HYBRID GFRP–METAL COMPOSITES FOR SHIPBUILDING: NUMERICAL SIMULATION AND STRUCTURAL PERFORMANCE ANALYSIS

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Hybrid composites of glass fiber-reinforced polymers (GFRP) and metals show promise for lighter, more reliable ship structures. This study evaluates the mechanical performance of GFRP–metal hybrid plates using a literature review and finite element simulations under static loading. The specific objectives of this study are to (1) compare the mechanical performance of three structural configurations: monolithic aluminum, monolithic glass fiber-reinforced polymer (GFRP), and aluminum–GFRP–aluminum sandwich structures; (2) analyze and contrast their stress distribution, total mechanical strain, and displacement behaviors under static loading; and (3) determine which configuration offers optimal load dispersion and structural efficiency. These assessments are conducted using literature review and finite element simulations within ANSYS Mechanical APDL. The findings indicate that the hybrid configuration offers enhanced load dispersion and structural efficiency, underscoring its significant potential for developing lightweight and durable naval structures. This approach paves the way for more resilient marine designs.

Keywords: Hybrid composites, GFRP, Composite materials, FEM simulation, Mechanical performance

List of abbreviations

GFRP	Glass Fiber Reinforced Polymer
VARTM	Vacuum Assisted Resin Transfer Molding
FML	Fibre Metal Laminates
GLARE	Glass Laminate Aluminum Reinforced Epoxy
FEA	Finite Element Analysis
APDL	ANSYS Parametric Design Language

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1. Introduction

In recent years, the shipbuilding industry has faced increasing demands for lighter, more efficient, and sustainable structural materials. Among the most promising solutions are hybrid composites that integrate glass fiber reinforced polymers (GFRP) with metallic components. This approach aims to combine the benefits of both: reduced weight and corrosion resistance from GFRP, and stiffness and load-bearing capacity from metals [1].

Glass fiber composites have been widely used in marine structures—particularly in small vessels—due to their mechanical reliability, cost-effectiveness, and good resistance to degradation in marine environments [1]. Their adoption has steadily expanded into hull components, superstructures, and internal equipment, driven by the need for enhanced service life and reduced maintenance costs.

However, when single-material solutions reach their limits, hybrid solutions—combining diverse matrices and reinforcement geometries—continue to hold promise [2]. In the development and research of advanced materials—particularly within naval engineering—experimental testing and interpretation of material behavior remain among the most complex yet essential stages. These processes are fundamental for validating designed materials and provide insights into their mechanical and physical performance under various loading conditions [3].

Still, experimental testing often faces challenges such as specimen preparation variability and parameter sensitivity. Additionally, occasional mismatches arise between experimental results and theoretical predictions. Factors such as geometry, fiber alignment, or scale effects can significantly influence measurements, including compressive strength or delamination tendencies [4]. Nevertheless, these studies provide valuable data that help improve hybrid materials and make them more reliable for marine applications [1], [4].

Building upon this context, the present paper only touches on the previous work revealed by the literature review but our paper strongly emphasizes the findings based on experimental work consisting on genuine numerical simulations and analysis of GFRP–metal hybrid composites. The study focuses on the mechanical response and interfacial behavior of hybrid structures intended for small marine vessels, aiming to evaluate their structural efficiency under specific loading conditions.

The novelty of this work lies in the numerical modeling and interpretation of hybrid metal–composite behavior using parameters relevant to marine applications, providing insights not reported in the reviewed literature.

Glass Fiber Reinforced Polymer (GFRP) composites are among the most widely used materials in marine and transport engineering due to their favorable combination of low density, high specific strength, stiffness, and corrosion resistance [1], [5]–[8]. They consist of continuous or woven glass fibers embedded in a polymer matrix—typically epoxy, polyester, or vinyl ester—which ensures efficient stress transfer and protects the fibers from moisture and environmental degradation [6], [7].

The type of glass fibers used—such as E-glass, S-glass, or R-glass—determines the composite's stiffness and tensile strength [6], [8], [9].

