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# Mechanical behavior of glass fiber-epoxy composite laminates for ship hull structures

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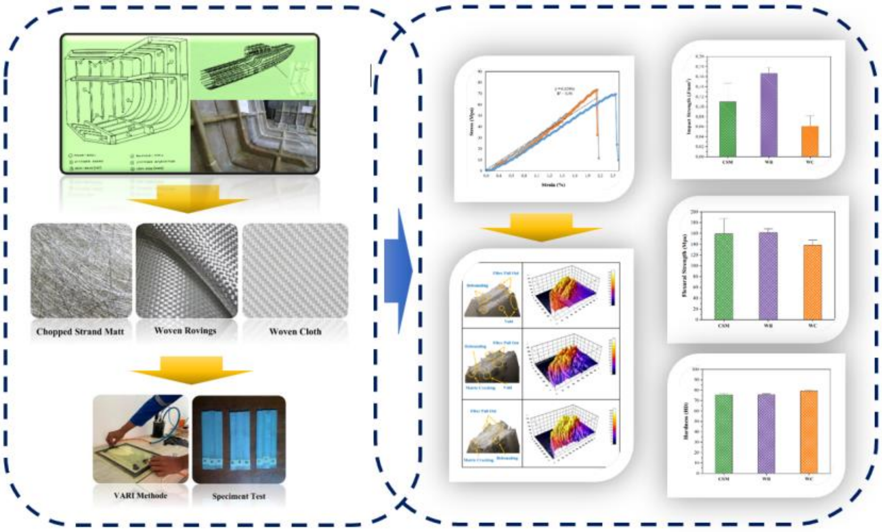


**Highlights:**

- Woven Cloth (WC) arrangement achieved the highest tensile strength of 73.24 MPa, showing better stress distribution.
- Woven Rovings (WR) fiber arrangement showed superior flexural strength of 6992.6 MPa, hardness of 75.66 HD, and highest impact resistance of 0.1789 J/mm but was weak in tensile properties.
- Fiber arrangement enhanced mechanical properties compared to random fibers, which was crucial for high-performance polymer composite materials in ship construction.

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## Abstract

Polymer composite is widely used in various structures due to its strength-to-load ratio. Despite the significant benefits, many structures are vulnerable to high-impact loads in practical situations. Therefore, this research aimed to explore the effect of fiber arrangement on the mechanical behavior of glass fiber-epoxy composite laminates. Experiments were conducted on several samples with glass fiber arrays of Chopped Strand Matt (CSM), Woven Rovings (WR), and Woven Cloth (WC). The composite fabrication was molded using the vacuum pressure infusion (VAPRI) method. The mechanical behavior of laminate composite was obtained using a tensile test, tree point bending, shore D hardness, Charrpy impact, fracture observation, and fiber-matrix delamination. The results showed that WR arrangement excelled in various mechanical behaviors, including flexural strength 6992.6 Mpa, Hardnes 75.66 HD, and Impact 0.1789 J/mm. In comparison, the highest tensile strength value was obtained in the WC arrangement of 73.24 Mpa. This research showed that both regular and arranged fiber provided better mechanical properties than random fiber. The incorporation of fiber arrangement could be recommended in the further development of high-performance polymer composite.

**Keywords:** Glass Fiber; Chopped Strand Matt; Woven Rovings; Woven Cloth; Composite; Mechanical Properties

# 1. Introduction

The introduction of material selection including metals for ship structures is essential in the maritime industry to ensure safety, performance, and durability [1], [2]. Traditionally, metals such as steel and aluminum have been widely used for their high strength and toughness. However, the search for lightweight and high-strength materials has led to the exploration and adoption of composite materials, particularly glass fiber-reinforced polymers (GFRP) [3]. Among various composite materials, glass fiber-epoxy laminates have shown significant advantages, including high strength-to-weight ratio, corrosion resistance, and ease of fabrication [4], [5].

The use of composite materials in shipbuilding is growing steadily, due to advances in materials science and engineering. The sandwich composite presented in **Figure 1**, consisting of a layered arrangement of fibers with a matrix and core material, has been used in the maritime industry to develop ship construction [8], [9]. This composite has various advantages such as lightweight, high strength, efficient energy design, impact resistance, thermal insulation, and high damping [10], [11]. However, its anisotropic nature causes stress distribution and failure to be more complex than metallic materials. Structural failures in composite experience localized and restructured that cannot be observed at the macro level [12], [13].

