Structural strength evaluation of a 3000 dwt river-barge, under oblique quasi-static design waves

D S Perijoc, L Domnisoru and C M Angheluta
"Dunarea de Jos" University of Galati, Department of Naval Architecture, Domneasca Street 111, 800201, Galati, Romania

E-mail: silviu.perijoc@ugal.ro

Abstract. The present study consists of the 3D-FEM global structural analysis of a typical open-top, double-hull, 3000 DWT inland navigation barge, having 90 m in length. The 3D-FEM model developed to perform the evaluation idealizes the barge structure with high accuracy, average element size being in the range of 50-75 mm. Two loading cases were analyzed, consisting of the ballast and full loading conditions. For the equilibrium floating condition in calm water and oblique design waves, an eigen iterative scheme has been used to generate the input parameters for the 3D-FEM analyzed cases. The push-barge finite element model has been subjected to oblique quasi-static design waves, headings ranging from 0 to 75 degrees. Wave heights considered in the analysis range from 0 to 1.2 m, step 0.3 m, corresponding to the Danube navigation conditions and freeboard limit imposed by the classification societies for inland navigation vessels. Numerical results following the FE analysis have been assessed by the yielding stress ratio, von Mises criterion, and the maximum deformation, thus indicating the structural areas that need to be improved in the design process.

1. Introduction and theoretical background

Performing a 3D-FEM analysis on extended FE models has become nowadays relatively accessible, allowing more improvements to be included in a single design step, resulting in a final product that meets the safety criteria over its entire life cycle [1]. A large range of commercial inland vessels is represented by un-propelled push-barge structures that offer great flexibility for operating companies at a seemingly low maintenance cost.

The slender body of the barge, combined with a long cargo-hold opening and a shallow draught results in a low bending and torsional rigidity. The sum of the above facts can lead to local failure and loss of structural integrity if stress levels are not evaluated properly in the design stage [2]. Since the structure of typical inland push-barge is subjected throughout its life cycle to structural changes due to minor collisions, either ship-to-ship or ship-to-quay, shallow-water groundings, corrosion, fatigue, the strength and stability of the barge structure can be drastically reduced [3].

The present study outlines the 3D-FEM global structural analysis of a typical open-top, double-hull, 3000 dwt inland navigation barge, having the main characteristics presented in table 1. The scantling and structural layout of the river-barge structure has been performed in accordance with the Bureau Veritas classification society principles for inland navigation vessels [4].

The global structural stress assessment of the river barge, considering the still water condition and different wave heights ($H_w$) conditions, as well as multiple heading angles were modeled considering the equivalent quasi-static approach [5-7]. Since the scantling calculation has been performed
considering the maximum wave height of 1.2 m, IN (1.2) [4], a number of 3 intermediate wave heights have been accounted for a better understanding of the structural behavior in waves’ condition.

The above conditions preceding the structural analysis, resulted in a number of 98 loading cases (LC) for wave crest (hogging wave condition) or wave through (sagging wave condition), heading angles in the range of 0-75° (15° steps) and wave heights from 0-1.2 m (0.3 m steps, zero wave height corresponding to still water condition). The numerical analysis involves 3D-FEM barge models and 1D barge models for the wave-barge equilibrium parameters computation and structural response assessment [1].

Table 1. Main characteristics of the 3000 dwt river-barge.

| Characteristic                  | Value   |
|--------------------------------|---------|
| Length overall                 | L_{OA} (m) 90 |
| Breadth                        | B (m) 11 |
| Depth                          | D (m) 4.5 |
| Draught                        | T (m) 3.8 |
| Displacement, Lightship        | D_{light} (t) 507.5 |
| Displacement, Ballast          | D_{ballast} (t) 529.5 |
| Displacement, Full load        | D_{full} (t) 3620.8 |
| Ballast, no trim condition     | M_{ballast} (t) 22 |

2. 3D-model and analysis description

The structural modeling, 3D-FEM model and analysis was developed and performed using Siemens FEMAP program, with Simcenter Nastran solver [8]. The FEA model developed for the current analysis study is presented in figures 1, 2, 3, and 4. The structural model is meshed in the major part of quad plate elements, the use of triangular elements being limited in areas where quad elements quality would be highly affected, thus insuring the aspect ratio within the limits of the Nastran solver (element Jacobian < 0.7). The 3D-FEM model resulted in a number of 2,949,355 elements, 2,886,618 nodes and element size between 50-75 mm, which includes the model from a meshing standpoint, in the fine FEM model category.