For marine applications, GFRP laminates are valued for their lightweight nature and chemical stability in seawater, making them suitable for hulls, decks, and structural reinforcements [10]. However, purely composite or purely metallic structures can exhibit limitations—such as low impact strength in composites and high corrosion susceptibility in metals.

To address these limitations, hybrid materials combining metallic and composite layers have been developed [11], [12], [15]. These Hybrid Metal–Composite Laminates (HMLs) aim to merge the advantages of both systems: the stiffness and ductility of metals with the corrosion resistance and low weight of composites.

Various manufacturing techniques are used for producing GFRP laminates, including manual lay-up, compression molding, and vacuum-assisted resin transfer molding (VARTM). Each process affects fiber alignment, void content, and resin distribution, influencing the final mechanical behavior of the composite [6]–[10].

The manual lay-up process is one of the most widely adopted for small- and medium-scale marine components due to its low cost, flexibility, and suitability for complex geometries [11].

In GFRP composites, the polymer matrix plays a critical role in transferring stresses between fibers, maintaining fiber alignment, and providing environmental protection. The choice of polymer significantly affects the composite's mechanical behavior, durability, and compatibility with metallic layers in hybrid configurations [16].

The most commonly used matrices in marine-grade GFRP composites are epoxy, polyester, and vinyl ester resins. Among them, epoxy systems—especially those based on bisphenol-A with amine hardeners—are preferred for high-performance structural components due to their excellent adhesion to glass fibers, low shrinkage during curing, and superior resistance to moisture and saltwater degradation [17], [18]. These characteristics ensure reliable performance in environments subjected to cyclic loading and thermal fluctuations.

Vinyl ester resins represent an attractive alternative because of their enhanced toughness, chemical resistance, and ease of processing compared to unsaturated polyesters. They provide a balance between cost and performance, making them suitable for marine and transport applications where moderate mechanical strength and high corrosion resistance are required [19], [20].

In marine applications, hybrid Al–GFRP–Al laminates offer enhanced corrosion resistance, improved stiffness-to-weight ratios, and reduced local stress concentrations compared to monolithic plates [3], [14]. Their high energy absorption capacity and interlaminar toughness make them promising for small-vessel structures, where lightweight design and damage tolerance are critical [12], [15].

Based on these findings from existing studies, the present work focuses on a numerical investigation of an Al–GFRP–Al hybrid plate configuration, aiming to evaluate its stress distribution and stiffness characteristics under controlled loading conditions. The modeling strategy and analysis are detailed in Section 2.

Furthermore, the scope is organized as follows: Section 2, Method, presents the modeling methodology, while Section 3, Results, discusses the results obtained during the experimental phase of the work. At last, the authors draw some concise yet practical conclusions from the work, highlighting both its strengths and weaknesses, as well as suggesting further research directions.

1. Method

Finite Element Modelling Approach

All models and numerical results presented in this section were developed by the authors, without the use of external experimental databases.

In this section, **the authors present their own numerical investigation** of the structural behavior of three plate types: monolithic aluminum, monolithic GFRP, and a hybrid aluminum–GFRP–aluminum (Al–GFRP–Al) sandwich. The analysis was performed using Finite Element Analysis (FEA) in ANSYS Mechanical APDL 15.0. The objective was to evaluate and compare stiffness and stress distribution patterns for each configuration under identical loading and boundary conditions.

Each plate had the same in-plane dimensions and a total thickness of 7 mm:

- Aluminium plate (monolithic): 7 mm thick,
- GFRP plate (monolithic): 7 mm thick,
- Hybrid sandwich: 2 mm aluminium + 3 mm GFRP + 2 mm aluminium.

A concentrated force of 1000 N was applied vertically at the geometric center of the upper surface of all models. Simply supported boundary conditions were applied to the two opposite edges. These allowed rotation but prevented vertical translation. This setup simulates classical bending, making it suitable for comparative assessments of stiffness and strength.