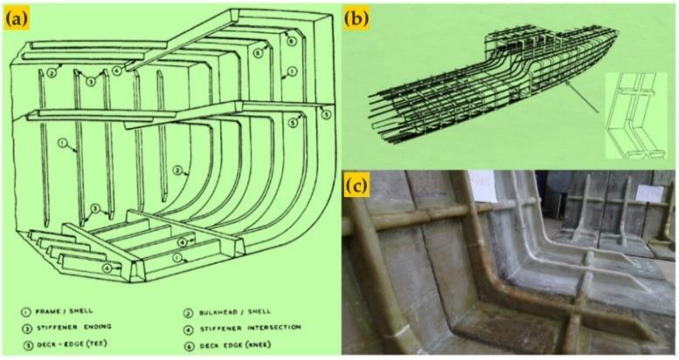


**Figure 1.** Framework for composite ship: (a) Framed design for a single skin hull; (b) Overall ship beam structure; (c) Sandwiched composite joint [6], [7]

The mechanical performance of materials used in ship structures is essential due to the demanding operational environment. Ship faces a variety of dynamic loads, including wave impact, hydrostatic pressure, and mechanical stress during navigation. The ability to resist these loads without significant deformation or failure is essential to the safety and longevity of ship [4], [14]. In this context, glass fiber-epoxy composite, with their tunable mechanical properties, offers a promising alternative to conventional materials [15]. Glass fiber-epoxy composite can be designed to meet specific structural requirements by optimizing the fiber arrangement and improving the overall performance and efficiency of ship structure [8]. This design facilitates the achievement of specific mechanical properties by manipulating fiber arrangement and orientation, which allows for optimized structural performance [13]. Fiber arrangement affects load distribution, stiffness, strength, and failure mechanisms of composite laminates [16], [17]. The adjustments are essential to resist the complex and varied loads experienced by ship structures, including tensile, compressive, and impact stresses.

Based on previous literature, understanding the effect of fiber arrangement on the mechanical properties of glass fiber-epoxy composite is essential for practical application in ship structures. By optimizing the mechanical properties through fiber arrangement, superior performance and long life can be obtained for ship structures. Therefore, this research aimed to investigate the effect of fiber arrangement on the mechanical behavior of glass fiber-epoxy composite laminates. The results were expected to provide practical insights and guidelines for the effective use of glass fiber-epoxy composite in future shipbuilding.

# 2. Material and Methods

## 2.1. Materials

According to the manufacturer's recommendations, composite was made using an epoxy epichlorohydrin Eposchon A type matrix mixed with epoxy polyaminoamide Eposchon B hardener in a 1:1 ratio according to the manufacturer's specification. Glass fiber material used three types of arrangements, namely Chopped Strand Matt (CSM-300), Woven Rovings (WR-300), and Woven Cloth (WC-300), as shown in **Figure 2**. Both materials were obtained from a local distributor, PT Justus Kimia Raya Surabaya, Indonesia. The mechanical properties of the matrix material and glass fiber in this research are shown in **Table 1**.


**Figure 2.** Glass fiber material: (a) Chopped strand matt; (b) Woven rovings; (c) Woven cloth

**Table 1.** Mechanical properties of glass fiber and matric

| Property | Glass Fiber | Epoxy Matric |
|---|---|---|
| Density | 2.54 g/cm$^3$ | 1.1 g/cm$^3$ |
| Tensile Strength | 3.45 Gpa | 37 MPa |
| Young's Modulus | 72.4 Gpa | 1.8 GPa |
| Elongation | 4.3 % | 8 % |
| Flexural Strength | - | 63 Mpa |
| Poisson's ratio | 0.21 | - |

## 2.2. Composite Manufacture

Composite fabrication was made using vacuum resin infusion (VARI) closed molding method based on American Society for Testing Materials (ASTM) standard of each mechanical test, as shown in **Figure 3**. VARI fabrication method was selected due to the ability to consistently reduce voids and produce composite products with a high strength-to-weight ratio [18], [19]. The process started with cutting and arranging each glass fiber in a mold with fiber and resin ratio of 60:40. Subsequently, mold was covered with a plastic bag tightly and vacuumed until evenly distributed using a vacuum pump with a pressure of 68 cmHg. The composite was dried for 3 days at room temperature ± 25°C and given a Code to prepare for testing in the laboratory, as shown in **Table 2**. To ensure the accuracy of the data in this research, each sample was molded three times.

