International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Vol. XVII, No. 3 / 2025
https://doi.org/ 10.54684/ijmmt.2025.17.3.36

ON THE STRUCTURAL DESIGN CONCEPT OF A RIVER-COASTAL RESEARCH-PASSENGER SHIP ASSESSMENT UNDER OBLIQUE WAVE SCENARIOS

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Abstract: Selected study focuses on the structural evaluation of a design concept for a river-coastal research-passenger ship, with a maximum length of 44.5 m, by parametric 3D strength analysis and non-linear equilibrium algorithm, under oblique wave scenarios. According to the operation cases, two relevant loading cases are selected, corresponding to the ship's draught minimum of 1.5 m and maximum of 1.7 m. The ship is for the navigation area corresponding to the river Danube and the Romanian coastal waterway, with a maximum 2.5 m wave height. By design, two constructive versions for the structural elements are analyzed, having the thickness standard 5-7 mm and enhanced 6-8 mm. This study leads to practical results by the strength assessment analysis of the research-passenger ship structure, delivering the polar safety operational limits diagram, and pointing out the significant influence of the selected constructive versions for the ship's design concept capabilities on the navigation area.
Key words: research-passenger ship, oblique equivalent waves, strength assessment criteria, river-coastal navigation.

1. INTRODUCTION

The design procedures for a new ship involve complex structural and hydrodynamic assessments based on the shipbuilding rules criteria [1], [2], [3]. For the design concept of a ship, either maritime or river-coastal type, the structural evaluation involves an integrated strength analysis methodology by 3D detailed models, under oblique wave scenarios, with equivalent quasi-static formulation [4], [5], [6]. The strength methodology includes the ship-wave equilibrium position computation for the design of oblique wave scenarios, based on a non-linear procedure by an equivalent ship hull model, and the strength assessment by a structural 3D model with the specific limit criteria [7],[8],[9] (section 2).

For this study a research-passenger ship is submitted for the structural design concept assessment, with two constructive versions, based on a preliminary evaluation of the ship hull type and resistance for body shape selection [10], with a modern structural layout, with a double engine room, double bottom, main, upper, and top decks, having onboard several laboratories, accommodation rooms, technical and social rooms (section 3). The first constructive version of the design has a standard thickness of the structural elements, based mainly on the requirements for inland Danube navigation ships [11]. To extend the navigation class up to coastal C(2.5), for the research-passenger ship, a second enhanced constructive version design is developed, with an increase of 1-2 mm of the structural elements thickness. Regarding loading conditions related to the onboard group of masses, two relevant conditions are selected corresponding to the minimum draught and the maximum draught, imposed by the river depth restrictions, and also to ensure the safety freeboard for the river-coastal by design navigation area.

For the two constructive versions of the research-passenger ship design concept the ship-wave equilibrium position is obtained by the new version of eigen program *EQSW.v5* [12], covering the whole river class up to IN(2.0), and coastal up to class C(2.5), including also the evaluation of the freeboard criterion linked to oblique wave conditions and the design at the aft and fore peak sides of the parapet elements (section 4).

The strength assessment of the research-passenger ship design concept, in river-coastal oblique wave conditions, involves a 3D-FEM model [13], [14] of the ship and wave pressure loads correlated to the equilibrium parameters, submitted to an equivalent quasi-static numerical analysis by *Femap/NX Nastran* [15] program and specific user-subroutines for pre-processing of the onboard masses and wave pressure, and also for in the post-processing steps of the results. The standard structural version (section 5) and the enhanced structural version (section 6) of the research-passenger ship design concept in oblique waves are assessed by admissible von Mises stress, vertical deflection, and buckling criteria, delivering the polar strength safety operational limits diagrams (section 7). The integrated strength analysis methodology provides the research passenger ship with the basis for a rational design concept selection linked to the desired river and coastal navigation capabilities.

2. THE RESEARCH-PASSENGER SHIP MAIN ANALYSIS STEPS FOR THE OPERATIONAL CAPABILITIES ASSESSMENT BY STRENGTH CRITERIA

The research-passenger ship (*RPS*) assessment by strength criteria requires an integrated methodology capable of ensuring accuracy for each step based on the logical scheme from Figure 1.

(1) Research passenger ship (*RPS*) design concept data definition for the river-coastal navigation conditions: SW, IN(0.6), IN(1.2), IN(2.0) and C(2.5).

↓

(2) Geometrical models of the research passenger ship (CAD) for structural analyses:
- 1D – equivalent stations and ship girder;
- 3D – detailed CAD model of the hull and superstructure, with surface objects.

↓

(3) Structural models of the research passenger ship (FEM) for global-local strength:
- 1D – equivalent stations and ship beam elements model;
- 3D – detailed FEM model of the *RPS* ship, with triangular shell elements;
- specific boundary conditions for 3D models full developed over the structure.

↓

(4) Research passenger ship (*RPS*) equivalent quasi-static equilibrium in oblique waves, by a non-linear approach, with the next parameters:
- sinkage (d_m) – referenced along the ship's vertical axis;
- trim angle (θ) – referenced around the ship's transversal axis;
- heel angle (φ) – referenced around the ship's longitudinal axis.

↓

(5) Research passenger ship (*RPS*) structural analyses, by 3D model, function to:
- the loading cases, with draughts T_{min}=1.5m (*RPS1*) and T_{max}=1.7 m (*RSP2*);
- the constructive version, with thicknesses t=5÷7 mm (*T1*) and t=6÷8 mm (*T2*);
- wave height in the range h_w = 0÷ 2.5 m (0.2);
- ship – wave encountering angle in the range μ = 0÷ 75 (90) (360) deg;
- oblique wave pressure quasi-static formulation for the equilibrium parameters:

$$p_{wave}(x,y)=\rho_w\cdot g\cdot[d_m+z_\theta(x)+z_\varphi(y)+z_w(x,y)];\ \ x\in[0,L] \text{ on the hull surface}$$

$$z_\theta(x)=(x-x_F)\cdot\theta\,;\ \ z_\varphi(y)=(y-y_F)\cdot tg(\varphi)\,;\ \ \varpi(x,y)=x\cdot\cos\mu+y\cdot\sin\mu\,;\ \lambda=L\cdot\cos\mu\,;$$

$$a_w=h_w/2\,;\ \ k=2\pi/\lambda\,;\ \ z_w(x,y)=\pm a_w\cdot\cos[k\cdot\varpi(x,y)]\,;\ y\in[-B/2,+B/2]$$

where: p_{wave} wave pressure; ρ_w water density; g gravity acceleration; d_m sinkage; θ, φ trim and heel angles; x, y, z coordinates in ship's axes system; L, B, T ship's length, breadth, and draught; x_F, y_F centre position of the wave's mid plane; μ ship- wave encountering angle; h_w, a_w, λ, k wave height, amplitude, length and number.

↓

(6) Research passenger ship (*RPS*) operational capabilities assessment (h_{wlimit} polar diagrams) in oblique waves, by several strength criteria:
- the von Mises stress (σ_{vMmax});
- the vertical deflection (w_{max});
- the bukling factor (B_{min});
- the freeboard (FB_{min}).

Fig. 1. Research-passenger ship (*RPS*) logical scheme for operational capabilities assessment by strength criteria.

For the initial step (figure 1, module 1), the research-passenger ship design concept is defined at the level of the shape and general layout (figure 2), by previous studies [10] concerning the main dimensions, hull type, and ship's resistance according to the ship's foreseen activities, like research and accommodation for the personal, and also the navigation operational conditions, like combining river and coastal class up to C(2.5) (table 1).
The second step (figure 1, module 2), based on the preliminary design concept of the research-passenger ship, includes the refinement of the ship's project by developing the 3D detailed CAD model of the hull and superstructure, with surface objects (figure 2), and also the 1D equivalent stations and ship girder model, delivering the geometrical models of the ship (CAD) for the structural analyses, by *Femap* [15] design modules.
Based on the CAD models, the third step (figure 1, module 3), continues with the development of the structural models of the research-passenger ship (FEM) for global-local strength, by *Femap* [15] meshing modules with shell elements [13], [14], including the 3D detailed FEM model of the ship, onboard masses and the boundary conditions (figure 2), and also the 1D equivalent stations and ship beam elements model.
In the fourth step (Figure 1, module 4), the research-passenger ship equilibrium position parameters (sinkage, trim angle, and heel angle) are computed for all the oblique wave scenarios, based on a non-linear procedure by the 1D equivalent ship hull model, implemented in the new version of *EQSW.v5* eigen code [12], enhanced in terms of convergence time, to better deal with the slender ship's shape all over the body (Figure 2).
The fifth step (figure 1, module 5), is the core for the strength of the research-passenger ship design concept evaluation by the 3D detailed model, by *NX/Nastran* [15] solver, for two constructive versions, relevant loading cases, corresponding to the minimum and maximum of the ship's draught, and the complete set of the oblique wave conditions for river up to class IN(2.0) and coastal up to class C(2.5) navigation areas. This step combines the 3D model from module 3 with the equilibrium parameters from module 4, for both ship constructive versions, and loading cases, with the design oblique waves' pressure by a quasi-static formulation, and user-defined *Femap* [15] macro-codes.
The last step (Figure 1, module 6) includes the research-passenger ship design concept assessment by the following strength criteria: admissible stress (von Mises) to the material yielding limit, buckling, and vertical deflection admissible limits. Also, the freeboard criterion is evaluated, being foreseen by the design of a proper parapet height so that the main deck is preserved dry for any oblique wave condition (Figure 3). Combining the strength criteria results, for the practical purpose, this integrated research-passenger ship assessment delivers the operational capabilities limits (polar diagrams) in oblique waves [3], [4], on the two relevant loading cases, and also the structural capabilities comparison of the two ships' constructive versions (figure 26, table 8).

3. THE RESEARCH-PASSENGER SHIP MAIN DATA AND STRUCTURAL MODEL

The selection of the hull type of the ship concept requires a preliminary study [10] for a very simplified design, with prismatic shape and vertical sides, without superstructure, for two constructive versions: mono-hull and catamaran. Based on strength and motion criteria specific to the research-passenger operations, the initial study [10] leads to the best selection of the mono-hull type for the ship design concept.
The research-passenger ship (*RPS*) design concept, starting from the preliminary version [10], is enhanced with a slender shape and a modern structural layout, with a double engine room, double bottom, main, upper, and top decks, so several laboratories, accommodation rooms, technical and social rooms are available onboard (Figure 2.a-d). The ship resistance prediction [10] linked to the final slender shape (Figure 2.b) leads to the main data of the ship design concept from Table 1. To extend the navigation area for the river-coastal conditions, with a maximum wave height of 2.5 m, at the fore and aft peak, the ship's parapet edge height is properly selected, so the freeboard criterion should be satisfied by design. Also, related to the extended Romanian coastal navigation area, two constructive versions for the hull structural elements are considered for the ship's concept, first with standard 5-7 mm (*T1*) and second with enhanced 6-8 mm (*T2*) thickness, which are submitted to a detailed parametric comparative study in terms of oblique waves by design conditions.
According to the onboard mass groups, as the specific supplies, various research equipment, passengers, and ballast, for the research-passenger ship, two limit loading cases are selected, corresponding to the ship's draught minimum of 1.5 m (*RPS1*) and draught maximum of 1.7 m (*RPS2*). Although the steel structure mass for the enhanced version is increased by 30.075 t compared to the standard version, the reference limit draught values, 1.5 and 1.7 m, are preserved for both loading cases, with a deadweight range 42.975 t up to 140.075 t, ensuring the capability for various onboard loading masses placement.
The strength assessment of the research-passenger ship design concept by the methodology from section 2, requires the development of a 1D equivalent stations and ship beam elements model for the first step of the analysis, to compute the ship-design wave equilibrium position for all the oblique wave scenarios by a non-linear procedure (figure 1, modules 2, 3, 4), and a 3D-FEM model (figure 2. c, d), with triangle shell (membrane and

thick plate formulation) elements [13], [14], including the hull and the whole superstructure, with the relevant structural details, with medium meshing size of 200 mm, for the second step of the analysis (figure 1, modules 2, 3, 5). The whole structure is made of standard steel grade A [11]. Specific boundary conditions (Figure 2.b) for 3D models fully developed over the structure are considered according to the design rules [1], [2], [3]. On the 3D model, for each ship-oblique wave condition, the equivalent wave pressure is applied on the immerged hull shell (figure 1, module 5), as figure 3 exemplifies for case T_{max}=1.7 m, h_w=2 m, μ=45 deg (sagging & hogging).
For the river-coastal research-passenger ship, with both constructive versions and the two limit loading cases, by the methodology from section 2 (figure 1), the next numerical analyses are focused on the strength assessment of the ship's design concept (sections 4-7).

Table 1. Research-passenger river-coastal ship (*RPS*) main data [10].