Figure 1. 3D-FEM, barge full model.  
Figure 2. 3D-FEM, aft structural detail.  
Figure 3. 3D-FEM, Typical midship structural detail.  
Figure 4. 3D-FEM, Fore structural model detail.
The input data for the iterative program P QSW are represented by the 3D offset line of the ship’s hull and the 1D mass diagram extracted from the 3D-FEM model, which has been previously developed. Based on the above numerical information and wave height, the iterative program computes the equilibrium parameters (tables 3 and 4), requiring no boundary conditions in the determination of the equilibrium floating position by program P_QSW. The governing law of the free surface description in oblique quasi-static waves is presented in equation (1) [5].

\[
\zeta_w(x, y) = T_M + (X - X_F) \theta + (Y - Y_F) t g \phi \pm a_w \cos k \xi
\]

where:
- \(a_w\) - the wave amplitude;
- \(L\) - ship’s length;
- \(X, Y\) - the coordinates referencing the ship’s coordinate system;
- \(X_F, Y_F\) - wave reference medium plane center position.

The resulted equilibrium parameters are implemented in the 3D-FEM model by user functions [5, 6] in order to apply the corresponding pressure loading on the ship’s hull for the different loading conditions (figures 5 and 6). The analysis study has been divided in 4 major study cases, the ballast loading condition hogging and sagging wave profile, and the full loading condition for similar wave profiles. For the ballast loading scenario 22 t of non-structural mass per area (table 1) have been placed in the aft compartment, reproducing the ballast water, in order to simulate the river- barge structure on an even keel floating condition. For the full loading scenario, the cargo mass has been introduced in the 3D-FEM model as non-structural mass on the cargo-hold floor, and a vertical hydrostatic pressure has been introduced on the longitudinal and transversal cargo-hold bulkheads panels (figures 7 and 8).
The boundary conditions were applied in accordance with ships’ classification societies guidelines for global structural analysis of ships with large deck openings (specifically for container ships) and adapted to the river-barges’ structural layout (table 2, figures 9 and 10) [10].

The above loading scenarios, combined with the boundary conditions (table 2) complete the 3D-FEM model, with respect to the shipbuilding classification societies regulations for FE analysis. All the reaction forces components that will be further obtained are to be in a state of equilibrium and are discussed in the next section. The global strength is assessed by yielding ratio and deflection ratio criteria defined in equation (2) [9, 10].

\[
\text{Yield ratio } \frac{\sigma_{Vmax}}{R_{eff}} \leq 1 ; \text{Deflection ratio } \frac{w_{max}}{w_{adm}} \leq 1
\]  

(2)

where: \( R_{eff} = 235 \text{ MPa} \) and \( w_{adm} = 180 \text{ mm} \).

**Table 2.** Boundary conditions, global support [10].

| Location | Direction |
|----------|------------|
| Aft end  | Z          |
| Centerline | Y         |
| Starboard | Z          |
| Fore end | X, Y, Z    |