The plates were discretized using SOLID185 elements. These elements are suitable for 3D modeling of layered solids with capabilities for large deformation and plasticity. A mapped meshing strategy was employed to enhance the accuracy of the results, particularly at layer interfaces. The glue operation ensured proper interaction between the bonded volumes in the sandwich configuration. This effectively simulated interfacial adhesion between aluminum and GFRP layers.

Aluminum was modeled as an isotropic, linear elastic material. GFRP was modeled as both isotropic (for comparison) and orthotropic (for the sandwich case). The principal material directions were aligned with the local coordinate system. This allowed a more realistic representation of the anisotropic stiffness behavior inherent to fiber-reinforced polymers.

No density was defined, as the analysis focused on static structural behavior rather than dynamic or inertial effects.

This finite element modeling strategy ensures a consistent and reproducible framework for evaluating hybrid and monolithic configurations. The results provide insight into how material composition and internal structure influence stress distribution, deformation, and overall stiffness under identical loading conditions.

Table 3 summarizes the basic mechanical properties of aluminum and GFRP, the two materials used in this study. Aluminum is modeled as an isotropic material, possessing uniform properties in all directions. GFRP is treated as orthotropic, with different mechanical responses along different axes to reflect its fiber-reinforced nature.

Table 3

Mechanical Properties of GFRP and Aluminium [16]

Material	**Young's Modulus (E) [GPa]**	**Poisson's Ratio (ν)**	**Type**
Aluminium	70	0.33	Isotropic
GFRP	EX = 35, EY = EZ = 9	ν12 = 0.28, ν13 = ν23 = 0.3	Orthotropic

Table 4

Detailed Mechanical Properties [16]

Mechanical Property	GFRP	Aluminium
Longitudinal modulus, EX (MPa)	35000	70000
Transverse modulus, EY (MPa)	9000	70000
Transverse modulus, EZ (MPa)	9000	70000
Poisson's ratio, PRXY	0.28	0.33
Poisson's ratio, PRYZ	0.3	0.33
Poisson's ratio, PRXZ	0.3	0.33
Shear modulus, GXY (MPa)	4000	26000
Shear modulus, GYZ (MPa)	3500	26000
Shear modulus, GXZ (MPa)	3500	26000
Longitudinal tensile strength, Xt (MPa)	1080	
Longitudinal compressive strength, Xc (MPa)	620	
Transverse tensile strength, Yt/Zt (MPa)	39	
Transverse compressive strength, Yc/Zc (MPa)	128	
Shear strength, S (MPa)	89	

To better capture the directional properties of GFRP in the model, detailed orthotropic properties, as listed in Table 4, were used. These include modulus, shear, and strength values for failure evaluation.

The validated numerical models described above formed the basis for the comparative analysis presented in Section 4, focusing on stress distribution and deformation behavior.

2. Results and discussion

In this section, **the authors present and analyze the numerical results obtained from the Finite Element Analysis (FEA)** of the hybrid and monolithic plates. The investigation focused on **stress distribution (Von Mises stress)** and **total mechanical strain**, allowing a direct comparison of stiffness and deformation characteristics among the three configurations.

The results reveal distinct mechanical responses for each plate type. The monolithic aluminum plate exhibited the highest stiffness but also localized stress concentrations near the loading point. The GFRP plate showed a more uniform stress distribution with higher overall deformation. The hybrid Al–GFRP–Al configuration demonstrated intermediate stiffness and efficient stress transfer across the metal–composite interfaces, confirming the beneficial synergistic effect of the layered structure.

3.1 Stress Distribution (Von Mises Stress)

The distribution of Von Mises stress was analyzed to assess the mechanical response of the three plate configurations under consistent boundary and loading conditions. This stress measure, widely used for ductile systems, identifies regions of elevated stress and potential yielding.