Main data		*FEM model data*		*Cases*	*RSP1-T1*	*RSP1-T2*	*RSP2-T1*	*RSP2-T2*	*Admissible criteria*	
L_{max} (m)	44.50	EL_{3D}	363801	T(m)	*min*		*max*		*von Mises stress*	
B_{max} (m)	9.00	ND_{3D}	169305	*mid, aft, fore*	1.5		1.7		σ_{vMadm} (MPa)	175
H_{mid} (m)	3.00	EL_{size}(mm)	200.00	Δ(t)	434.725		501.750		*vertical deflection*	
H_{fore} (m)	3.45	EL_{1D}	229	x_G(m)	23.359		23.177		w_{adm}(m)	0.089
H_{aft} (m)	3.10	ND_{1D}	230	y_G(m)	0.000		0.000		*buckling*	
Steel grade A		*Wave data*		z_G(m)	3.120		3.036		B_{min} (-)	1.5
R_{eH} (MPa)	235	h_w (m)	0÷2.5	t(mm)	5÷7	6÷8	5÷7	6÷8	*freeboard*	
ρ_{steel} (t/m^3)	7.85	δh_w (m)	0.2	M_{steel}(t)	150.373	180.448	150.373	180.448	FB_{min} (m)	0.000
E (kPa)	2.1E+8	μ (deg)	0÷75(360)	Δ_{light}(t)	361.675	391.750	361.675	391.750	*Navigation areas (extended)*	
ν (-)	0.3	$\delta\mu$(deg)	15	Dw(t)	73.050	42.975	140.075	110.000	IN(0.6), IN(1.2), IN(2.0), C(2.5)	

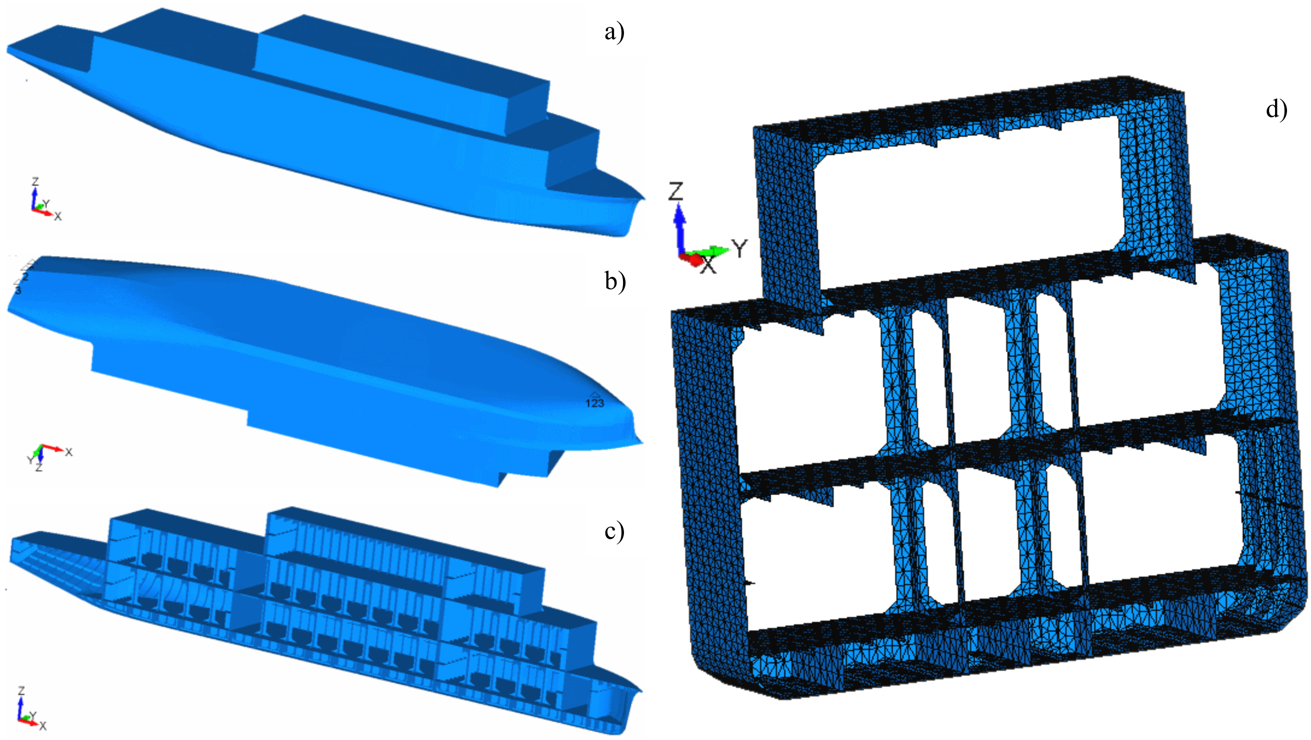

Fig. 2. Research-passenger ship, (a) 3D view, (b) bottom view and boundary conditions, (c) and (d) FEM structural details.

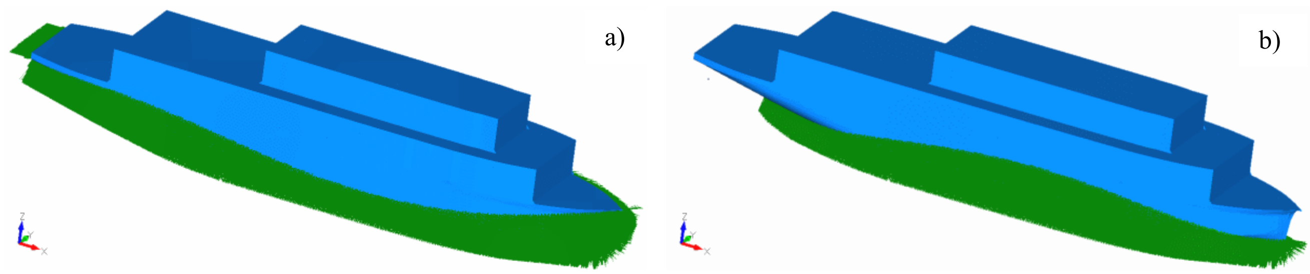

Fig. 3. Research-passenger ship, waves pressure, T_{max}=1.7 m, h_w=2 m, μ=45 deg (a) sagg. and (b) hogg.

4. THE RESEARCH-PASSENGER SHIP EQUILIBRIUM IN OBLIQUE WAVES AND FREEBOARD CRITERION EVALUATION

For the first loading case of the research-passenger ship, with minimum draught T_{min}=1.5 m (*RPS1-T1, T2*), by the 1D equivalent stations and ship beam elements model and the non-linear approach (figure 1, module 4) [12], the equivalent quasi-static equilibrium of the ship in oblique waves is computed, for the selected navigation conditions: h_w=0÷2.5 m (δh_w=0.2 m), μ=0÷180 deg (μ=15 deg), sagging and hogging waves. Table 2 presents a selection of the equilibrium parameters for the first loading case (*RSP1*).
Based on the equilibrium parameters results, the freeboard criterion is in the limits for any of the oblique wave conditions (Figure 4), with the minimum value of FB_{min}=0.284 m > 0 for case h_w=2.5 m (μ=0 deg, sagging). Due to the slender shape of the research-passenger ship all over the length (figure 2.b), the equilibrium parameters are recording noticeable variations: d_m = 1.173÷1.670 m, θ = -0.00156÷0.01254 rad, and φ = -0.01103÷0.00950 rad.

Table 2. Research-passenger ship, minimum draught (T_{min}=1.5m) case (*RPS1*), equilibrium in oblique waves and freeboard.

h_w(m)	T_{min}=1.5m	Sagging Oblique Wave						Hogging Oblique Wave					
	μ(deg)	0	15	30	45	60	75(90)	0	15	30	45	60	75(90)
		180	165	150	135	120	105	180	165	150	135	120	105
0	d_m(m)			1.500						1.500			
	θ(rad)			0.0						0.0			
	φ(rad)			0.0						0.0			
	x_f(m)			21.916						21.916			
	y_f(m)			0.0						0.0			
	FB_{min}(m)			1.500						1.500			
0.6	d_m(m)	1.549	1.548	1.544	1.534	1.508	1.465	1.440	1.441	1.445	1.456	1.48535	1.529
	θ(rad)	0.00142	0.00139	0.00131	0.00110	0.00059	-0.00055	0.00025	0.00026	0.00027	0.00031	0.00041	0.00110
	φ(rad)	0.00000	0.00064	0.00133	0.00206	0.00251	-0.00019	0.00000	-0.00021	-0.00046	-0.00084	-0.00158	-0.00150
	x_f(m)	21.869	21.871	21.876	21.888	21.925	22.063	22.061	22.058	22.049	22.027	21.967	21.802
	y_f(m)	0.0000	0.0006	0.0012	0.0018	0.0022	-0.0007	0.0000	-0.0003	-0.0004	-0.0007	-0.0014	-0.0013
	FB_{min}(m)	1.282	1.284	1.299	1.339	1.458	1.319	1.260	1.262	1.272	1.298	1.371	1.373
1.2	d_m(m)	1.591	1.589	1.581	1.563	1.537	1.440	1.367	1.370	1.379	1.400	1.430	1.537
	θ(rad)	0.00393	0.00385	0.00358	0.00298	0.00165	-0.00047	0.00235	0.00235	0.00235	0.00235	0.00227	0.00263
	φ(rad)	0.00000	0.00156	0.00319	0.00479	0.00521	-0.00214	0.00000	0.00012	0.00020	0.00004	-0.00127	-0.00460
	x_f(m)	21.887	21.888	21.892	21.906	21.963	22.247	22.312	22.306	22.287	22.238	22.103	21.714
	y_f(m)	0.0000	0.0013	0.0027	0.0041	0.0045	-0.0019	0.0000	0.0001	0.0002	0.0000	-0.0011	-0.0039
	FB_{min}(m)	0.995	0.997	1.023	1.098	1.304	1.120	1.033	1.038	1.060	1.116	1.292	1.169
2.0	d_m(m)	1.640	1.637	1.626	1.597	1.567	1.447	1.253	1.257	1.271	1.306	1.341	1.484
	θ(rad)	0.00806	0.00789	0.00728	0.00597	0.00343	-0.00070	0.00771	0.00772	0.00776	0.00781	0.00759	0.00279
	φ(rad)	0.00000	0.00294	0.00595	0.00870	0.00814	-0.00744	0.00000	0.00143	0.00291	0.00427	0.00360	-0.00871
	x_f(m)	21.957	21.956	21.955	21.961	22.038	22.559	22.785	22.778	22.749	22.674	22.448	21.497
	y_f(m)	0.0000	0.0025	0.0050	0.0074	0.0070	-0.0068	0.0000	0.0013	0.0026	0.0038	0.0031	-0.0073
	FB_{min}(m)	0.628	0.637	0.674	0.790	1.119	0.802	0.751	0.755	0.786	0.873	1.191	0.919
2.5	d_m(m)	1.670	1.664	1.650	1.614	1.577	1.462	1.173	1.177	1.194	1.237	1.280	1.471
	θ(rad)	0.01094	0.01042	0.00961	0.00786	0.00468	-0.00156	0.01230	0.01232	0.01239	0.01254	0.01228	0.00179
	φ(rad)	0.00000	0.00375	0.00757	0.01089	0.00912	-0.00301	0.00000	0.00264	0.00544	0.00841	0.00950	-0.01103
	x_f(m)	22.014	22.005	22.001	22.003	22.099	22.477	23.145	23.136	23.102	23.016	22.739	21.319
	y_f(m)	0.0000	0.0031	0.0064	0.0092	0.0078	-0.0027	0.0000	0.0025	0.0051	0.0077	0.0083	-0.0091
	FB_{min}(m)	**0.284**	0.303	0.383	0.604	1.019	0.627	0.588	0.590	0.625	0.729	1.117	0.721

For the second loading case of the river-coastal ship, with maximum draught T_{max}=1.7 m (*RPS2-T1, T2*), by the 1D equivalent stations and ship beam elements model, using the non-linear approach with three parameters (figure 1, module 4) [12], the ship under oblique waves quasi-static equivalent equilibrium results, covering the SW, IN(0.6), IN(1.2), IN(2.0), C(2.5) navigation areas with h_w=0÷2.5 m (δh_w=0.2 m), μ=0÷180 deg (μ=15 deg), and sagging – hogging conditions. Table 3 presents, for the second loading case (*RSP2*) a selection of the three equilibrium parameters (sinkage, trim, and heel angles) obtained by the non-linear procedure implemented in the enhanced new version of *EQSW.v5* [12] own program.