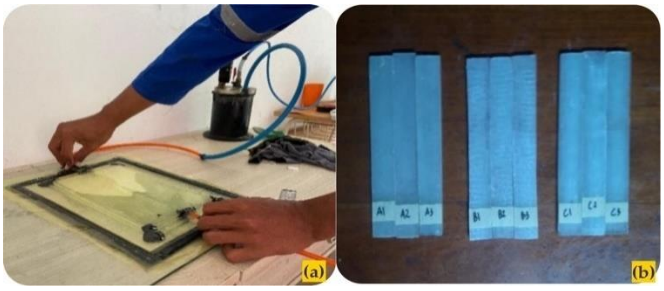


**Figure 3.** (a) VARI fabrication method; (b) Specimen test

**Table 2.** Nomenclature of codes used for composite specimens

| Composite | Code | Description |
|---|---|---|
| GFRP: Chopped Strand Matt/Epoxy | CSM | Discontinuous randomly oriented |
| GFRP: Woven Rovings/Epoxy | WR | Woven fiber bidirectional oriented |
| GFRP: Woven Cloth/Epoxy | WC | Woven cloth oriented |

## 2.3. Tensile and Flexural Strength Test

Tensile and flexural strength were investigated using a Universal Testing Machine, TARNO GROCKI, UPH-100 kN. In the Tensile test, the machine was operated at 0.5 mm/s at room temperature ± 32 °C. Specimens were made according to ASTM D 3039 standards with 3 mm thick, 25 mm wide, and 250 mm long. Eq. (1) to Eq. (3) were used to assess the results and tensile strength value of the composite was calculated by comparing the load (P) with the cross-sectional area (A) in N/mm$^2$ [5], [20].

$$\sigma = \frac{P}{A} \tag{1}$$

$$\mathcal{E} = \frac{l_i - l_0}{l_0} = \frac{\Delta l}{l_0} \tag{2}$$

$$E = \frac{\Delta\sigma}{\Delta\mathcal{E}} \tag{3}$$

Strain (Ɛ) was calculated by comparing the increase in length (Δl) with the initial size (l_0). The elastic modulus of the composite (E) was calculated by comparing the stress (σ) with the strain (Ɛ). The composite flexural strength test was conducted with the tree point bending method according to ASTM D790 standard procedures using specimen dimensions of 5 mm thick, 25.4 mm wide, and 152 mm long. The testing machine was operated at a speed of 2 mm/s and a distance between supports of 60 mm [21], [22]. The interpretation of the flexural strength for each composite was calculated using Eq. (4), where σb is the value of flexural strength (MPa), P is the load (N), L is the span length between the fulcrum (mm), H is the thickness (mm), and B is the width of the specimen (mm).

$$\sigma b = \frac{3.P.L}{2.B.H^2} \tag{4}$$

## 2.4. Hardness Shore-D Test

Hardness Shore-D test was conducted based on ASTM D2240 standard with composite specimen dimensions of 3 mm thick, 15 mm wide, and 35 mm long. Hardness test was performed indoors at a temperature of ± 25 °C using a Durometer GS-720 N Teclock Durometer, Japan, with a penetration load of 5 kg (49 N). Shore-D data was collected at 10 points from 1 second to 15 seconds, followed by the evaluation of the average value [22].

## 2.5. Impact Test

Impact test was carried out to determine the material's ability to absorb impact energy until it experienced plastic deformation. This test was conducted using the Charpy method according to ASTM E23-05 with dimensions of 10 mm thick, 10 mm wide, and 55 mm long. The specimen was placed horizontally in the opposite direction of the V-notch and impacted with a pendulum of 8.3 kg. Using Eq. (5), Is is the Impact Strength Value (J/mm$^2$), Es is the energy absorbed after impact (J), Eo is the energy without specimen (J), and A is the cross-sectional area (mm$^2$).

$$\mathrm{Is} = \frac{Es - Eo}{A} \tag{5}$$

## 2.6. Fracture Analysis

Fracture analysis of composite was carried out to understand the adhesion between glass fiber and epoxy matrix due to the tensile and flexural strength. In this research, fracture of the composite was observed using Canon EOS R50 RF-S18-45mm f/4.5-6.3 IS STM digital camera manufactured by Canon Inc. Japan. The results of the macro photo observations were analyzed using ImageJ software, which focused on qualitative confirmation of fracture.