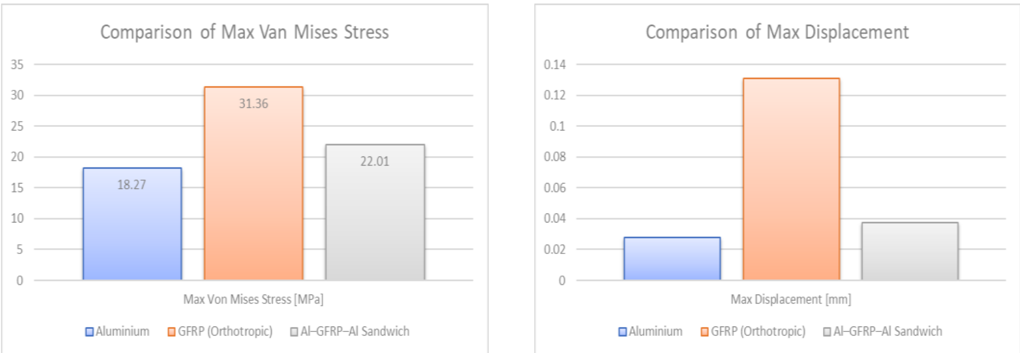
Building on this analysis, post-processing produced detailed stress contour maps for each configuration. These maps show differences in both the intensity and location of peak stresses. The monolithic aluminium and GFRP plates had distinct stress patterns, while the hybrid laminate displayed a more even stress distribution due to its layered composition.

Taken together, these results allow a comparative evaluation of the stress-handling capabilities of homogeneous versus hybrid structures. They offer insights into the effectiveness of the aluminium–GFRP–aluminium assembly in redistributing internal stresses. Representative stress contours are shown in the following figures, and maximum values are reported in Table 5.

Table 5

Comparison of Stress and Displacement for Different Plate Configurations

Plate Type	Max Von Mises Stress [MPa]	Max Displacement [mm]
Aluminium	18.27	0.02775
GFRP (Orthotropic)	31.36	0.13098
Al–GFRP–Al Sandwich	22.01	0.03756

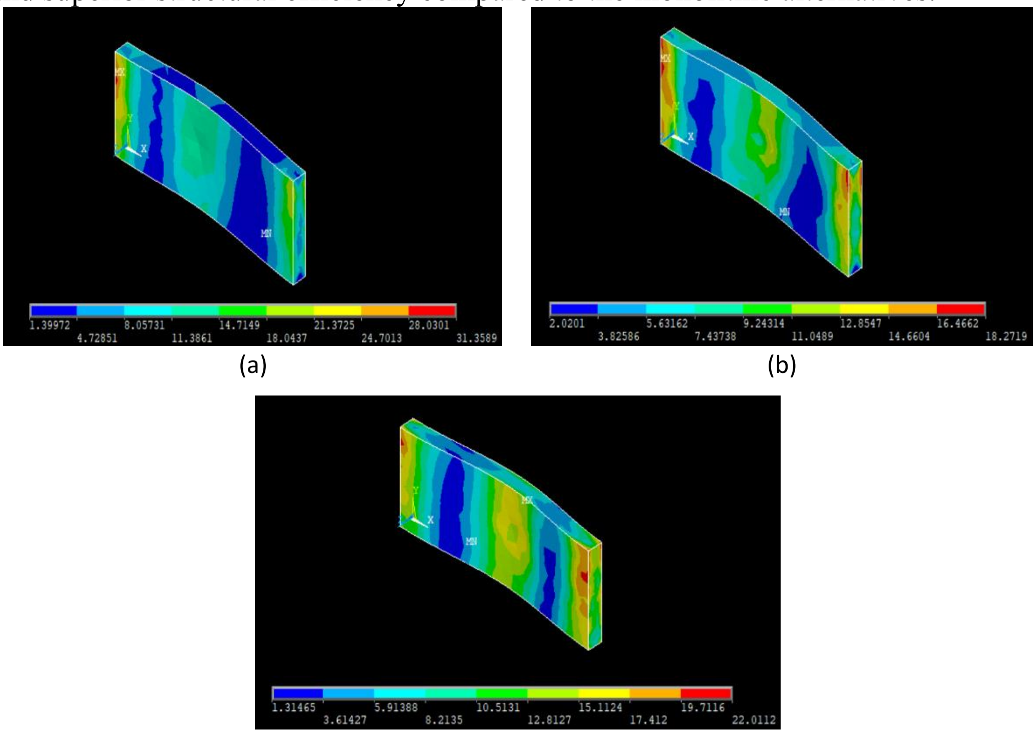


(a) (b)