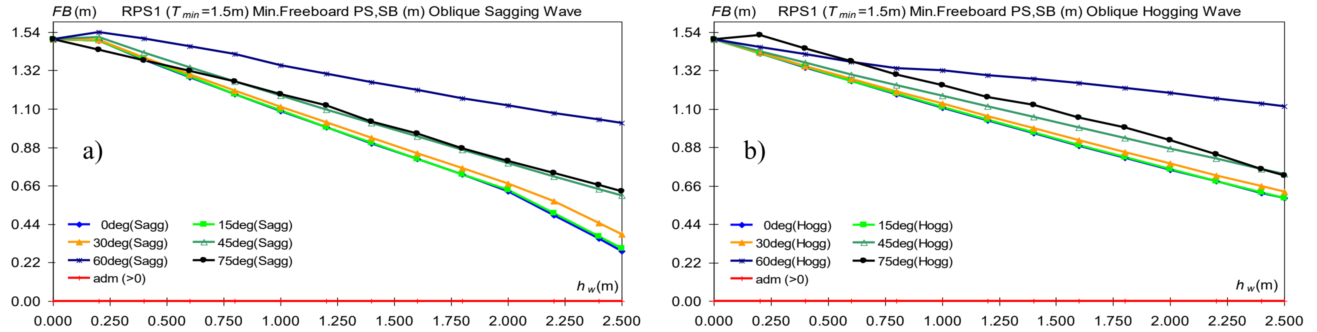

Fig. 4. Research-passenger ship, minimum draught (T_{min}=1.5m) case (*RPS1*), min. freeboard criterion, (a) sagg. and (b) hogg.

Based on the equilibrium parameters results (Table 3), with also the parapet structure at the fore and aft peak (Table 1), the freeboard criterion is on the limit for wave case h_w=2.5 m (μ=15 deg, sagging), FB_{min}=0.014 m > 0, and without restrictions for any oblique wave conditions (Figure 5). Similar to the first loading case, the three equilibrium parameters present noticeable changes due to the river-coastal ship shape geometric non-linearities: d_m = 1.404÷1.866 m, θ = -0.00210÷0.01385 rad, and φ = -0.01387÷0.01241 rad.

Table 3. Research-passenger ship, maximum draught (T_{max}=1.7m) case (*RPS2*), equilibrium in oblique waves and freeboard.

h_w(m)	T_{max}=1.7m	Sagging Oblique Wave						Hogging Oblique Wave					
	μ(deg)	0	15	30	45	60	75(90)	0	15	30	45	60	75(90)
		180	165	150	135	120	105	180	165	150	135	120	105
0	d_m(m)			1.700						1.700			
	θ(rad)			0.0						0.0			
	φ(rad)			0.0						0.0			
	x_f(m)			21.484						21.484			
	y_f(m)			0.0						0.0			
	FB_{min}(m)			1.300						1.300			
0.6	d_m(m)	1.743	1.742	1.738	1.730	1.705	1.667	1.648	1.649	1.653	1.663	1.68991	1.729
	θ(rad)	0.00221	0.00217	0.00204	0.00171	0.00089	-0.00128	-0.00092	-0.00091	-0.00085	-0.00070	-0.00028	0.00165
	φ(rad)	0.00000	0.00077	0.00160	0.00253	0.00329	0.00044	0.00000	-0.00043	-0.00092	-0.00159	-0.00266	-0.00188
	x_f(m)	21.487	21.487	21.489	21.494	21.509	21.576	21.552	21.550	21.544	21.530	21.493	21.417
	y_f(m)	0.0000	0.0009	0.0014	0.0021	0.0028	0.0007	0.0000	-0.0007	-0.0009	-0.0014	-0.0023	-0.0016
	FB_{min}(m)	1.105	1.106	1.118	1.154	1.263	1.117	1.053	1.054	1.063	1.089	1.162	1.183
1.2	d_m(m)	1.780	1.779	1.772	1.756	1.732	1.643	1.584	1.586	1.595	1.615	1.643	1.834
	θ(rad)	0.00514	0.00504	0.00470	0.00388	0.00196	-0.00210	-0.00016	-0.00014	-0.00006	0.00011	0.00060	0.00358
	φ(rad)	0.00000	0.00173	0.00358	0.00554	0.00669	-0.00064	0.00000	-0.00039	-0.00089	-0.00175	-0.00387	-0.00508
	x_f(m)	21.529	21.528	21.527	21.528	21.545	21.702	21.722	21.718	21.703	21.665	21.567	21.367
	y_f(m)	0.0000	0.0015	0.0030	0.0046	0.0057	-0.0006	0.0000	-0.0003	-0.0008	-0.0015	-0.0033	-0.0042
	FB_{min}(m)	0.830	0.831	0.853	0.920	1.108	0.924	0.816	0.821	0.841	0.894	1.067	0.998
2.0	d_m(m)	1.825	1.821	1.811	1.785	1.759	1.649	1.480	1.483	1.497	1.531	1.565	1.694
	θ(rad)	0.00939	0.00946	0.00872	0.00714	0.00357	-0.00124	0.00343	0.00346	0.00358	0.00382	0.00424	0.00457
	φ(rad)	0.00000	0.00332	0.00631	0.00873	0.01047	-0.00475	0.00000	0.00046	0.00084	0.00083	-0.00171	0.00380
	x_f(m)	21.612	21.622	21.612	21.601	21.609	21.984	22.110	22.103	22.078	22.012	21.819	21.230
	y_f(m)	0.0000	0.0000	0.0052	0.0073	0.0088	-0.0042	0.0000	0.0004	0.0007	0.0007	-0.0015	0.0031
	FB_{min}(m)	0.410	0.412	0.477	0.625	0.918	0.612	0.520	0.528	0.565	0.659	0.972	0.769
2.5	d_m(m)	1.866	1.837	1.835	1.803	1.770	1.630	1.404	1.409	1.426	1.468	1.509	1.691
	θ(rad)	0.01385	0.00000	0.01080	0.00880	0.00450	-0.00168	0.00692	0.00697	0.00714	0.00750	0.00813	0.00589
	φ(rad)	0.00000	0.00396	0.00789	0.01198	0.01241	-0.00815	0.00000	0.00141	0.00283	0.00400	0.00235	-0.01387
	x_f(m)	21.715	21.237	21.651	21.634	21.653	22.131	22.423	22.415	22.386	22.309	22.076	21.123
	y_f(m)	0.0000	0.0033	0.0065	0.0099	0.0105	-0.0073	0.0000	0.0012	0.0025	0.0034	0.0020	-0.0108
	FB_{min}(m)	0.018	**0.014**	0.166	0.386	0.806	0.437	0.347	0.354	0.396	0.509	0.912	0.574

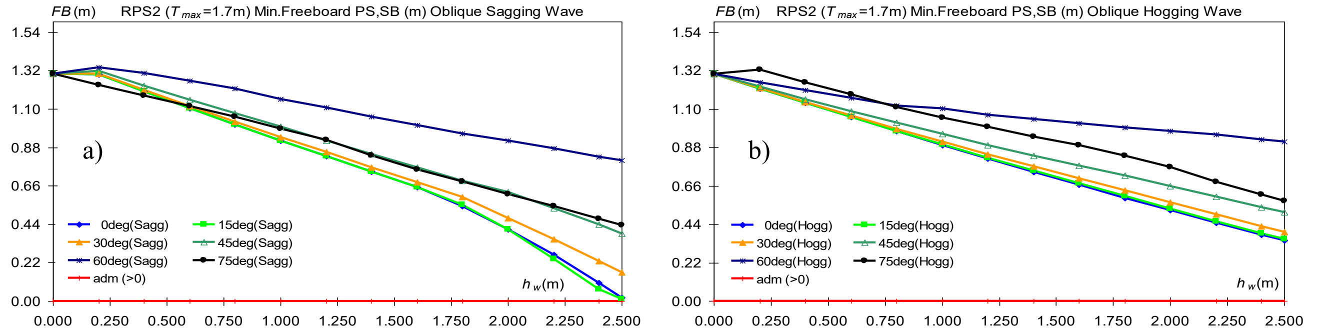

Fig. 5. Research-passenger ship, maximum draught (T_{max}=1.7m) case (*RPS2*), min. freeboard criterion, (a) sagg. and (b) hogg.

5. THE STRENGTH EVALUATION OF THE RESEARCH-PASSENGER SHIP STRUCTURE FOR THE MINIMUM DRAUGHT CASE

For the first loading case (T_{min}=1.5 m), the strength evaluation of the two constructive versions of the research-passenger ship involves the structural analyses (figure 1, modules 5, 6) by the detailed hull and superstructure 3D-FEM model (figure 2), developed with *Femap/NX Nastran* application [15], and the user macro-subroutines for the equivalent wave pressure idealization on the ship's shell, with the ship's equilibrium parameters related to the minim draught case and all by design oblique waves range (table 2).

Table 4 presents a selection of the strength criteria assessment for the standard constructive version and the first loading case (*RPS1-T1*), on the relevant navigation conditions, SW, IN(0.6), IN(1.2), IN(2.0), and C(2.5).

The stress criterion (figures 6.a.b, 10.a, table 4, *RPS1-T1*) records no restrictions for any wave conditions, the maximum von Mises stress values being in the range σ_{vM} = 40.409÷139.976 < 175 MPa. The maximum stress values result at the aft peak structure corresponding to the engine room compartments, where a single bottom structure is provided, and at the transversal bulkhead sections.

The vertical deflection criterion (figures 7.a.b, 9.b, 10.b, table 4, *RPS1-T1*) records no restrictions under any wave state, the maximum values being in the range w = 0.0014÷0.0079 < 0.089 m. The local deformations present a uniform dispersion around the averaged global vertical deflection, due to the proper layout of the longitudinal strength elements over the ship's panels.

The buckling criterion (figures 8.a.b, 9.a, table 4, *RPS1-T1*) has no restriction for hogging oblique waves (B>1.5), and operational restrictions for sagging oblique waves for the navigation conditions: C(2.2 m; 60 deg), C(2.4 m; 30÷60 deg), and C(2.5 m; 15÷60 deg), with values B = 1.329÷1.490 < 1.5. The structural buckling collapse is recorded at the joint of the upper deck and transversal bulkheads, in sagging wave conditions. Due to the restrictions by buckling criterion, the operational area of the research-passenger ship with standard structure (*RPS1-T1*) must be restricted to the coastal class ≈ C(2.2), being unsafe for extreme coastal case C(2.5).

Table 4. Research-passenger ship, minimum draught (T_{min}=1.5m) case (*RPS1-T1*) standard structure, strength criteria.

h_w(m)	T_{min}=1.5m	Sagging Oblique Wave						Hogging Oblique Wave					
	μ(deg)	0	15	30	45	60	75(90)	0	15	30	45	60	75(90)
		180	165	150	135	120	105(270)	180	165	150	135	120	105(270)
0	σ_{vM}(MPa)			40.409						40.409			
	%adm			23.09%						23.09%			
	B(-)			3.802						3.802			
	limit			>1.5						>1.5			
	w(m)			-0.0018						0.0014			
	%adm			2.01%						1.62%			
0.6	σ_{vM}(MPa)	55.128	54.968	54.260	52.512	47.562	44.072	48.138	48.243	48.434	48.801	49.878	49.076
	%adm	31.50%	31.41%	31.01%	30.01%	27.18%	25.18%	27.51%	27.57%	27.68%	27.89%	28.50%	28.04%
	B(-)	3.888	3.885	3.878	3.869	3.640	3.921	3.663	3.661	3.657	3.647	3.619	3.667
	limit	>1.5	>1.5	>1.5	>1.5	>1.5	>1.5	>1.5	>1.5	>1.5	>1.5	>1.5	>1.5
	w(m)	-0.0019	-0.0018	-0.0018	-0.0019	-0.0018	-0.0017	0.0019	0.0018	0.0018	0.0019	0.0018	0.0017
	%adm	2.14%	2.02%	2.02%	2.14%	2.02%	1.91%	2.14%	2.02%	2.02%	2.14%	2.02%	1.91%
1.2	σ_{vM}(MPa)	83.086	82.815	81.664	78.537	74.241	51.128	55.454	55.765	56.142	56.847	57.609	57.017
	%adm	47.48%	47.32%	46.67%	44.88%	42.42%	29.22%	31.69%	31.87%	32.08%	32.48%	32.92%	32.58%
	B(-)	2.813	2.716	2.607	2.467	2.400	2.695	3.114	3.095	3.064	3.009	3.000	3.204
	limit	>1.5	>1.5	>1.5	>1.5	>1.5	>1.5	>1.5	>1.5	>1.5	>1.5	>1.5	>1.5

	w(m)	-0.0048	-0.0049	-0.0049	-0.0050	-0.0048	-0.0044	0.0045	0.0045	0.0046	0.0047	0.0046	0.0041
	%adm	*5.39%*	*5.51%*	*5.51%*	*5.62%*	*5.39%*	*4.94%*	*5.06%*	*5.06%*	*5.17%*	*5.28%*	*5.17%*	*4.61%*
2.0	σ_{vM}(MPa)	118.610	118.298	116.924	112.661	108.547	75.206	64.378	64.994	65.713	66.747	67.268	66.052
	%adm	*67.78%*	*67.60%*	*66.81%*	*64.38%*	*62.03%*	*42.97%*	*36.79%*	*37.14%*	*37.55%*	*38.14%*	*38.44%*	*37.74%*
	B(-)	1.881	1.808	1.729	1.632	1.619	2.012	2.410	2.387	2.345	2.265	2.329	2.825
	limit	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*
	w(m)	-0.0065	-0.0065	-0.0066	-0.0068	-0.0062	-0.0044	0.0055	0.0054	0.0055	0.0058	0.0056	0.0041
	%adm	*7.33%*	*7.33%*	*7.38%*	*7.60%*	*6.98%*	*4.98%*	*6.13%*	*6.06%*	*6.14%*	*6.57%*	*6.24%*	*4.61%*
2.5	σ_{vM}(MPa)	139.976	140.035	138.525	133.581	128.313	99.397	69.416	70.248	71.198	72.436	73.086	72.727
	%adm	*79.99%*	*80.02%*	*79.16%*	*76.33%*	*73.32%*	*56.80%*	*39.67%*	*40.14%*	*40.68%*	*41.39%*	*41.76%*	*41.56%*
	B(-)	1.552	**1.485**	**1.419**	**1.338**	**1.329**	1.772	2.111	2.090	2.052	1.979	2.035	2.551
	limit	*>1.5*	***<1.5***	***<1.5***	***<1.5***	***<1.5***	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*
	w(m)	-0.0079	-0.0079	-0.0079	-0.0082	-0.0075	-0.0042	0.0062	0.0061	0.0062	0.0067	0.0064	0.0050
	%adm	*8.86%*	*8.87%*	*8.92%*	*9.18%*	*8.38%*	*4.74%*	*6.96%*	*6.87%*	*6.99%*	*7.52%*	*7.17%*	*5.63%*