**Table 3.** Equilibrium parameters, 1D barge model, oblique waves, ballast loading case.

| No. | \( \mu \) (deg.) | \( H_w \) (mm) | \( \theta \) (rad) | \( \phi \) (rad) | \( X_F \) (mm) | \( Y_F \) (mm) | \( T_M \) (mm) | \( No. \) | \( \theta \) (rad) | \( \phi \) (rad) | \( X_F \) (mm) | \( Y_F \) (mm) | \( T_M \) (mm) |
|-----|----------------|----------------|----------------|----------------|----------------|----------------|----------------|---------|----------------|----------------|----------------|----------------|----------------|----------------|
| LC_1 | 0.00001 | 0 | 42170.49 | 0 | 565.27 | - | - | - | - | - |
| LC_2 | 0.000076 | 0 | 42103.59 | 0 | 554.71 | - | - | - | - | - |
| LC_3 | 0.000158 | 0 | 42035.69 | 0 | 542.65 | - | - | - | - | - |
| LC_4 | 0.000243 | 0 | 41967.38 | 0 | 528.00 | - | - | - | - | - |
| LC_5 | 0.000367 | 0 | 41895.14 | 0 | 505.49 | - | - | - | - | - |
| LC_6 | 0.000076 | 0 | 42103.60 | 0 | 554.77 | - | - | - | - | - |
| LC_7 | 0.00158 | 0 | 42035.71 | 0 | 542.78 | - | - | - | - | - |
| LC_8 | 0.00242 | 0 | 41967.43 | 0 | 528.23 | - | - | - | - | - |
| LC_9 | 0.00366 | 0 | 41895.17 | 0 | 505.63 | - | - | - | - | - |
| LC_10 | 0.00074 | 0 | 42103.65 | 0 | 554.98 | - | - | - | - | - |
| LC_11 | 0.00155 | 0 | 42035.82 | 0 | 543.27 | - | - | - | - | - |
| LC_12 | 0.00238 | 0 | 42030.07 | 0 | 528.95 | - | - | - | - | - |
| LC_13 | 0.00365 | 0 | 41895.29 | 0 | 506.13 | - | - | - | - | - |
| LC_14 | 0.00071 | 0 | 42103.77 | 0 | 555.52 | - | - | - | - | - |
| LC_15 | 0.00147 | 0 | 42099.84 | 0 | 543.44 | - | - | - | - | - |
| LC_16 | 0.00227 | 0 | 42031.72 | 0 | 530.93 | - | - | - | - | - |
| LC_17 | 0.00361 | 0 | 41895.61 | 0 | 507.47 | - | - | - | - | - |
| LC_18 | 0.00059 | 0 | 42112.68 | 0 | 551.08 | - | - | - | - | - |
| LC_19 | 0.00125 | 0 | 42101.24 | 0 | 548.02 | - | - | - | - | - |
| LC_20 | 0.00194 | 0 | 42034.3 | 0 | 537.11 | - | - | - | - | - |
| LC_21 | 0.00343 | 0 | 41913.22 | 0 | 512.42 | - | - | - | - | - |
| LC_22 | 0.00009 | 0 | 42170.17 | 0 | 564.25 | - | - | - | - | - |
| LC_23 | 0.00023 | 0 | 42169.81 | 0 | 564.63 | - | - | - | - | - |
| LC_24 | 0.00042 | 0 | 42168.97 | 0 | 565.74 | - | - | - | - | - |
| LC_25 | 0.00074 | 0 | 42142.98 | 0 | 566.37 | - | - | - | - | - |
Table 4. Equilibrium parameters, 1D barge model, oblique waves, full loading case.