Fig. 5. Graphical comparison of maximum Von Mises stress and displacement for the three plate configurations: (a) Maximum Von Mises Stress [MPa]; (b) Maximum Displacement [mm]

The stress distribution analysis under a 1000 N central point load reveals distinct behaviors across the three configurations. In Fig. 6a, the monolithic GFRP plate shows localized stress near the load application point, with directional propagation influenced by its orthotropic nature. Fig. 6b illustrates the aluminum plate’s more uniform stress dispersion, attributed to the isotropic material properties.

In Fig. 6c, the hybrid aluminum–GFRP–aluminum plate demonstrates improved stress distribution, with the aluminum skins absorbing surface loads and the GFRP core enhancing stiffness. This configuration shows reduced peak stresses and superior structural efficiency compared to the monolithic alternatives.



(a) (b)

(c)

Fig. 6. Von Mises Stress Distribution for Different Plate Configurations: (a) GFRP, (b) Aluminium, (c) Aluminium–GFRP–Aluminium Sandwich Plate [17]

3.2 Total Mechanical Strain

To further assess the mechanical behavior of the plates under the same loading conditions, the total mechanical strain distribution was analyzed for each configuration. The equivalent elastic strain (EPTOEQV), extracted from ANSYS, provides insight into the deformation pattern and intensity across the structure, capturing the combined effect of axial and shear components.

Figure 8 illustrates the total strain distributions for the plates examined in this study, specifically highlighting: the monolithic GFRP plate, the monolithic aluminium plate, and the hybrid Al–GFRP–Al sandwich plate.

As shown in Fig. 8a, the GFRP plate exhibits the highest peak strain (0.002416), which is primarily concentrated near the area of load application. The anisotropic material response results in an asymmetric strain field. In contrast, Fig. 8b shows the aluminium plate, which exhibits a more uniform strain distribution due to the material's isotropic nature and a significantly lower peak strain (0.000261). Similarly, Fig. 8c shows the hybrid sandwich structure, which exhibits better strain dispersion than both monolithic cases and a moderate maximum value (0.000325), indicating improved stiffness and deformation resistance due to the coaction between aluminium skins and the GFRP core.

Table 6

Comparison of Total Mechanical Strain for Different Plate Configurations

Plate Type	Max Total Mechanical Strain [-]
Aluminium	0.000261
GFRP (Orthotropic)	0.002416
Al–GFRP–Al Sandwich	0.000325

As discussed in the previous section, material selection and structural design have a significant impact on the mechanical response. Table 6 presents the maximum equivalent (Von Mises) strain values obtained for each plate configuration under a central point load of 1000 N. The results reflect the influence of material anisotropy and structural composition on strain distribution. The GFRP plate exhibits the highest strain, the aluminium–GFRP–aluminium sandwich plate exhibits intermediate strain due to the benefits of combining stiff aluminium faces with a compliant GFRP core, and the aluminium plate exhibits the lowest strain, reflecting the comparative stiffness of their structures.