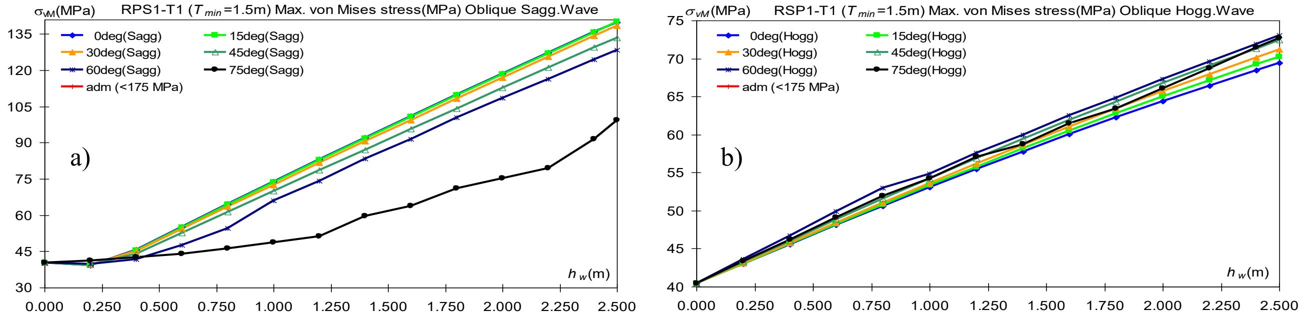

Fig. 6. Research-passenger ship, T_{min}=1.5m case *RPS1-T1*, standard structure, σ_{vM}(MPa) criterion, (a) sagg. and (b) hogg.

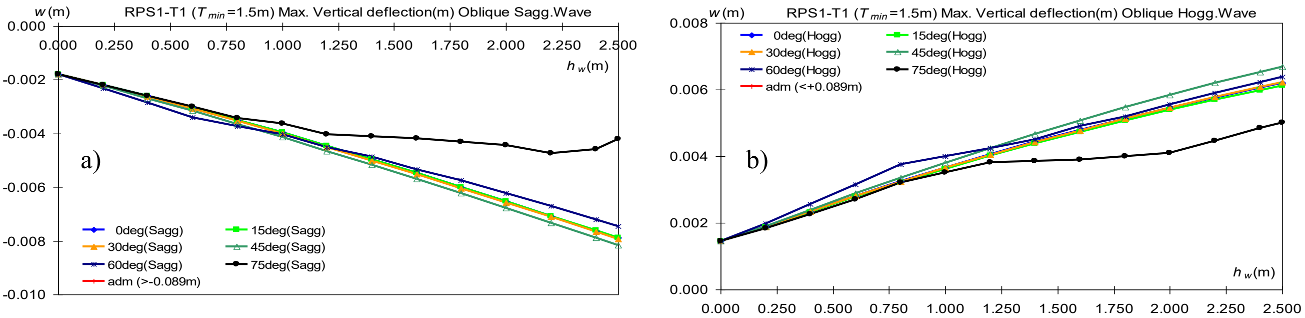

Fig. 7. Research-passenger ship, T_{min}=1.5m case *RPS1-T1*, standard structure, *w*(m) criterion, (a) sagg. and (b) hogg.

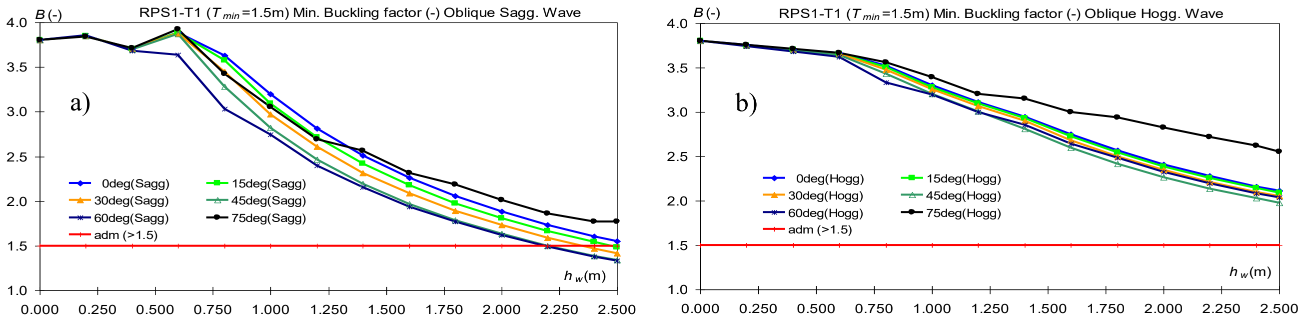

Fig. 8. Research-passenger ship, T_{min}=1.5m case *RPS1-T1*, standard structure, *B*(-) criterion, (a) sagg. and (b) hogg.

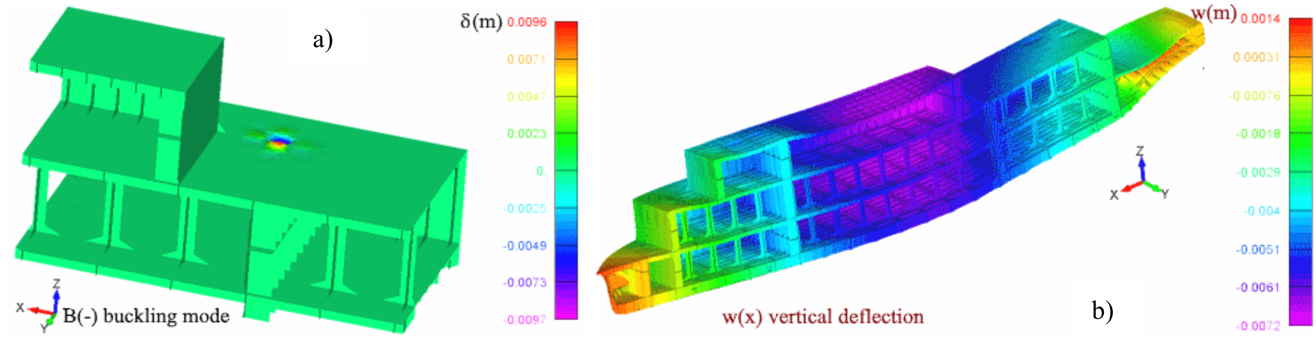

Fig. 9. Research-passenger ship, T_{min}=1.5m, *RPS1-T1*, standard structure, h_w=2m, μ=45deg, sagg. (a) *B*(-) and (b) *w*(m).

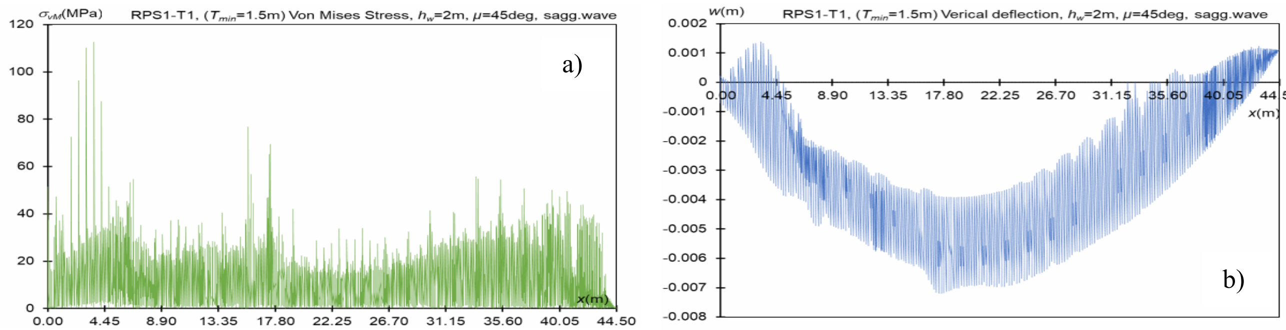

Fig. 10. Research-passenger ship, T_{min}=1.5m, *RPS1-T1*, standard, h_w=2m, μ=45deg, sagg. (a) σ_{vM}(MPa) and (b) *w*(m) charts.

For the enhanced constructive version and the first loading case (*RPS1-T2*), table 5 presents a selection of the strength criteria assessment, for the main navigation conditions: inland IN(0; 0.6; 1.2; 2.0), and coastal C(2.5).
The stress criterion (figures 11.a.b, 15.a, table 5, *RPS1-T2*) leads to no restrictions for any wave conditions, and the maximum von Mises stresses are in the range σ_{vM} = 33.734÷116.938 < 175 MPa. The maximum stresses result at the amidship structure, hull and superstructure, having the overall stress distribution with smaller values in comparison to the standard constructive version.
The vertical deflection criterion (figures 12.a.b, 14.b, 15.b, table 5, *RPS1-T2*) leads to no restrictions for any wave state, and the maximum deflections are in the range w = 0.0010÷0.0065 < 0.089 m, resulting that the overall distribution of the vertical deflection denotes a stiffener ship girder in comparison to the initial version.
The buckling criterion (figures 13.a.b, 14.a, table 5, *RPS1-T2*) has no restriction for any oblique wave conditions in comparison to the standard constructive version, with the minim recorded buckling factor B = 2.283 > 1.5 at the transversal bulkhead section, between upper and top deck panels, for oblique sagging wave C(2.5m; 60 deg).

Table 5. Research-passenger ship, minimum draught (T_{min}=1.5m) case (*RPS1-T2*) enhanced structure, strength criteria.

h_w(m)	T_{min}=1.5m	Sagging Oblique Wave						Hogging Oblique Wave					
	μ(deg)	0	15	30	45	60	75(90)	0	15	30	45	60	75(90)
		180	165	150	135	120	105(270)	180	165	150	135	120	105(270)
0	σ_{vM}(MPa)			33.734						33.734			
	%adm			*19.28%*						*19.28%*			
	B(-)			6.527						6.527			
	limit			*>1.5*						*>1.5*			
	w(m)			-0.0015						0.0010			
	%adm			*1.64%*						*1.17%*			
0.6	σ_{vM}(MPa)	45.787	45.653	45.064	43.613	39.504	36.813	40.041	40.141	40.290	40.742	41.640	40.963
	%adm	*26.16%*	*26.09%*	*25.75%*	*24.92%*	*22.57%*	*21.04%*	*22.88%*	*22.94%*	*23.02%*	*23.28%*	*23.79%*	*23.41%*
	B(-)	6.680	6.677	6.671	6.661	6.247	6.735	6.285	6.282	6.274	6.258	6.223	6.293
	limit	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*
	w(m)	-0.0025	-0.0025	-0.0025	-0.0026	-0.0028	-0.0025	0.0022	0.0021	0.0022	0.0022	0.0025	0.0021
	%adm	*2.80%*	*2.80%*	*2.83%*	*2.92%*	*3.15%*	*2.77%*	*2.42%*	*2.40%*	*2.42%*	*2.49%*	*2.76%*	*2.34%*
1.2	σ_{vM}(MPa)	69.044	68.816	67.858	65.259	61.683	42.477	46.036	46.266	46.603	47.328	48.096	47.318
	%adm	*39.45%*	*39.32%*	*38.78%*	*37.29%*	*35.25%*	*24.27%*	*26.31%*	*26.44%*	*26.63%*	*27.04%*	*27.48%*	*27.04%*
	B(-)	4.829	4.664	4.476	4.235	4.120	4.626	5.375	5.344	5.291	5.196	5.180	5.532
	limit	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*
	w(m)	-0.0045	-0.0046	-0.0046	-0.0047	-0.0045	-0.0041	0.0042	0.0042	0.0043	0.0044	0.0043	0.0038