# 3. Results and Discussion

## 3.1. Tensile Strength Analysis

Tensile strength is an important parameter that shows the amount of stress a material can withstand before damage. In this research, the characteristics of tensile test of composite were presented in a graph of the stress and strain relationship, as shown in **Figure 4**. The results showed significant differences in response between WC, CSM, and WR, with stress values of 71.66 ± 2.01 Mpa, 56.42 ± 3.83 Mpa, and 39.12 ± 3.75 Mpa, respectively. Based on the results, WC tended to have the highest stress and strain values compared to others. WC used a woven pattern that allowed glass fiber to be arranged in two directions, namely the warp and weft. This weave pattern created a more uniform and robust structure, as fiber was mechanically interwoven allowing even distribution of tensile stress across the material [16].

In woven composite, glass fiber was arranged in a very controlled and uniform orientation, leading to even load distribution. This was shown in the tensile test results of WC, which was woven in shape and had higher strength than CSM with randomly dispersed fiber. The optimal arrangement in the woven pattern allowed the material to withstand tensile loads more effectively as the applied stress was arranged with the direction of the muscular fibers. This woven pattern also allowed better interaction between glass fiber and the epoxy matrix. Fiber was closely entwined in the matrix, contributing to high load transfer, which was the main load-bearing element, leading to higher tensile strength. WC distributed stress more evenly across the material due to the intertwining of fiber. The even distribution reduced stress concentrations that could cause cracking or material failure at weak points, thereby increasing the overall tensile strength. Since fiber in WC is more regular and tightly bonded, there was less chance of micro-defects such as voids or small cracks that could weaken the material. This more homogeneous structure improved the mechanical integrity of the material.