| No. | μ  | Hw  | θ (deg) | ϕ (rad) | X_F (mm) | Y_F (mm) | T_M (mm) | No. | θ (rad) | ϕ (rad) | X_F (mm) | Y_F (mm) | T_M (mm) |
|-----|----|-----|---------|---------|----------|----------|----------|-----|---------|---------|----------|----------|----------|
| LC_50 | 0  | 300 | -0.00254 | 44968.32 | 0 | 3798.20 | 0 | LC_74 | -0.00253 | 44968.32 | 0 | 3798.47 |
| LC_51 | 0  | 600 | -0.00255 | 44968.32 | 0 | 3797.93 | 0 | LC_75 | -0.00253 | 44968.32 | 0 | 3798.75 |
| LC_52 | 900 | -0.00256 | 44968.32 | 0 | 3797.65 | 0 | LC_76 | -0.00252 | 44968.32 | 0 | 3799.02 |
| LC_53 | 1200 | -0.00258 | 44968.32 | 0 | 3797.04 | 0 | LC_77 | -0.00251 | 44968.32 | 0 | 3799.29 |
| LC_54 | 300 | -0.00254 | 44968.32 | 0 | 3798.2 | 0 | LC_78 | -0.00251 | 44968.32 | 0 | 3799.75 |
| LC_55 | 600 | -0.00255 | 44968.32 | 0 | 3797.93 | 0 | LC_79 | -0.00252 | 44968.32 | 0 | 3799.74 |
| LC_56 | 900 | -0.00256 | 44968.32 | 0 | 3797.66 | 0 | LC_80 | -0.00252 | 44968.32 | 0 | 3799.92 |
| LC_57 | 1200 | -0.00258 | 44968.32 | 0 | 3797.06 | 0 | LC_81 | -0.00252 | 44968.32 | 0 | 3799.92 |
| LC_58 | 300 | -0.00254 | 44968.32 | 0 | 3798.21 | 0 | LC_82 | -0.00252 | 44968.32 | 0 | 3799.72 |
| LC_59 | 600 | -0.00255 | 44968.32 | 0 | 3797.95 | 0 | LC_83 | -0.00252 | 44968.32 | 0 | 3799.73 |
| LC_60 | 900 | -0.00255 | 44968.32 | 0 | 3797.69 | 0 | LC_84 | -0.00252 | 44968.32 | 0 | 3799.90 |
| LC_61 | 1200 | -0.00258 | 44968.32 | 0 | 3797.06 | 0 | LC_85 | -0.00252 | 44968.32 | 0 | 3799.92 |
| LC_62 | 300 | -0.00254 | 44968.32 | 0 | 3798.24 | 0 | LC_86 | -0.00252 | 44968.32 | 0 | 3799.61 |
| LC_63 | 600 | -0.00255 | 44968.32 | 0 | 3798.00 | 0 | LC_87 | -0.00252 | 44968.32 | 0 | 3799.71 |
| LC_64 | 900 | -0.00255 | 44968.32 | 0 | 3797.77 | 0 | LC_88 | -0.00252 | 44968.32 | 0 | 3799.94 |
| LC_65 | 1200 | -0.00257 | 44968.32 | 0 | 3797.34 | 0 | LC_89 | -0.00252 | 44968.32 | 0 | 3799.92 |
| LC_66 | 300 | -0.00254 | 44968.32 | 0 | 3798.23 | 0 | LC_90 | -0.00252 | 44968.32 | 0 | 3799.92 |
| LC_67 | 600 | -0.00255 | 44968.32 | 0 | 3798.15 | 0 | LC_91 | -0.00252 | 44968.32 | 0 | 3799.74 |
| LC_68 | 900 | -0.00255 | 44968.32 | 0 | 3797.98 | 0 | LC_92 | -0.00252 | 44968.32 | 0 | 3798.80 |
| LC_69 | 1200 | -0.00255 | 44968.32 | 0 | 3797.89 | 0 | LC_93 | -0.00252 | 44968.32 | 0 | 3798.96 |
| LC_70 | 300 | -0.00254 | 44968.32 | 0 | 3798.62 | 0 | LC_94 | -0.00252 | 44968.32 | 0 | 3799.13 |
| LC_71 | 600 | -0.00254 | 44968.32 | 0 | 3798.77 | 0 | LC_95 | -0.00252 | 44968.32 | 0 | 3798.80 |
| LC_72 | 900 | -0.00254 | 44968.32 | 0 | 3798.92 | 0 | LC_96 | -0.00252 | 44968.32 | 0 | 3798.18 |
| LC_73 | 1200 | -0.00248 | 44968.32 | 0 | 3800.05 | 0 | LC_97 | -0.00253 | 44968.32 | 0 | 3798.03 |

Figure 9. 3D-FEM model, Boundary conditions, Aft end.  
Figure 10. 3D-FEM model, Boundary conditions, Fore end.
3. Global strength in barge ballast loading condition

This section presents the results obtained following the analysis of the 3D-FEM model for the river barge in ballast loading condition. The loading cases’ sets are as following:

- LC_1 presents the still water condition results;
- LC_2 – LC_25 presents the oblique quasi-static results for heading angles between $\mu=0-75^\circ$, and hogging wave (wave crest) heights from $H_w=0.3-1.2$ m.
- LC_26 – LC_49 presents the results for similar heading angles and wave heights for the sagging condition (wave through).