	%adm	*5.06%*	*5.17%*	*5.17%*	*5.28%*	*5.06%*	*4.61%*	*4.72%*	*4.72%*	*4.83%*	*4.94%*	*4.83%*	*4.27%*
2.0	σ_{vM}(MPa)	98.594	98.330	97.185	93.641	90.190	62.476	53.289	53.751	54.356	55.344	56.161	54.716
	%adm	*56.34%*	*56.19%*	*55.53%*	*53.51%*	*51.54%*	*35.70%*	*30.45%*	*30.71%*	*31.06%*	*31.63%*	*32.09%*	*31.27%*
	B(-)	3.231	3.105	2.970	2.802	2.781	3.454	4.165	4.126	4.053	3.915	4.028	4.877
	limit	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*
	w(m)	-0.0054	-0.0054	-0.0054	-0.0056	-0.0052	-0.0037	0.0043	0.0043	0.0043	0.0046	0.0044	0.0031
	%adm	*6.07%*	*6.06%*	*6.11%*	*6.30%*	*5.79%*	*4.12%*	*4.84%*	*4.79%*	*4.84%*	*5.18%*	*4.90%*	*3.53%*
2.5	σ_{vM}(MPa)	116.638	116.692	115.428	111.346	106.641	82.555	57.415	58.100	58.885	60.044	61.019	60.244
	%adm	*66.65%*	*66.68%*	*65.96%*	*63.63%*	*60.94%*	*47.17%*	*32.81%*	*33.20%*	*33.65%*	*34.31%*	*34.87%*	*34.43%*
	B(-)	2.666	2.551	2.437	2.297	**2.283**	3.042	3.647	3.611	3.545	3.420	3.517	4.415
	limit	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*
	w(m)	-0.0065	-0.0065	-0.0066	-0.0068	-0.0062	-0.0044	0.0049	0.0049	0.0049	0.0053	0.0050	0.0039
	%adm	*7.33%*	*7.35%*	*7.40%*	*7.62%*	*6.96%*	*4.91%*	*5.51%*	*5.46%*	*5.52%*	*5.95%*	*5.65%*	*4.35%*

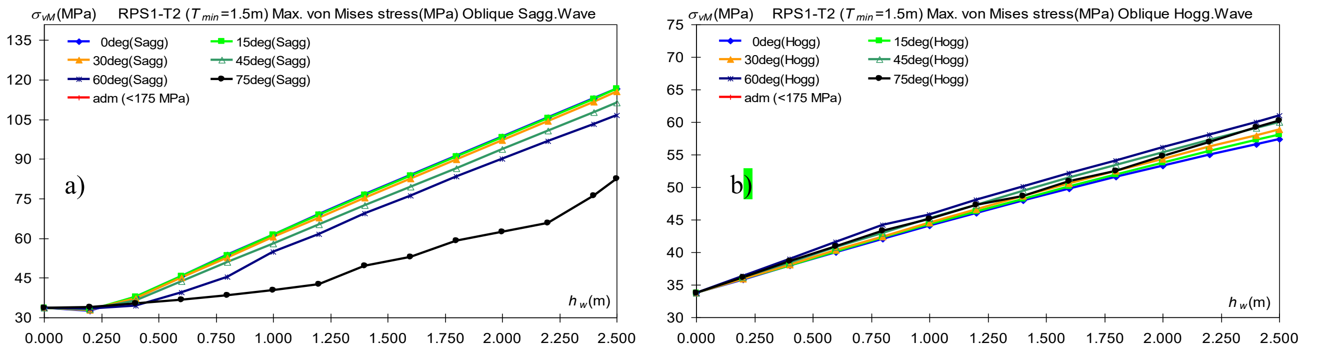

Fig. 11. Research-passenger ship, T_{min}=1.5m case *RPS1-T2*, enhanced structure, σ_{vM}(MPa) criterion, (a) sagg. and (b) hogg.

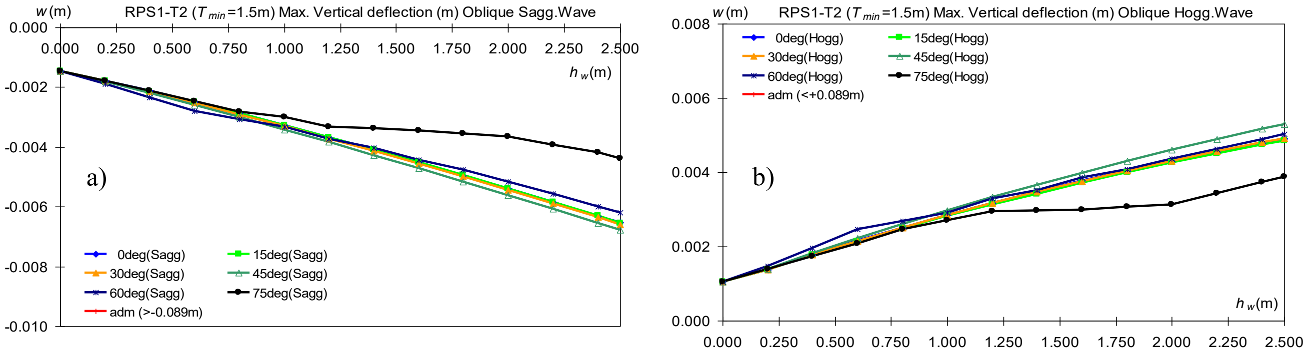

Fig. 12. Research-passenger ship, T_{min}=1.5m case *RPS1-T2*, enhanced structure, w(m) criterion, (a) sagg. and (b) hogg.

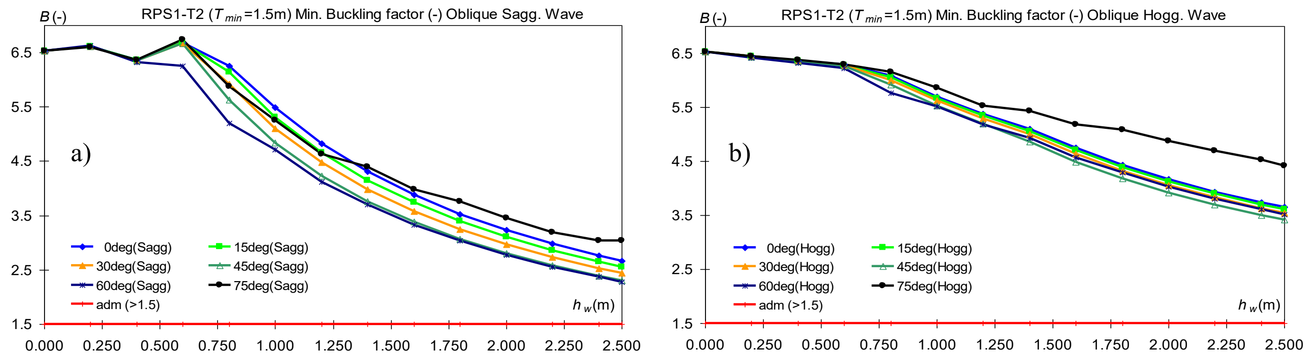

Fig. 13. Research-passenger ship, T_{min}=1.5m case *RPS1-T2*, enhanced structure, B(-) criterion, (a) sagg. and (b) hogg.

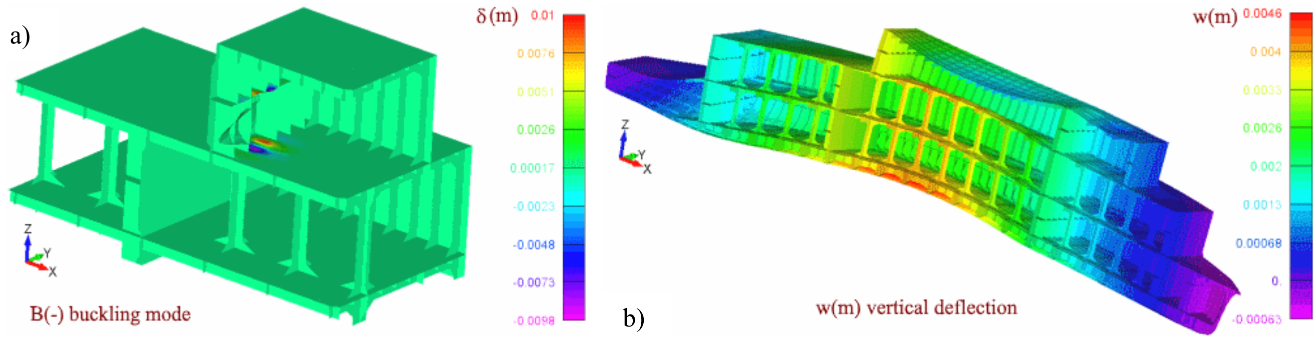

Fig. 14. Research-passenger ship, T_{min}=1.5m, *RPS1-T2*, enhanced structure, h_w=2m, μ=45deg, hogg. (a) *B*(-) and (b) *w*(m).

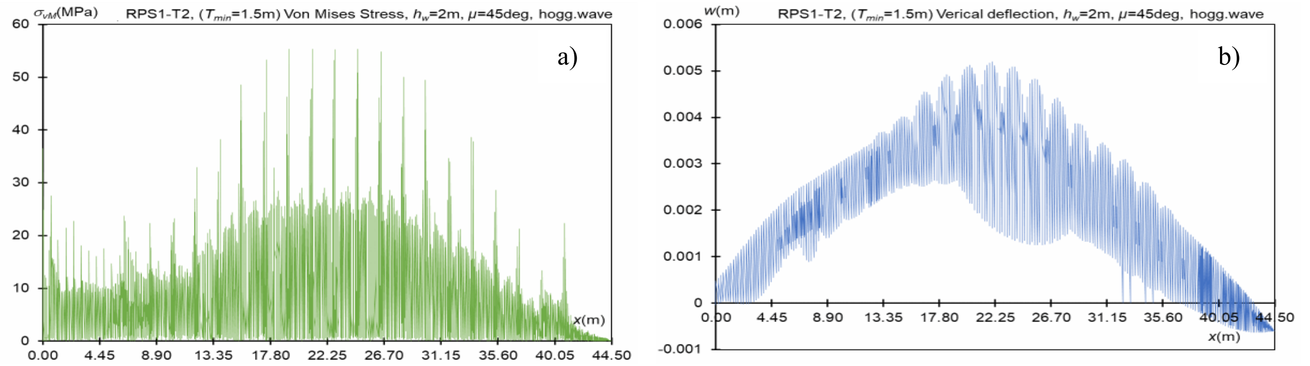

Fig. 15. Research-passenger ship, T_{min}=1.5m, *RPS1-T2*, enhanced, h_w=2m, μ=45deg, hogg. (a) σ_{vM}(MPa) and (b) *w*(m) charts.

For the research-passenger ship with enhanced structure and first loading case with minimum draught (*RPS1-T2*), the increase of the structural elements thickness leads to no restrictions by the strength criteria, the ship being safe for river and coastal navigation conditions up to the class C(2.5), but with a noticeable reduction of the ship's deadweight from 73.050 t down to 42.975 t.

6. THE STRENGTH EVALUATION OF THE RESEARCH-PASSENGER SHIP STRUCTURE FOR THE MAXIMUM DRAUGHT CASE

For the second loading case (T_{max}=1.7 m), the assessment of the two constructive versions' strength for the research-passenger ship is based on the 3D-FEM ship whole model (figure 2), with supplementary onboard masses of 67.025 t. The specific structural approach by the algorithm from figure 1 (modules 5, 6), involves the user macro-subroutines for oblique wave pressure application on the ship's shell, related to the ship's equilibrium parameters for the maximum draught case (table 3).

Table 6 presents a selection of the strength criteria assessment for the standard constructive version and the second loading case (*RPS2-T1*), for main river-coastal navigation conditions, h_w = 0, 0.6, 1.2, 2.0, 2.5 m.

The stress criterion (figures 16.a.b, 19.a, 20.a, table 6, *RPS2-T1*), for any wave condition, has no restrictions, with the maximum von Mises stresses σ_{vM} = 46.850÷158.681 < 175 MPa, increased in comparison to the minimum draught case. The maximum stresses are at the aft peak and scattered hot spots at the joints of the longitudinal stiffeners with the bulkhead's panels.

The vertical deflection criterion (figures 17.a.b, 20.b, table 6, *RPS2-T1*), for any wave state, has no restrictions, with the maximum deflections w = 0.0014÷0.0088 < 0.089 m. In comparison to the minimum draught case, the local deformations have a wider dispersion around the averaged global vertical deflection, due to the supplementary onboard added masses.

The buckling criterion (figures 18.a.b, 19.b, table 6, *RPS2-T1*) in the hogging oblique wave conditions has no restrictions (*B*>1.5). For sagging oblique waves, the buckling criterion leads to noticeable operational restrictions: C(2.0 m; 45÷60 deg), C(2.2 m; 30÷60 deg), C(2.4 m; 0÷60 deg), and C(2.5 m; 0÷60 deg), with factor *B* = 1.235÷1.498 < 1.5, with structural collapse at the upper deck. For the research-passenger ship with standard structure on maximum draught case (*RPS2-T1*), the operations have more restrictions due to the buckling criterion, corresponding to the river class ≈ IN(2.0), being unsafe for any of the coastal navigation area.