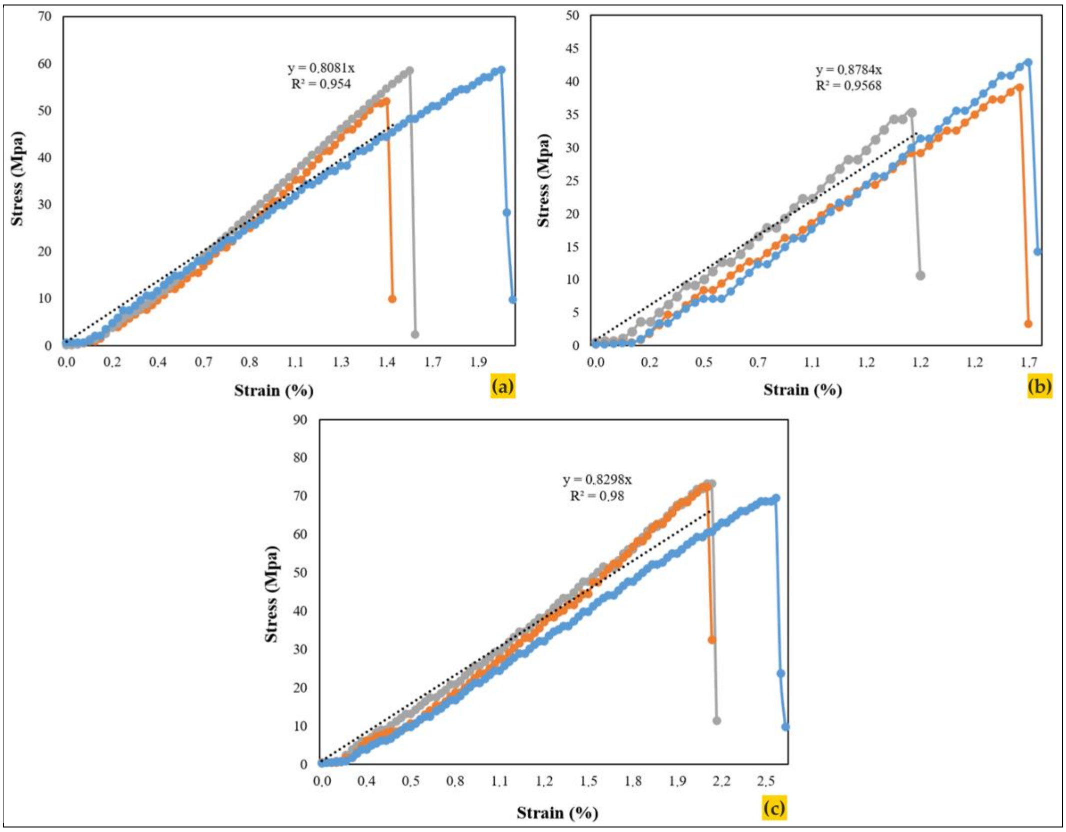


**Figure 4.** Stress-strain glass-epoxy: (a) CSM; (b) WR; (c) WC

WR had the lowest tensile strength values because fiber was woven in a less dense and coarser pattern compared to WC. The weave pattern in woven roving was looser with thicker fibers, leading to less even stress distribution. This phenomenon could lead to weak points where stress was more easily concentrated, lowering the material's tensile strength. Micro-defects such as voids or pores quickly occurred in composite structures with looser weave patterns due to the loose gaps being filled by the resin, and a shrinkage mechanism (defect) [23]. These voids caused the stress transfer of the reinforcement to the matrix to be suboptimal, acting as a starting point for failure or crack when the material was subjected to tensile loads [18]. Additionally, the effect of thicker fiber webbing caused an increase in stiffness, leading to a decrease in flexibility towards the matrix. Fiber stiffness was shown by WR higher modulus of elasticity than CSM and low elongation, including irregular stress-strain graph.

In ship construction, it is essential to determine tensile properties, including tensile strength, elasticity, and toughness of materials. This information ensures that the materials used in shipbuilding can withstand the loads and stresses during operation. Ship must withstand extreme conditions such as storms, high waves, and pressure from heavy cargo. Therefore, the determination of tensile properties allows for material selection that provides safety assurance for the crew and cargo. In this research, some literature reviews on the tensile properties of shipbuilding construction materials are presented in **Table 3**. Referring to the Design Guide for Marine Applications of Composite, WR shows superior performance to some Glass/Polyester Balsa Sandwich and Carbon/Epoxy Nomex Sandwich Prepreg composite.

## 3.2. Flexural Strength Analysis

Bending test is a mechanical method used to evaluate the properties of materials when subjected to bending loads. It provides information on the ability of materials to withstand deformation without damage. Bending test is also essential in applications where the material must withstand bending loads without cracking or breaking in ship structure due to dynamic loads caused by wave impact, hydrostatic pressure, and mechanical stress during navigation. Additionally, bending test allows the identification of the material's elastic and plastic properties. Some of the main parameters that are often measured and evaluated to understand bending characteristics are flexural strength, flexural modulus, and stiffness, as shown in **Figure 5**.

**Table 3.** Tensile properties overview of shipbuilding construction materials

| Composite Laminate | Tensile Strength (Mpa) | Modulus of Elasticity (Mpa) | Elongation (%) | References |
|---|---|---|---|---|
| Chopped Strand Matt (CSM)/Epoxy Vacuum Assist | 56.42 ± 3.83 | 2,846.74 ± 407.50 | 0.02 ± 0.003 | Current Research |
| Woven Roving (WR)/Epoxy Vacuum Assist | 39.12 ± 3.75 | 2,906.53 ± 409.58 | 0.013 ± 0.003 | Current Research |
| Woven Cloth (WC)/Epoxy Vacuum Assist | 71.66 ± 2.01 | 3,006.13 ± 353.35 | 0.024 ± 0.002 | Current Research |
| Solid Glass/Polyester Hand Lay-Up | 138 | 9,660 | n/a | [24] |
| Glass/Polyester Balsa Sandwich Vacuum Assist | 41 | 2,760 | n/a | [24] |
| Glass/Vinyl Ester PVC SCRIMP Sandwich | 41 | 2,760 | n/a | [24] |
| Solid Carbon/Epoxy Filament Wound | 607 | 60,000 | n/a | [24] |
| Carbon/Epoxy Nomex Sandwich Prepreg | 62 | 3,450 | n/a | [24] |