Table 5 summarizes the maximum values for the following evaluation parameters: von Mises stress ($\sigma_{VM}$), maximum deflection ($w_{max}$) and the yield stress ratio, which represents the coefficient of the structural usage (2).

| No. | $\mu$ (deg.) | $H_w$ (mm) | $\sigma_{VM}$ (MPa) | $w_{max}$ (mm) | Yield Deflection | No. | $\sigma_{VM}$ (MPa) | $w_{max}$ (mm) | Yield Deflection |
|-----|--------------|------------|---------------------|----------------|-----------------|-----|---------------------|----------------|-----------------|
| LC_1 | 0 | 19.00 | 15.64 | 0.095 | 0.087 | - | - | - | - |
| LC_2 | 300 | 25.57 | 27.13 | 0.128 | 0.151 | LC_26 | 18.54 | 4.051 | 0.093 | 0.023 |
| LC_3 | 600 | 35.56 | 38.24 | 0.178 | 0.212 | LC_27 | 17.80 | 8.213 | 0.089 | 0.046 |
| LC_4 | 900 | 46.23 | 48.75 | 0.231 | 0.271 | LC_28 | 22.67 | 20.229 | 0.114 | 0.112 |
| LC_5 | 1200 | 55.52 | 57.66 | 0.278 | 0.320 | LC_29 | 34.75 | 32.372 | 0.174 | 0.180 |
| LC_6 | 300 | 25.57 | 27.17 | 0.128 | 0.151 | LC_30 | 18.55 | 4.165 | 0.093 | 0.023 |
| LC_7 | 600 | 35.62 | 38.37 | 0.178 | 0.213 | LC_31 | 17.99 | 8.532 | 0.090 | 0.047 |
| LC_8 | 900 | 46.32 | 48.98 | 0.232 | 0.272 | LC_32 | 22.76 | 20.710 | 0.114 | 0.115 |
| LC_9 | 1200 | 55.58 | 57.89 | 0.278 | 0.322 | LC_33 | 34.86 | 32.998 | 0.175 | 0.183 |
| LC_10 | 300 | 25.55 | 27.26 | 0.128 | 0.151 | LC_34 | 18.56 | 4.435 | 0.093 | 0.025 |
| LC_11 | 600 | 35.65 | 38.59 | 0.178 | 0.214 | LC_35 | 17.94 | 8.895 | 0.090 | 0.049 |
| LC_12 | 900 | 46.38 | 49.43 | 0.232 | 0.275 | LC_36 | 22.76 | 21.214 | 0.114 | 0.118 |
| LC_13 | 1200 | 55.51 | 58.33 | 0.278 | 0.324 | LC_37 | 34.86 | 33.647 | 0.175 | 0.187 |
| LC_14 | 300 | 25.48 | 27.39 | 0.128 | 0.151 | LC_38 | 18.41 | 4.917 | 0.092 | 0.027 |
| LC_15 | 600 | 35.62 | 39.09 | 0.178 | 0.217 | LC_39 | 17.66 | 9.361 | 0.088 | 0.052 |
| LC_16 | 900 | 46.36 | 50.25 | 0.232 | 0.279 | LC_40 | 22.58 | 21.820 | 0.113 | 0.121 |
| LC_17 | 1200 | 55.18 | 59.04 | 0.276 | 0.328 | LC_41 | 34.58 | 34.389 | 0.173 | 0.191 |
| LC_18 | 300 | 25.28 | 27.69 | 0.127 | 0.154 | LC_42 | 17.69 | 5.832 | 0.089 | 0.032 |
| LC_19 | 600 | 35.35 | 39.91 | 0.177 | 0.222 | LC_43 | 18.73 | 10.072 | 0.094 | 0.056 |
| LC_20 | 900 | 46.12 | 51.80 | 0.231 | 0.288 | LC_44 | 21.78 | 22.672 | 0.109 | 0.126 |
| LC_21 | 1200 | 54.19 | 58.18 | 0.271 | 0.334 | LC_45 | 32.94 | 34.640 | 0.165 | 0.192 |
| LC_22 | 300 | 26.83 | 27.78 | 0.134 | 0.154 | LC_46 | 19.55 | 8.386 | 0.098 | 0.047 |
| LC_23 | 600 | 36.84 | 40.95 | 0.184 | 0.228 | LC_47 | 23.67 | 11.740 | 0.119 | 0.065 |
| LC_24 | 900 | 48.58 | 54.42 | 0.243 | 0.302 | LC_48 | 27.79 | 23.820 | 0.139 | 0.132 |
| LC_25 | 1200 | 59.96 | 68.06 | 0.300 | 0.378 | LC_49 | 35.18 | 29.323 | 0.176 | 0.163 |

Figures 11-22 present the vertical deflections (mm) and von Mises stress (MPa) over the length $x$(mm) of the 3D-FEM model, ballast loading case and hogging wave considering with heights between 0 and 1.2 m, step 0.3 m.
Figure 11. Vertical deflection (mm) over length \( x_{(mm)} \), \( \mu=0^\circ \), Ballast case, hogging wave.

