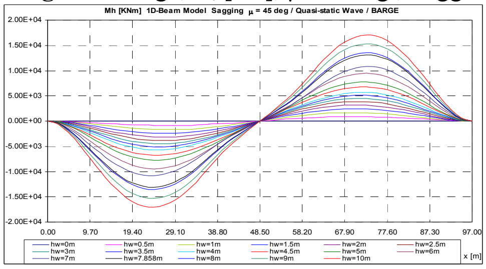

Fig.24.a Barge, M_h [kNm], μ=45 deg., sagg.

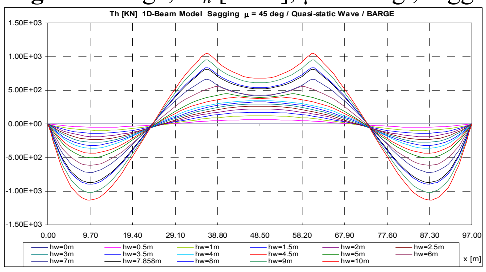

Fig.24.b Barge, T_h [kN], μ=45 deg., sagg.

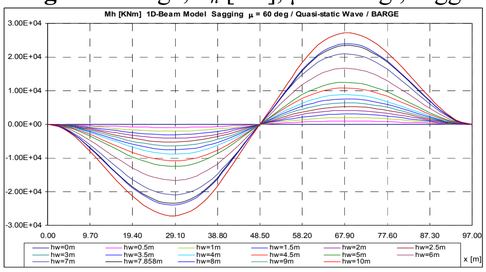

Fig.25.a Barge, M_h [kNm], μ=60 deg., sagg.

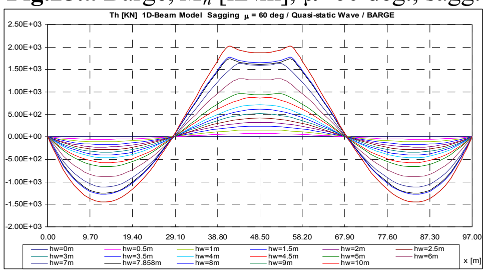

Fig.25.b Barge, T_h [kN], μ=60 deg., sagg.

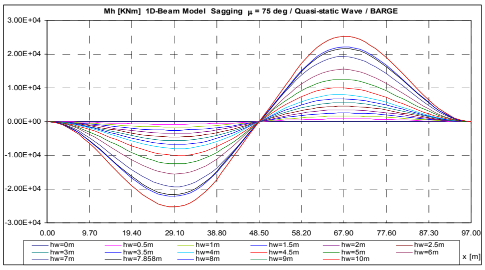

Fig.26.a Barge, M_h [kNm], μ=75 deg., sagg.

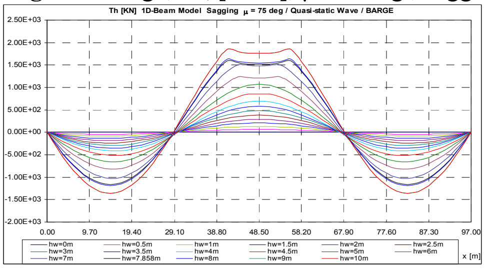

Fig.26.b Barge, T_h [kN], μ=75 deg., sagg.

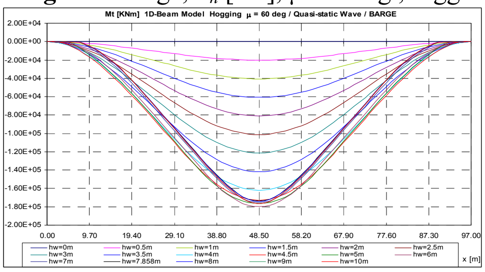

Fig.27 Barge, M_t [kNm], μ=60 deg., hogg.

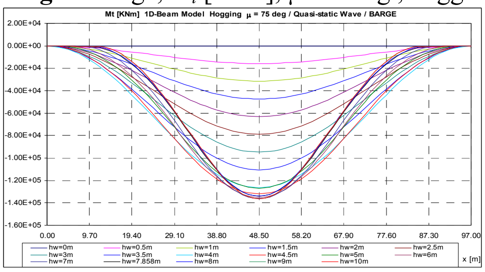

Fig.28 Barge, M_t [kNm], μ=75 deg., hogg.

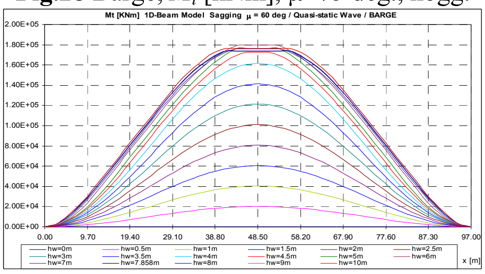

Fig.29 Barge, M_t [kNm], μ=60 deg., sagg.

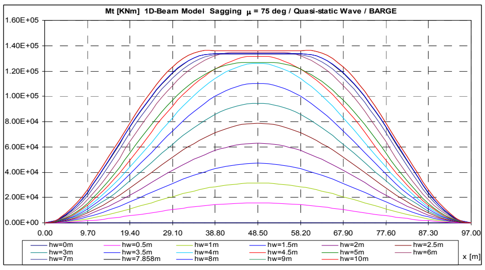

Fig.30 Barge, M_t [kNm], μ=75 deg., sagg.