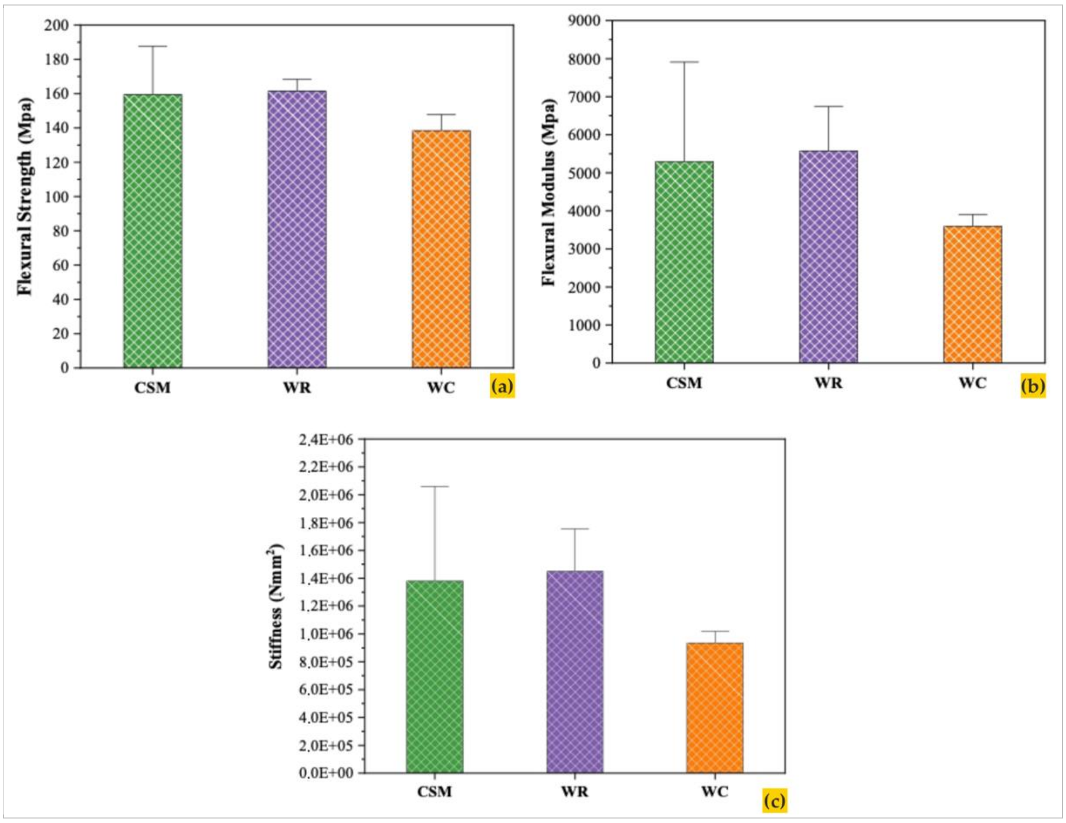


**Figure 5.** (a) Flexural strength; (b) Flexural modulus; (c) Stiffness

Flexural modulus significantly influenced material stiffness in bending tests. Materials with high flexural modulus would have greater stiffness, meaning the material will experience less deformation under a specific bending load. In the bending test results, WR had the highest flexural strength value of 161.44 Mpa, followed by CSM at 159.40 Mpa, and WC at 138.40 Mpa. Generally, materials with a high flexural modulus often have an elevated flexural strength because rigid materials tend to be more robust to withstand loads before breaking. This was shown by the linear relationship between flexural strength, flexural modulus, and stiffness, presented in **Figure 5**.

The results of WR with high strength compared to CSM and WC were closely related to tensile test presented in **Table 2**. The high value of the bending modulus of elasticity caused WR to be stiffer, leading to reduced tensile strength value. To overcome this phenomenon, hybrid arrangement of glass fiber between CSM, WC, and WR should be considered for future research [25]. The hybrid effect of tow and ply caused stress synergy to be distributed more evenly, making composite more resistant to complex loading, such as tensile and compressive [26].

## 3.3. Hardness

The hardness value of the composite material was used to determine the strength and resistance under certain conditions, such as significant stress in ship structure. As shown in Figure 6, the average hardness value of each composite had no significant difference, namely CSM 76.77 ± 0.5 HD, WR 75.66 ± 0.66 HD, and WC 79.22 ± 0.69 HD. Compared to others the high hardness value of WC was caused by the binding of polyester matrix and filling the void of fiber interlayer. The regular pattern of WC provided a more stable distribution of matrix in maintaining the shape of one another. This configuration made WC denser and more deformation-resistant, leading to a higher hardness value [5], [22].