Figure 12. Vertical deflection (mm) over length \( x_{(mm)} \), \( \mu=15^\circ \). Ballast case, hogging wave.

Figure 13. von Mises stress (MPa) over length \( x_{(mm)} \), \( \mu=0^\circ \). Ballast case, hogging wave.

Figure 14. von Mises stress (MPa) over length \( x_{(mm)} \), \( \mu=15^\circ \). Ballast case, hogging wave.

Figure 15. Vertical deflection (mm) over length \( x_{(mm)} \), \( \mu=30^\circ \). Ballast case, hogging wave.

Figure 16. Vertical deflection (mm) over length \( x_{(mm)} \), \( \mu=45^\circ \). Ballast case, hogging wave.
Figures 23-34 include the results in the form of vertical deflections (mm) and von Mises stress (MPa) over the length $x$(mm) of the 3D-FEM model, ballast loading case and sagging wave with heights between 0 and 1.2 m, step 0.3 m.
Figure 23. Vertical deflection (mm) over length $x$(mm), $\mu=0^\circ$. Ballast case, sagging wave.

Figure 24. Vertical deflection (mm) over length $x$(mm), $\mu=15^\circ$. Ballast case, sagging wave.

Figure 25. von Mises stress (MPa) over length $x$(mm), $\mu=0^\circ$. Ballast case, sagging wave.

Figure 26. von Mises stress (MPa) over length $x$(mm), $\mu=15^\circ$. Ballast case, sagging wave.

Figure 27. Vertical deflection (mm) over length $x$(mm), $\mu=30^\circ$. Ballast case, sagging wave.

Figure 28. Vertical deflection (mm) over length $x$(mm), $\mu=45^\circ$. Ballast case, sagging wave.

Figure 29. von Mises stress (MPa) over length $x$(mm), $\mu=30^\circ$. Ballast case, sagging wave.

Figure 30. von Mises stress (MPa) over length $x$(mm), $\mu=45^\circ$. Ballast case, sagging wave.
From the ballast case global analysis of the river-barge structure in oblique equivalent quasi-static waves the following comments can be formulated:

- Vertical deflections of the hull are consistent in value for all heading angles, with maximum deflection $w_{\text{max}}=68$ mm for the LC_25, hogging wave, corresponding to $\mu=75^\circ$, and $H_w=1.2$ m. The torsional effect with the highest relative displacement between ship sides has been identified for the same loading case (LC_25), with an approximate value of 30 mm.

- The highest value for the von Mises stress of 59.96 MPa corresponds to LC_25. High peaks of local relative stress can be observed in the fore and aft part of the ship, with around 20 MPa difference from the surrounding structural stress values. The high stress peaks indicate hot-spot points in the structure, and the layout of local structure should be updated for a better local distribution of stresses.

4. Global strength in barge full cargo loading condition

The current section presents the results following the analysis of the 3D-FEM river-barge structure in the full cargo loading condition. The loading cases’ sets are below described:

- LC_50 – LC_73 present the results for the equivalent oblique quasi-static design waves in hogging condition, for heading angles between $\mu=0-75^\circ$ and wave heights $H_w=0.3-1.2$ m.
- LC_74 presents the still water results at full cargo loading condition.
- LC_75 – LC_98 present the results following the equivalent oblique quasi-static design waves in sagging conditions, heading angles between $\mu=0-75^\circ$ and wave heights $H_w=0.3-1.2$ m.