Table 6. Research-passenger ship, maximum draught (T_{max}=1.7m) case (*RPS2-T1*) standard structure, strength criteria.

h_w(m)	T_{max}=1.7m	*Sagging Oblique Wave*						*Hogging Oblique Wave*					
	μ(deg)	**0**	**15**	**30**	**45**	**60**	**75(90)**	**0**	**15**	**30**	**45**	**60**	**75(90)**
		180	**165**	**150**	**135**	**120**	**105(270)**	**180**	**165**	**150**	**135**	**120**	**105(270)**
0	σ_{vM}(MPa)			46.850						46.850			
	%adm			*26.77%*						*26.77%*			
	B(-)			3.841						3.841			
	limit			*>1.5*						*>1.5*			
	w(m)			-0.0022						0.0014			
	%adm			*2.49%*						*1.57%*			
0.6	σ_{vM}(MPa)	75.149	75.021	74.454	73.035	68.837	60.141	53.717	53.808	53.972	54.323	55.249	54.212
	%adm	*42.94%*	*42.87%*	*42.55%*	*41.73%*	*39.34%*	*34.37%*	*30.70%*	*30.75%*	*30.84%*	*31.04%*	*31.57%*	*30.98%*
	B(-)	3.616	3.533	3.436	3.310	3.124	3.457	3.697	3.695	3.690	3.650	3.588	3.701
	limit	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*
	w(m)	-0.0036	-0.0036	-0.0036	-0.0037	-0.0039	-0.0034	0.0026	0.0026	0.0026	0.0026	0.0028	0.0023
	%adm	*4.01%*	*4.02%*	*4.04%*	*4.12%*	*4.33%*	*3.82%*	*2.91%*	*2.88%*	*2.88%*	*2.95%*	*3.18%*	*2.55%*
1.2	σ_{vM}(MPa)	102.311	102.126	101.250	98.896	96.062	75.296	61.383	61.647	61.960	62.652	63.320	62.054
	%adm	*58.46%*	*58.36%*	*57.86%*	*56.51%*	*54.89%*	*43.03%*	*35.08%*	*35.23%*	*35.41%*	*35.80%*	*36.18%*	*35.46%*
	B(-)	2.468	2.390	2.304	2.196	2.144	2.416	3.061	3.042	3.012	2.961	2.954	3.241
	limit	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*
	w(m)	-0.0051	-0.0051	-0.0051	-0.0052	-0.0050	-0.0043	0.0040	0.0039	0.0039	0.0041	0.0040	0.0030
	%adm	*5.69%*	*5.69%*	*5.72%*	*5.84%*	*5.63%*	*4.88%*	*4.48%*	*4.42%*	*4.43%*	*4.58%*	*4.51%*	*3.37%*
2.0	σ_{vM}(MPa)	137.118	136.040	135.212	132.121	130.820	99.263	70.917	71.453	72.067	73.087	73.517	71.964
	%adm	*78.35%*	*77.74%*	*77.26%*	*75.50%*	*74.75%*	*56.72%*	*40.52%*	*40.83%*	*41.18%*	*41.76%*	*42.01%*	*41.12%*
	B(-)	1.711	1.644	1.577	**1.498**	**1.486**	1.835	2.451	2.427	2.385	2.306	2.383	2.799
	limit	*>1.5*	*>1.5*	*>1.5*	***<1.5***	***<1.5***	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*
	w(m)	-0.0072	-0.0072	-0.0073	-0.0074	-0.0068	-0.0048	0.0056	0.0055	0.0055	0.0059	0.0055	0.0038
	%adm	*8.10%*	*8.14%*	*8.16%*	*8.31%*	*7.59%*	*5.42%*	*6.24%*	*6.14%*	*6.18%*	*6.58%*	*6.18%*	*4.27%*
2.5	σ_{vM}(MPa)	157.518	158.100	158.681	154.907	152.234	112.914	76.375	77.110	77.939	79.165	79.637	78.044
	%adm	*90.01%*	*90.34%*	*90.67%*	*88.52%*	*86.99%*	*64.52%*	*43.64%*	*44.06%*	*44.54%*	*45.24%*	*45.51%*	*44.60%*
	B(-)	**1.454**	**1.380**	**1.315**	**1.245**	**1.235**	1.547	2.114	2.093	2.055	1.985	2.052	2.499
	limit	***<1.5***	***<1.5***	***<1.5***	***<1.5***	***<1.5***	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*
	w(m)	-0.0084	-0.0085	-0.0086	-0.0088	-0.0080	-0.0055	0.0064	0.0063	0.0064	0.0068	0.0064	0.0046
	%adm	*9.46%*	*9.57%*	*9.67%*	*9.86%*	*8.97%*	*6.19%*	*7.19%*	*7.06%*	*7.14%*	*7.65%*	*7.18%*	*5.17%*

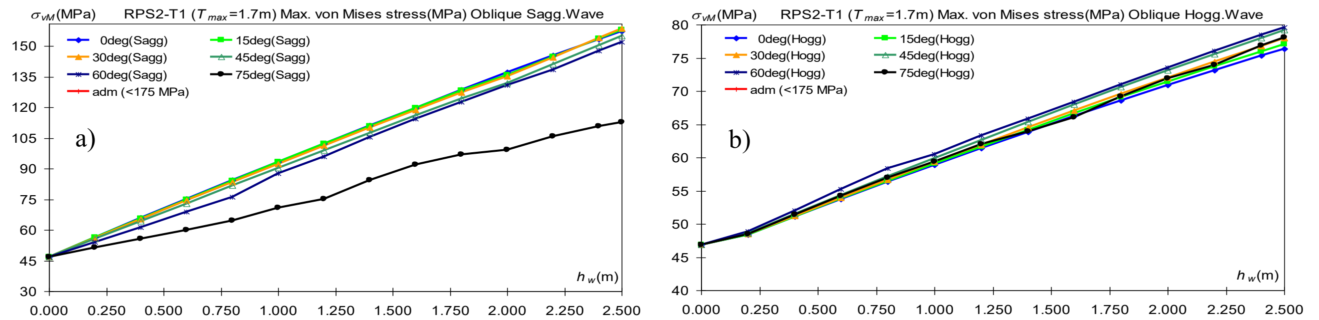

Fig. 16. Research-passenger ship, T_{max}=1.7m case *RPS2-T1*, standard structure, σ_{vM}(MPa) criterion, (a) sagg. and (b) hogg.

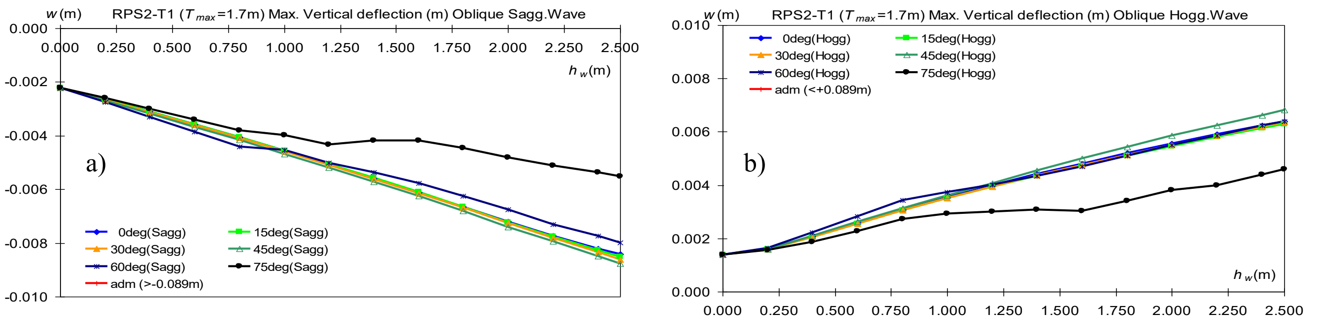

Fig. 17. Research-passenger ship, T_{max}=1.7m case *RPS2-T1*, standard structure, w(m) criterion, (a) sagg. and (b) hogg.

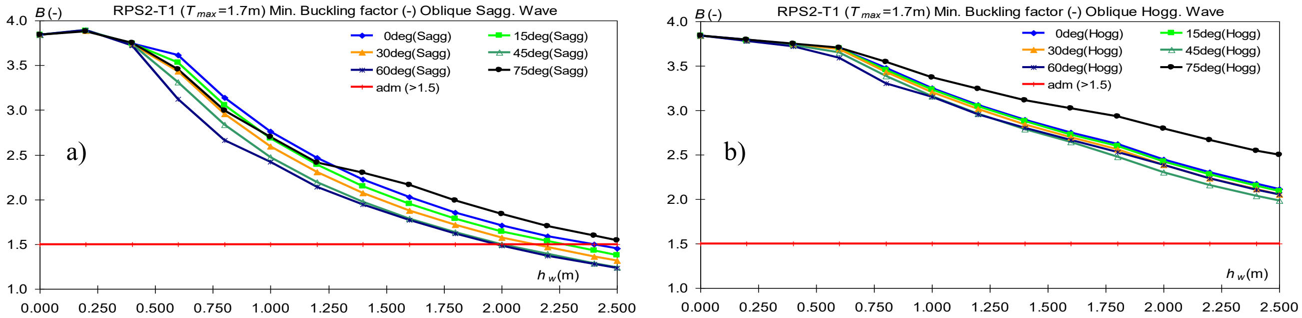

Fig. 18. Research-passenger ship, T_{max}=1.7m case *RPS2-T1*, standard structure, *B*(-) criterion, (a) sagg. and (b) hogg.

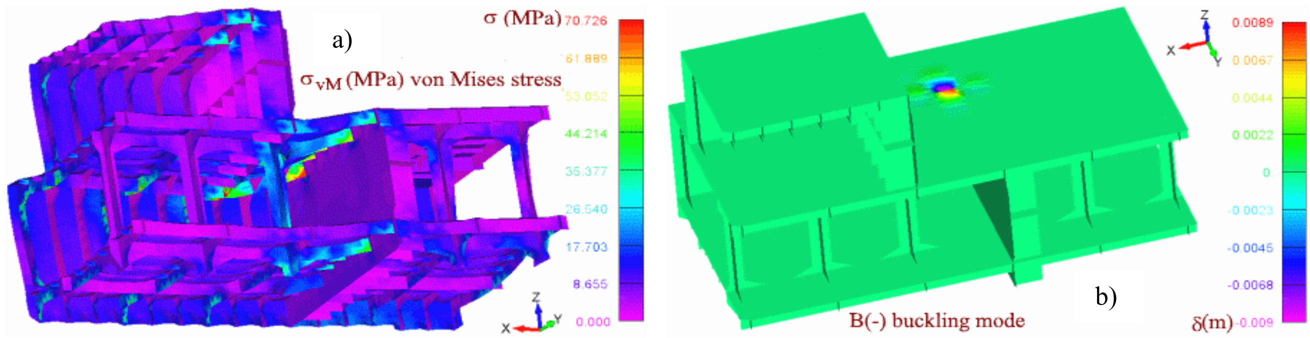

Fig. 19. Research-passenger ship, T_{max}=1.7m, *RPS2-T1*, standard, h_w=2m, μ=75deg, sagg. (a) σ_{vM}(MPa) detail and (b) *B*(-).

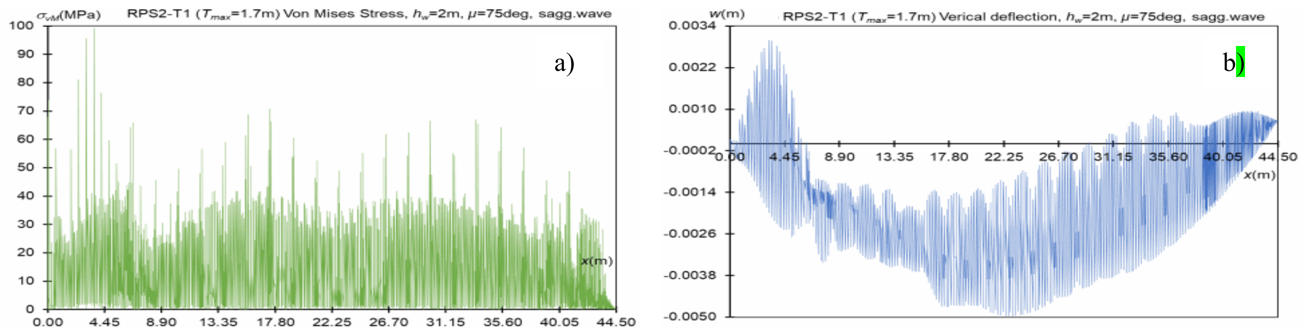

Fig. 20. Research-passenger ship, T_{max}=1.7m, *RPS2-T1*, standard, h_w=2m, μ=75deg, sagg. (a) σ_{vM}(MPa) and (b) *w*(m) charts.