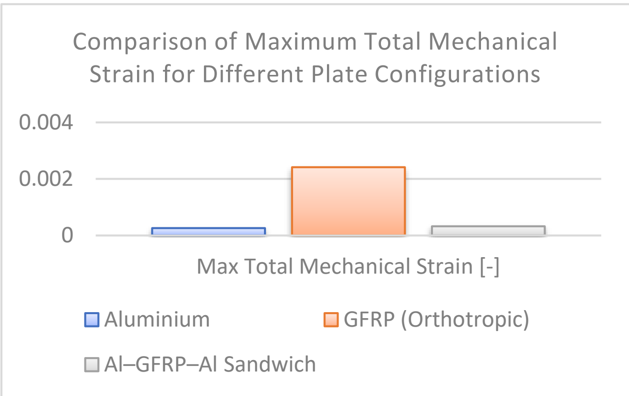
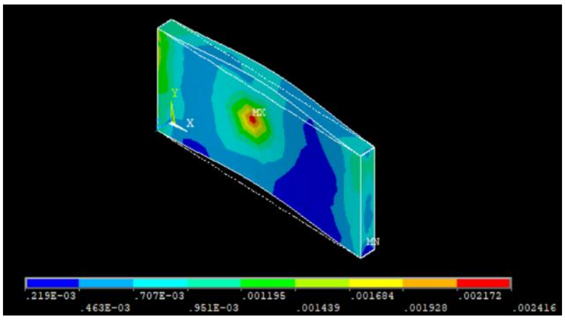
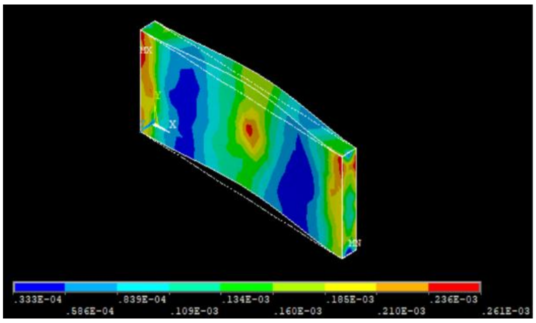


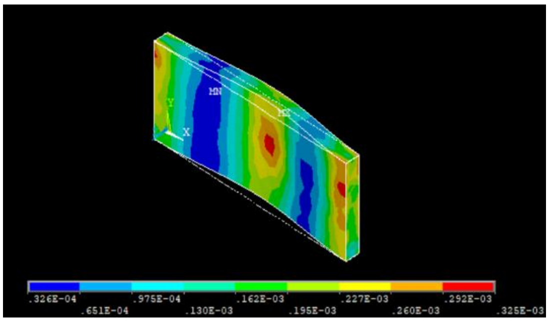
Fig. 7. Total mechanical strain in aluminium, GFRP, and hybrid sandwich plates.



(a)



(b)



(c)

Fig. 8. Total Mechanical Strain Distribution for Different Plate Configurations: (a) GFRP, (b) Aluminium, (c) Aluminium–GFRP–Aluminium Sandwich Plate [17]

The comparative analysis clearly highlights the different deformation and stress transfer mechanisms in the studied configurations. The aluminum plate, while providing the highest stiffness, exhibited pronounced local stresses near the loading point. The GFRP plate showed greater flexibility and a more homogeneous stress distribution, though with higher overall strain. The hybrid Al–GFRP–Al structure demonstrated a balanced response, combining the stiffness of the metallic layers with the ductility of the composite core.

These results confirm the effectiveness of the hybrid configuration in improving structural efficiency and reducing local stress concentrations, thus supporting its potential use in lightweight marine applications.

4. Conclusions

This study combined a concise literature review with the authors' **original finite element simulations** to investigate the structural performance of hybrid aluminium–GFRP composites designed for small marine vessels. Three configurations were compared—monolithic aluminium, monolithic GFRP, and Al–GFRP–Al sandwich plates—under identical boundary and loading conditions.

The results demonstrate that the hybrid configuration provides a balanced mechanical response, combining the stiffness of the metallic layers with the flexibility of the composite core. Compared to single-material plates, the Al–GFRP–Al structure effectively reduces local stress concentrations while maintaining adequate stiffness, confirming its potential as a **lightweight and efficient solution for marine structures**.

The originality of this work lies in the **numerical modelling and comparative analysis** performed by the authors, which provide valuable insights into stress and strain transfer mechanisms within hybrid laminates.

Future work will focus on experimental validation, fatigue and impact studies, and optimization of fibre orientation to further enhance the structural reliability and long-term performance of hybrid metal–composite materials.

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