Table 6 summarizes the maximum values for the following evaluation parameters: von Mises stress ($\sigma_{\text{VM}}$), maximum deflection ($w_{\text{max}}$) and the yield stress ratio (2).
Table 6. Full loading condition, von Mises stresses and maximum deflections, yield stress and deflection ratios.

| No. | \( \mu \) (deg.) | \( H_w \) (mm) | \( \sigma_{VM} \) (MPa) | \( w \) (mm) | Yield Deflection Ratio | No. | \( \sigma_{VM} \) (MPa) | \( w \) (mm) | Yield Deflection Ratio |
|-----|------------------|----------------|-------------------------|------------|------------------------|-----|-------------------------|------------|------------------------|
| LC_50 | 0                | 300            | 151.20                  | 103.900    | 0.757                  | LC_74 | 123.80                  | 118.49     | 0.620                  |
| LC_51 | 15               | 300            | 151.20                  | 103.970    | 0.758                  | LC_79 | 130.57                  | 133.14     | 0.654                  |
| LC_52 | 30               | 151.20         | 103.900                 | 0.757      | 0.758                  | LC_82 | 158.18                  | 177.07     | 0.792                  |
| LC_53 | 45               | 151.20         | 103.970                 | 0.757      | 0.758                  | LC_92 | 130.59                  | 132.96     | 0.654                  |

Figures 35-46 present the vertical deflections (mm) and von Mises stress (MPa) over the length \( x \) (mm) of the 3D-FEM model in full loading condition and hogging wave considering with heights between 0 and 1.2 m, step 0.3 m.

**Figure 35.** Vertical deflection (mm) over length \( x \) (mm), \( \mu=0^\circ \). Full load case, hogging wave.

**Figure 36.** Vertical deflection (mm) over length \( x \) (mm), \( \mu=15^\circ \). Full load case, hogging wave.
Figure 37. von Mises stress (MPa) over length $x$(mm), $\mu=0^\circ$. Full load case, hogging wave.

Figure 38. von Mises stress (MPa) over length $x$(mm), $\mu=15^\circ$. Full load case, hogging wave.

Figure 39. Vertical deflection (mm) over length $x$(mm), $\mu=30^\circ$. Full load case, hogging wave.

Figure 40. Vertical deflection (mm) over length $x$(mm), $\mu=45^\circ$. Full load case, hogging wave.

Figure 41. von Mises stress (MPa) over length $x$(mm), $\mu=30^\circ$. Full load case, hogging wave.

Figure 42. von Mises stress (MPa) over length $x$(mm), $\mu=45^\circ$. Full load case, hogging wave.

Figure 43. Vertical deflection (mm) over length $x$(mm), $\mu=60^\circ$. Full load case, hogging wave.

Figure 44. Vertical deflection (mm) over length $x$(mm), $\mu=75^\circ$. Full load case, hogging wave.
Figures 45-58 include the results for the vertical deflections (mm) and von Mises stress (MPa) over the length $x$ (mm) of the 3D-FEM model in full loading condition and sagging wave considering with heights between 0 and 1.2 m, step 0.3 m.

Figure 45. von Mises stress (MPa) over length $x$ (mm), $\mu=60^\circ$. Full load case, hogging wave.

Figure 46. von Mises stress (MPa) over length $x$ (mm), $\mu=75^\circ$. Full load case, hogging wave.

Figure 47. Vertical deflection (mm) over length $x$ (mm), $\mu=0^\circ$. Full load case, sagging wave.

Figure 48. Vertical deflection (mm) over length $x$ (mm), $\mu=15^\circ$. Full load case, sagging wave.

Figure 49. von Mises stress (MPa) over length $x$ (mm), $\mu=0^\circ$. Full load case, sagging wave.

Figure 50. von Mises stress (MPa) over length $x$ (mm), $\mu=15^\circ$. Full load case, sagging wave.
Figure 51. Vertical deflection (mm) over length $x$(mm), $\mu=30^\circ$. Full load case, sagging wave.

Figure 52. Vertical deflection (mm) over length $x$(mm), $\mu=45^\circ$. Full load case, sagging wave.

Figure 53. von Mises stress (MPa) over length $x$(mm), $\mu=30^\circ$. Full load case, sagging wave.

Figure 54. von Mises stress (MPa) over length $x$(mm), $\mu=45^\circ$. Full load case, sagging wave.

Figure 55. Vertical deflection (mm) over length $x$(mm), $\mu=60^\circ$. Full load case, sagging wave.

Figure 56. Vertical deflection (mm) over length $x$(mm), $\mu=75^\circ$. Full load case, sagging wave.

Figure 57. von Mises stress (MPa) over length $x$(mm), $\mu=60^\circ$. Full load case, sagging wave.