For the enhanced constructive version and the second loading case (*RPS2-T2*), table 7 presents a selection of the strength criteria assessment, for the inland IN(0; 0.6; 1.2; 2.0) and coastal C(2.5) navigation conditions.
The stress criterion (figures 21.a.b, 24.a, 25.a, table 7, *RPS2-T2*), for any oblique wave, has no restrictions, with the maximum von Mises stresses σ_{vM} = 38.884÷134.190< 175 MPa, all over the superstructure, lower in comparison to the standard constructive version, but increased to those for the first loading case.
The vertical deflection criterion (figures 22.a.b, 25.b, table 7, *RPS2-T2*), for any oblique wave, has no restrictions, with the maximum deflections w = 0.0010÷0.0073 < 0.089 m, with the overall distribution of the local deflection having a significantly wider distribution in comparison to the first loading case, as a consequence of the supplementary onboard masses.

Table 7. Research-passenger ship, maximum draught (T_{max}=1.7m) case (*RPS2-T2*) enhanced structure, strength criteria.

h_w(m)	T_{max}=1.7m	Sagging Oblique Wave						Hogging Oblique Wave					
	μ(deg)	0	15	30	45	60	75(90)	0	15	30	45	60	75(90)
		180	165	150	135	120	105(270)	180	165	150	135	120	105(270)
0	σ_{vM}(MPa)			38.884						38.884			
	%adm			*22.22%*						*22.22%*			
	B(-)			6.594						6.594			
	limit			*>1.5*						*>1.5*			
	w(m)			-0.0018						0.0010			
	%adm			*2.04%*						*1.18%*			
0.6	σ_{vM}(MPa)	62.422	62.315	61.843	60.663	57.178	49.944	44.719	44.804	44.928	45.350	46.121	45.247
	%adm	*35.67%*	*35.61%*	*35.34%*	*34.66%*	*32.67%*	*28.54%*	*25.55%*	*25.60%*	*25.67%*	*25.91%*	*26.35%*	*25.86%*
	B(-)	6.206	6.063	5.897	5.680	5.361	5.931	6.343	6.339	6.331	6.311	6.200	6.352

	limit	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*
	w(m)	-0.0022	-0.0023	-0.0023	-0.0024	-0.0021	-0.0021	0.0020	0.0019	0.0019	0.0020	0.0022	0.0017
	%adm	*2.47%*	*2.58%*	*2.58%*	*2.70%*	*2.36%*	*2.36%*	*2.20%*	*2.17%*	*2.17%*	*2.22%*	*2.42%*	*1.92%*
1.2	σ_{vM}(MPa)	85.018	84.861	84.130	82.174	79.811	62.547	51.042	51.242	51.529	52.225	52.861	51.211
	%adm	*48.58%*	*48.49%*	*48.07%*	*46.96%*	*45.61%*	*35.74%*	*29.17%*	*29.28%*	*29.45%*	*29.84%*	*30.21%*	*29.26%*
	B(-)	4.237	4.103	3.956	3.770	3.681	4.147	5.286	5.253	5.201	5.112	5.100	5.628
	limit	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*
	w(m)	-0.0042	-0.0042	-0.0042	-0.0043	-0.0041	-0.0034	0.0031	0.0030	0.0031	0.0032	0.0031	0.0022
	%adm	*4.70%*	*4.70%*	*4.73%*	*4.83%*	*4.66%*	*3.78%*	*3.47%*	*3.42%*	*3.43%*	*3.57%*	*3.48%*	*2.52%*
2.0	σ_{vM}(MPa)	114.029	113.072	112.379	109.809	108.708	82.456	58.792	59.187	59.733	60.761	61.375	59.615
	%adm	*65.16%*	*64.61%*	*64.22%*	*62.75%*	*62.12%*	*47.12%*	*33.60%*	*33.82%*	*34.13%*	*34.72%*	*35.07%*	*34.07%*
	B(-)	2.938	2.822	2.709	2.573	2.552	3.151	4.237	4.196	4.123	3.988	4.122	4.832
	limit	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*
	w(m)	-0.0060	-0.0060	-0.0060	-0.0061	-0.0056	-0.0040	0.0044	0.0043	0.0043	0.0046	0.0043	0.0029
	%adm	*6.71%*	*6.73%*	*6.76%*	*6.89%*	*6.30%*	*4.48%*	*4.90%*	*4.82%*	*4.85%*	*5.16%*	*4.82%*	*3.22%*
2.5	σ_{vM}(MPa)	131.385	134.190	132.379	129.256	127.049	93.801	63.229	63.772	64.485	65.625	66.485	64.525
	%adm	*75.08%*	*76.68%*	*75.65%*	*73.86%*	*72.60%*	*53.60%*	*36.13%*	*36.44%*	*36.85%*	*37.50%*	*37.99%*	*36.87%*
	B(-)	2.498	2.370	2.258	2.138	2.121	2.655	3.654	3.617	3.552	3.430	3.549	4.315
	limit	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*	*>1.5*
	w(m)	-0.0070	-0.0069	-0.0071	-0.0073	-0.0066	-0.0046	0.0050	0.0050	0.0050	0.0054	0.0050	0.0035
	%adm	*7.83%*	*7.80%*	*8.03%*	*8.20%*	*7.46%*	*5.13%*	*5.66%*	*5.58%*	*5.62%*	*6.02%*	*5.63%*	*3.93%*

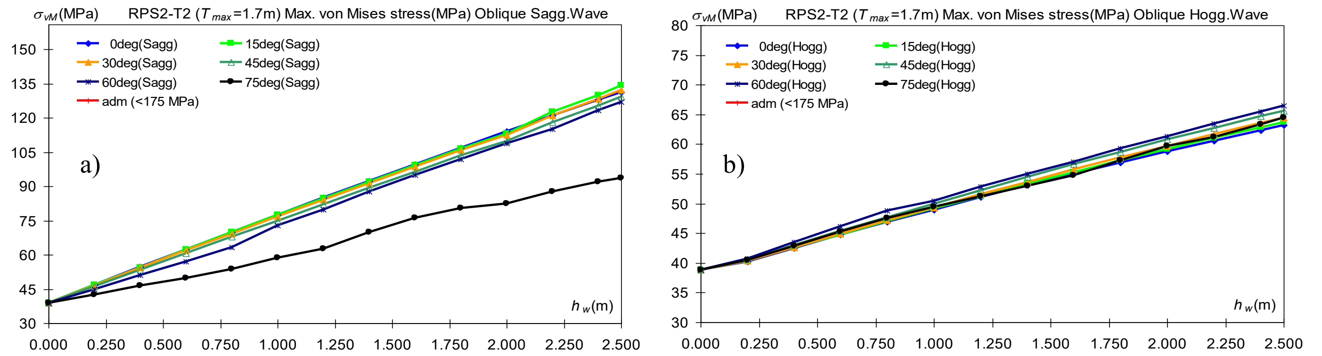

Fig. 21. Research-passenger ship, T_{max}=1.7m case *RPS2-T2*, enhanced structure, σ_{vM}(MPa) criterion, (a) sagg. and (b) hogg.

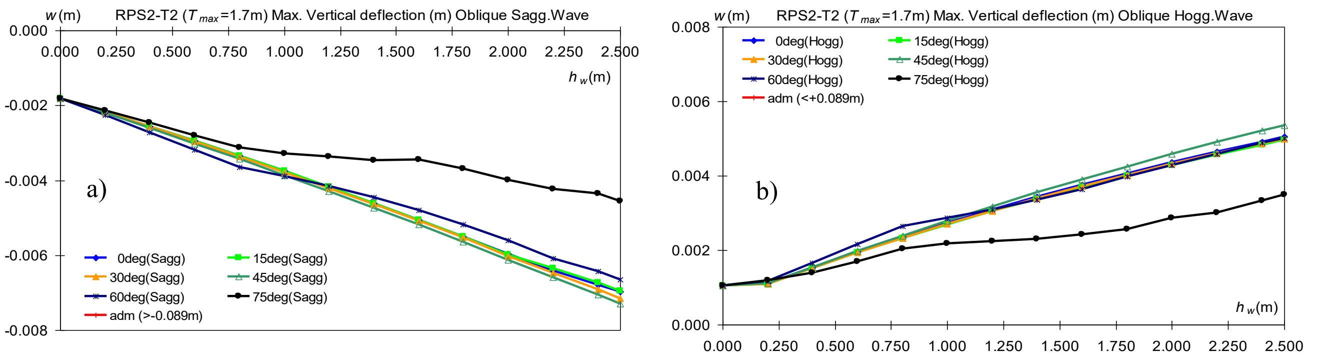

Fig. 22. Research-passenger ship, T_{max}=1.7m case *RPS2-T2*, enhanced structure, *w*(m) criterion, (a) sagg. and (b) hogg.

The buckling criterion (figures 23.a.b, 24.b, table 7, *RPS2-T2*) for any oblique wave conditions, has no restrictions in comparison to the standard constructive version, with the minim buckling factor value B = 2.121 > 1.5, at the middle of the upper deck panel, oblique sagging wave C(2.5 m; 60 deg), proving an increased structural capability of the enhanced structure in comparison to the standard version.

For the maximum draught case, the research-passenger ship with enhanced structure (*RPS2-T2*), records no restrictions on the strength criteria, resulting in the ship being safe up to the navigation class C(2.5), involving a reduction of the ship's deadweight from 140.075 t down to 110 t.

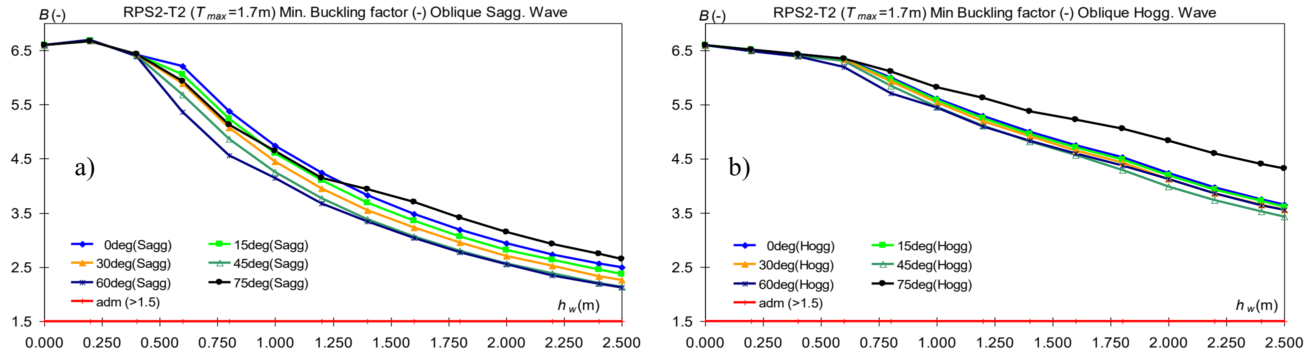

Fig. 23. Research-passenger ship, T_{max}=1.7m case *RPS2-T2*, enhanced structure, B(-) criterion, (a) sagg. and (b) hogg.

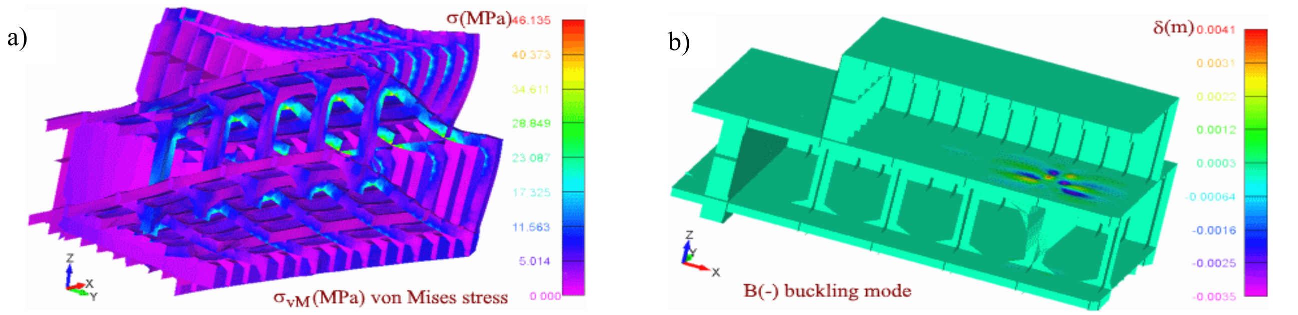

Fig. 24. Research-passenger ship, T_{max}=1.7m, *RPS2-T2*, enhanced, h_w=2m, μ=75deg, sagg. (a) σ_{vM}(MPa) detail and (b) B(-).

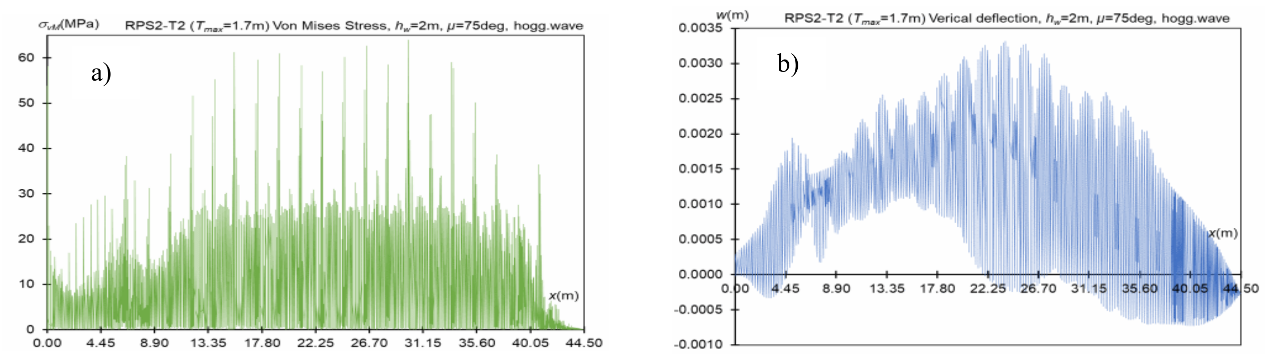

Fig. 25. Research-passenger ship, T_{max}=1.7m, *RPS2-T2*, enhanced, h_w=2m, μ=75deg, hogg. (a) σ_{vM}(MPa) and (b) w(m) charts.