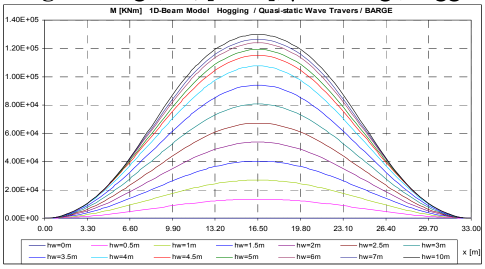

Fig.31.a Barge, M_{tr} [kNm], μ=90 deg., hogg.

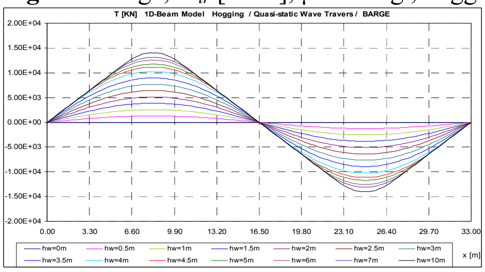

Fig.31.b Barge, T_{tr} [kN], μ=90 deg., hogg.

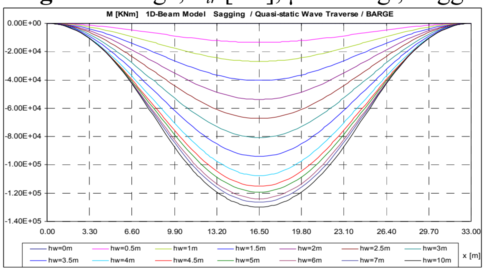

Fig.32.a Barge, M_{tr} [kNm], μ=90 deg., sagg.

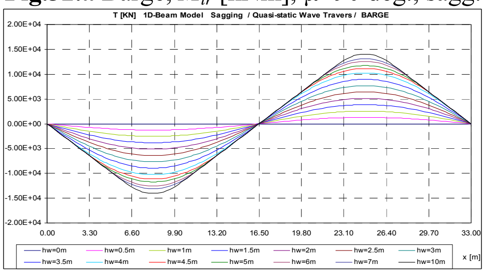

Fig.32.b Barge, T_{tr} [kN], μ=90 deg., sagg.

Table 5. Maximum wave loads, h_w=7.858m

Sagging [kNm, kN]						
μ[deg]	0	15	30	45	60	75
λ/L	1	0.966	0.866	0.707	0.500	0.259
M_v	3.76E5	3.68E5	3.36E5	2.83E5	9.52E4	6.26E4
T_v	1.35E4	1.29E4	1.06E4	8.01E3	4.83E3	4.79E3
M_h	0	2.80E3	6.44E3	1.31E4	2.34E4	2.17E4
T_h	0	2.33E2	5.00E2	8.65E2	1.72E3	1.59E3
M_t	0	4.37E4	8.98E4	1.34E5	1.74E5	1.34E5
Hogging [kNm, kN]						
μ[deg]	0	15	30	45	60	75
λ/L	1	0.966	0.866	0.707	0.500	0.259
M_v	3.76E5	3.64E+5	3.36E5	2.83E5	9.52E4	3.55E4
T_v	1.35E4	1.27E4	1.06E4	8.01E3	4.83E3	4.79E3
M_h	0	7.71E3	1.57E4	2.41E4	2.28E4	1.69E4
T_h	0	6.88E2	1.39E3	2.04E3	1.64E3	1.14E3
M_t	0	4.69E4	8.93E4	1.33E5	1.74E5	1.35E5

Based on classification societies rules [1], [3], [5], [7], the long-term statistical maximum design bending moments, shear forces and torsion moment result from Table 6, function of wave height h_w=7.858 m and L,B,T,c_B ship data (Table 1), with probability of occurrence of $P=10^{-8}$ (20 years period).

For this barge, due to the prismatic hull and uniform mass distribution, the still water bending moments and shear forces are zero.

Table 6. Maximum and rules loads [kNm,kN]

Load	*max.*	*BV*	*DNV*	*GL*	*ABS*
M_v	3.76E+5	4.64E+5	4.64E+5	4.64E+5	4.64E+5
T_v	1.35E+4	1.28E+4	1.28E+4	1.28E+4	1.28E+4
M_h	2.41E+4	3.98E+4	1.55E+5	1.62E+5	5.15E+4
T_h	2.04E+3	1.22E+3	4.98E+3	5.20E+3	1.66E+3
M_t	1.74E+5	1.20E+5	1.27E+5	2.05E+5	2.23E+5

4. CONCLUSIONS

Based on the numerical results from sections 3 for the barge hull, at global strength analysis on 1D-beam model, the following conclusions can be drawn:

1. For h_w > 4m the geometric non-linearities occur, due to the low ship height H = 4 m (Tables 2-4), being significant for the statistical rule-based equivalent quasi-static wave design height of h_w=7.858 m.
2. The transversal bending moment (μ=90 deg.) has maximum values around those of the torsion moment. In this case the wave length is equal to B (Figs.31-32).
3. The maximum vertical bending moments and shear forces are in the case of head (follow) wave μ=0, on sagging and hogging conditions (Table 5), (Figs.17-20).
4. The maximum horizontal bending moments and shear forces are obtained in the case of μ=60 deg. sagging condition and in the case of μ=45 deg. hogging condition (Table 5), (Figs.21-26).
5. The maximum torsion moments are obtained in the case of μ=60 deg., on sagging and hogging conditions (Table 5), (Figs.27-30).
6. The maximum wave loads obtained by direct calculation (Table 5) are in the range of rules maximum design values (Table 6). The horizontal and torsion rules design values are scattered, according to the society.
7. Further study will be focused on various ship types and the use of the equilibrium ship-wave parameters on 3D-FEM models analyses.

Acknowledgements

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