Figure 58. von Mises stress (MPa) over length $x$(mm), $\mu=75^\circ$. Full load case, sagging wave.
Summarizing the results for the full loading global analysis of the river-barge structure in equivalent oblique quasi-static waves, the following comments can be formulated:

- The vertical deflections of the hull, similarly with the ballast loading condition, are consistent in value for all heading angles, with a maximum deflection of $w_{max}=177.14$ mm for LC_82, sagging wave, heading angle $\mu=15^o$ and wave height $H_w=1.2$ m. The torsional effect having the highest relative displacement between ship sides has been identified in the loading case LC_98 and has an approximate value of 50 mm.

- The highest value registered for the von Mises stress of 158.18 MPa has been identified in the loading case LC_78 and LC_82. The hot-spot areas, where the local relative stress is higher than the surrounding structure, are in the full loading cases present more evenly distributed on the ship’s length, registering higher values in the fore and aft structure. As previously discussed, hot-spot areas have to be redesigned in order to redistribute the local occurring stresses.

5. Conclusions

The current study presents a global structural 3D-FEM analysis of a typical open-top, double-hull barge, having a cargo capacity of 3000 dwt. In the framework of analysis and data interpreting processes, the following conclusions have been obtained:

- The current structural layout of the river-barge does not present any structural risk. The FE evaluation pointed out the structural hot-spots that require updates for a better distribution of the local occurring stresses.

- The maximum calculated deflections are close to the limitations that the shipbuilding classification societies can inflict on ships’ hull structures with large deck openings. The deflection ratio coefficient (2) is maximum for LC_82 ($\mu=15^o$, $H_w=1.2$m, sagging wave), with a value of $DR=0.984$.

- The maximum structural usage, represented in the form of the yielding stress ratio coefficient (2), has been identified for two full cargo loading cases, LC_78 ($\mu=0^o$, $H_w=1.2$m, sagging wave) and LC_82 ($\mu=15^o$, $H_w=1.2$m, sagging wave), being equal to $YR=0.792$. An almost 80% structural usage has been registered for the 3000 dwt barge hull that has been dimensioned by Bureau Veritas Rules [4] for inland vessels to withstand a maximum wave design height of $H_w=1.2$m.

- Further investigations have to be performed after the structural update of the identified hot-spot areas, completed by other strength criteria [4].

6. References

[1] Domnisoru L 2015 Numerical approach for global ship strength analysis based in 1D-Beam model, under oblique equivalent quasi-static wave loads Galati University Press: Shipbuilding 38 27–36.

[2] Savin M, Presura A, Chirica I 2019 Environmental protection using structural analysis of ships SeaConf, IOP Conference Series: Journal of Physics (1297) Article 012015.

[3] Meinken A and Schlüter H J 2002 Collapse behaviour of a push-barge Marine Structures 15(2) 193–209.

[4] BV 2020 Rules for the classification of inland navigation vessels: Part B - Hull design and construction (Paris: Bureau Veritas).

[5] Domnisoru L 2017 Special chapters on ship’s structures analysis. Applications (Galati: The University Foundation „Dunarea de Jos” Publishing House).

[6] Domnisoru L 2019 Strength assessment in oblique design waves for a Europe B2 1740T river barge type Galati University Press: Shipbuilding 41 23–28.

[7] Domnisoru L 2020 On the strength assessment of a small liquid petroleum gas carrier in oblique waves by 1D and 3D-FEM analyses ModTech, IOP Conference Series: Materials Science and Engineering (916) Article 012027.
[8] FNN 2020 *Femap/NX Nastran Users’ Manual. Academic License* (Siemens PLM Software Inc.).

[9] Costache M, Jagite G 2014 Global Strength Analysis in Head Waves, for an Offshore Support Vessel *Asian Journal of Applied Science and Engineering* 3(8) 73-88.

[10] GL 2014 *Rules for Classification and Construction Chapter V-1-1: Guidelines for Global Strength Analysis of Container Ships* (Hamburg: Germanischer Lloyd).

**Acknowledgements**

The authors wish to express their gratitude towards the Research Centre of the Naval Architecture Faculty and Doctoral School of Mechanical and Industrial Engineering, at “Dunarea de Jos” University of Galati.