7. OPERATION CAPABILITIES EVALUATION OF THE RESEARCH-PASSENGER SHIP BY STRENGTH CRITERIA FOR THE TWO DRAUGHT CASES

The research-passenger ship with two constructive versions, standard (*T1*) and enhanced (*T2*), at minimum (*RPS1*) and maximum (*RPS2*) draught loading conditions (Figures 2, 3, and Table 1), has the operational capabilities evaluated in oblique waves navigation conditions, by 3D structural models and the methodology algorithm from figure 1.

Initially, based on research-passenger ship equilibrium parameters in oblique waves by the 1D models and non-linear iterative approach (figure 1), the freeboard criterion is assessed for the first (Figure 4, Table 2) and second (figure 5, table 3) loading cases, and leads to no operational limits (FB_{min}>0), due to a suitable ship's parapet height by design (table 1). The recorded von Mises stresses are maximum for the second loading case on the standard structure (Figure 16, Table 6) and minimum for the first loading case on the enhanced structure (Figure 11, Table 5). For both loading cases the stresses on sagging wave conditions, more significant at the aft part, are larger than those on hogging wave conditions, more significant amidships part, (Figures, 6, 11, 16, 21, and Tables 4-7), the maximum stress values being recorded for the extreme coastal h_w=2.5 m, μ=0-15 deg sagging wave case. The enhanced structure (Figures 11, 21) provides a noticeable strength of the research-passenger ship's structure compared to the standard structure (Figures 6, 16). For any oblique wave navigation condition, the stress criterion leads to no limits for the operational area (σ_{vMmax} < 175 MPa).

The research-passenger ship vertical deflections have small values for both loading cases, around 10% of the admissible limits, more reduced for the enhanced structure (figures 12, 22, tables 5, 7) in comparison to the

standard structure (figures 7, 17, tables 4, 6). The vertical deflections have a wider dispersion around the value of global deflection in the second loading case, where supplementary onboard masses are placed on the main horizontal ship's panels. For any oblique wave cases, no operational limits are recorded by the vertical criterion (w_{max} <0.089 m).
The buckling criterion for the research-passenger ship on hogging oblique waves, on both loading cases and both constructive versions (figures 8.b, 13.b, 18.b, 23.b, tables 4-7), leads to no restrictions for the operational area (B>1.5). On sagging oblique waves, for enhanced structure with supplementary strengthening (figures 13.a, 23.a, tables 5, 7), the buckling criterion is also satisfied for both research-passenger ship loading cases (B>1.5). For the standard structure (figures 8.a, 18.a, tables 4, 6), the buckling criterion for the research-passenger ship, in sagging oblique wave conditions, leads to significant operational navigation restrictions (B<1.5), on first loading case h_{wlimit}= 2.185 m (*RPS1-T1*) and second loading case h_{wlimit}= 1.979 m (*RPS2-T1*).
The combined strength criteria operational limits, by 3D hull and superstructure full extended model, of the research-passenger ship are presented in table 8, leading to the practical structural polar safety limit diagrams in terms of wave height (h_w) and heading angle (μ), in figure 26.a for the first loading case on minimum ship's draught (*RPS1-T1, T2*), and in figure 26.b for the second loading case on maximum ship's draught (*RPS2-T1, T2*).

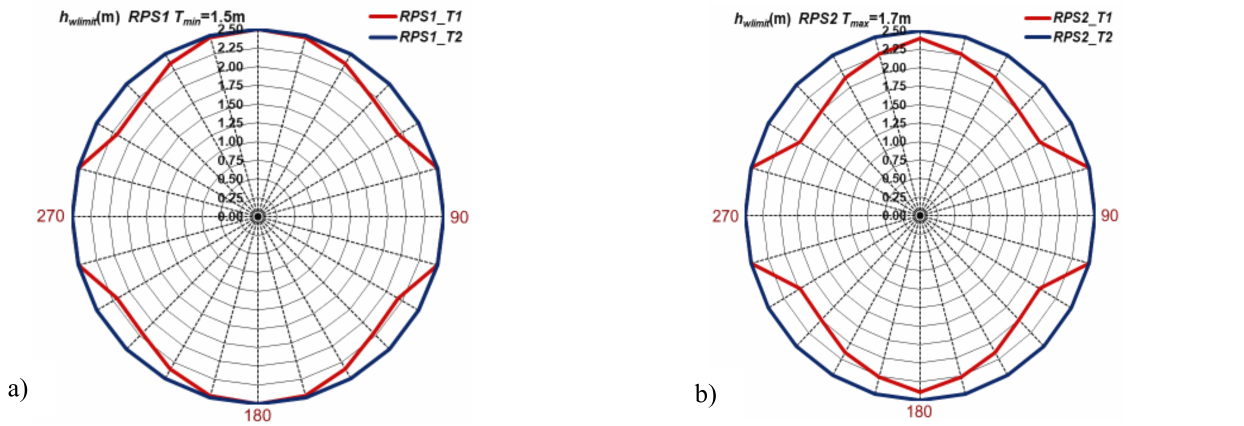

Fig. 26. Research-passenger ship, h_{wlimit}(m) operation capabilities by strength criteria, (a) *RPS1-T1,T2* and (b) *RSP2-T1,T2*.

Table 8. Research-passenger ship operation capabilities evaluation h_{wlimit}(m) by strength criteria, both draught cases.

h_{wlimit}(m)	μ(deg)	0(360)	15(345)	30(330)	45(315)	60(300)	75(285)(90)	Limit strength	Navigation
Case	***Version***	**180**	**165(195)**	**150(210)**	**135(225)**	**120(240)**	**105(255)(270)**	**criterion**	**limit**
RPS1	T1	2.500	2.474	2.353	2.202	**2.185**	2.500	Buckling, Sagg.	≈ C(2.2)
T_{min}=1.5 m	T2	2.500	2.500	2.500	2.500	2.500	2.500	---	C(2.5)
RPS2	T1	2.391	2.263	2.143	1.997	**1.979**	2.500	Buckling, Sagg.	≈ IN(2.0)
T_{min}=1.7 m	T2	2.500	2.500	2.500	2.500	2.500	2.500	---	C(2.5)

8. CONCLUSIONS

The structural design concept of the research-passenger ship (Figure 2) is evaluated by an integrated methodology and code for strength analysis in oblique waves (Figure 1), enhanced for the slender hull ships with shape non-linearities all over the body, capable of computing the ship's equilibrium in extreme waves, up to the flooding limit of the main deck, and to deliver accurate equilibrium position parameters.
The research-passenger ship design concept is developed in two constructive versions (Table 1), the initial standard structure and the enhanced structure, with supplementary thickness of the constitutive elements, being submitted for the strength analysis on two relevant loading conditions, minimum draught (T_{min}=1.5 m) and maximum draught (T_{max}=1.7 m), according to the selected onboard masses. The navigation area of the research-passenger ship is imposed by design on river and coastal domains, up to class C(2.5).
For the two loading cases, the height of the parapets at the aft and fore peak are selected by design (table 1), so that the criterion of minimum freeboard is satisfied for any oblique wave condition (figures 4, 5, tables 2, 3).
The initial standard structure version (*T1*) of the research-passenger ship, on both loading cases, results with no restrictions by admissible stress (figures 6, 16) and vertical deflections (figures 7, 17) criteria, but there are recorded significant navigation restrictions by the buckling criterion (figures 8, 18, tables 4, 6) on the sagging state. For the standard structure, the research-passenger ship navigation area is restricted to coastal class C(2.2),

for the first loading condition (figure 26.a), and to inland class IN(2.0) for the second loading condition (figure 26.b), pointing out that the standard constructive version is not capable of ensuring the design requirement for the navigation area up to class C(2.5), being safe only for inland operational limits (table 8) [11].
The second enhanced structure version (*T2*) of the research-passenger ship has been developed as a necessity to ensure the navigation capability on the coastal area up to class C(2.5) imposed by design requirements (figure 26, table 8), so that this version has no restriction by any strength criteria for any oblique wave conditions (figures 11-13, 21-23, tables 5, 7). The only disadvantage of the enhanced version is that the light displacement has increased by 30.075 t, which reduces the deadweight in comparison to the standard version, preserving the ship's operational draught limits (T=1.5÷1.7 m) imposed by the freeboard criterion and the water depth limits on the river domain. Nevertheless, the deadweight ensured by the research-passenger ship with enhanced structure at maximum draught (*RPS2-T2*) is 110 tdw, satisfying the design requirements for this ship to accommodate the quantity of onboard masses for the research activities.
In conclusion, the parametric study of the research-passenger ship on the two constructive versions by strength criteria has revealed that only the enhanced structure (*T2*) can satisfy the safety on navigation conditions up to coastal class C(2.5). Still, the standard structure (*T1*) can also be considered safe for navigation conditions over the whole river area up to inland class IN(2.0) and ensures a larger cargo capacity (table 1, table 8, figure 26).
Further studies of the research-passenger ship design concept will continue with a dynamic parametric study by seakeeping criteria to reveal the capabilities of the river-coastal ship in irregular wave navigation conditions.

Author contributions: The paper was written by only one author.
Funding source: There is no funding source.
Conflicts of interest: There is no conflict of interest.
Acknowledgments: Thanks for the support of the Naval Architecture (UDJG) Research Centre and the REXDAN (UDJG) Research Centre during the development of the initial ship's design concept.

REFERENCES

1. BV, (2025). *Direct Strength Analysis. Hull Girder Strength*, Bureau Veritas, Paris.
2. DNV, (2025). *Finite Element Analysis. Hull Girder Strength*, Det Norske Veritas, Novik.
3. ISSC, (2022). *Design Principles and Criteria. Quasi-Static Response*, Proceeding of the 21th Int. Ship and Offshore Structures, (Wang Z. and Pegg N. Eds.), ISSC / SNAME, Vancouver.
4. Caridis, P.A., (2025). *Global Strength of Ships: Analysis and Design using Mathematical Methods*, Cambridge University Press, Cambridge.
5. Wang, T., (2023). *Hull Structure Design and Global Strength Analysis of a Novel Non-Ship-Shaped FPSO for Offshore Marginal Field Developments in Shallow Water*, The 33rd International Ocean and Polar Engineering Conference, Paper No. ISOPE-I-23-156, Ottawa, available at: https://publications.isope.org/proceedings/ISOPE/ISOPE%202023/data/pdfs/288-2023-TPC-0127.pdf
6. Costache, M.; Jagite, G., (2014). *Global Strength Analysis in Head Waves, for an Offshore Support Vessel*, Asian Journal of Applied Science and Engineering (AJASE), 3(8), 73-88.
7. Domnisoru, L.; Stoicescu, L.; Dumitru, D.; Pitulice, D., (2005). *Linear-nonlinear Analysis of Ship Hull Structure Strength and Ship Service Life Estimation*, UDJG Publishing House, Galati.
8. Paik, J.K.; Thayamballi, A.K., (2007). *Ship Shaped Offshore Installations*, Cambridge University Press, Cambridge.
9. Mansour, A.; Liu, D., (2008). *Strength of Ships and Ocean Structures*, The Principles of Naval Architecture Series, SNAME, New Jersey.
10. Domnisoru, L., (2023). *Preliminary Hydrodynamic Analyses for a River Research Ship. Comparative Study of Mono-hull and Catamaran Ship Type*, Galati University Press, Fascicle XI, Shipbuilding, 46, 39-47.
11. BV, (2025). *Rules for the Classification of Inland Navigation Vessels*, Bureau Veritas, Paris.
12. Domnisoru, L., (2025). *EQSW.v5 Software for the Analysis of the Ship's Equilibrium Position in Design Oblique Wave conditions and Preliminary Global Strength Evaluation*, Naval Architecture (UDJG) Research Centre, Galati.
13. Bathe, K.J., (2007). *Finite Element Procedures*, Prentince Hall, Pearson Education Inc., New Jersey.
14. Koutromanos, I., (2017). *Fundamentals of Finite Element Analysis: Linear Finite Element Analysis*, John Wiley & Sons, New Jersey.
15. FEMAP, (2025). *User Guide of Femap/NX Nastran Program*. Siemens PLM Software (Academic License).

Received: March 11th, 2025 / Accepted: November 5th, 2025 / Paper available online: December 20th, 2025