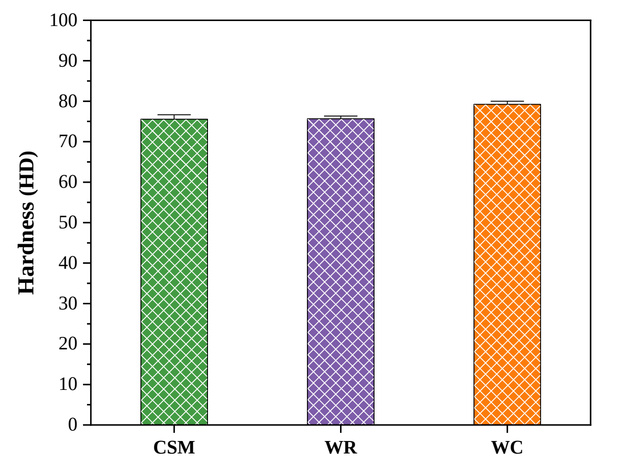


**Figure 6.** Hardness

## 3.4. Impact Resistance

Impact test was conducted to determine the amount of energy material could absorb after receiving a sudden load. By conducting impact tests, engineers and shipbuilders ensured that ship was designed and built to withstand the impact and harsh conditions during operation, thereby ensuring safety, reliability, and durability. This test was carried out to determine the ability of the material to withstand the impact and harsh conditions without damage. The results of impact resistance values on each of CSM, WR, and WC were presented in Figure 7.

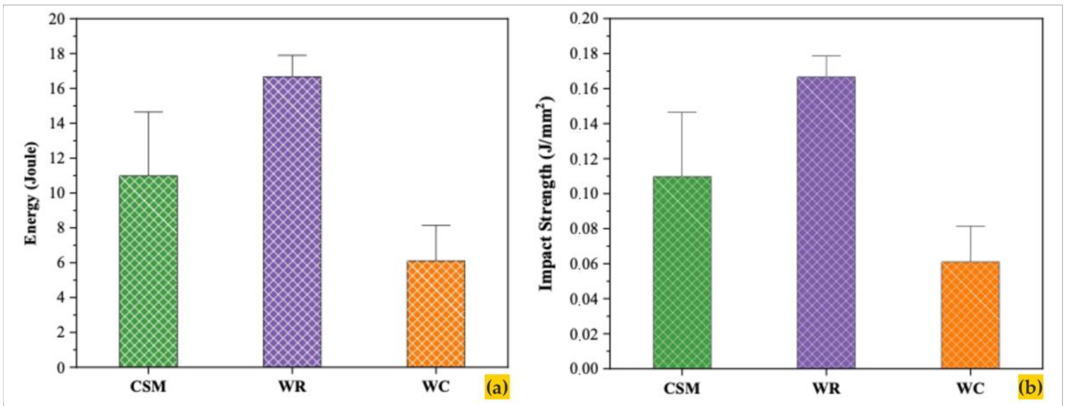


**Figure 7.** (a) Impact energy; (b) Impact strength

Composite materials can absorb energy during impact through elastic and plastic deformation and mechanisms such as cracks, delamination, and fiber breakage. Generally, as energy received from the composite increases, the deformations become greater. Materials with high impact strength can absorb more energy before reaching the point of failure. In this research, the highest impact resistance value of 0.166 J/mm$^2$ was found in WR, followed by CSM at 0.109 J/mm$^2$, and WC J/mm$^2$. These results were also confirmed by high tensile strength and modulus of elasticity values of WR. Therefore, WR with a larger fiber arrangement had stiff and slightly ductile properties, generating high-impact energy and weak tensile loads. The impact resistance increased along with the stiffness of the glass fiber-reinforced composite [27]. This occurred because fiber would carry the maximum share of impact energy exposed to the composite material. WR pattern resembling a jute basket pattern had good dynamic resistance characteristics in composite [28]. This pattern developed a stiffer structure in WR compared to WC, which helped the material to withstand higher loads and provided better resistance to deformation, thereby preventing fracture under impact loading conditions.

## 3.5. Fracture Analysis

Macro digital photography and image topography were used to analyze composite specimens subjected to tensile and flexural fracture. The main objective was to understand the adhesion between fibers and matrix under loading. Figure 8 shows the surface images of CSM, WR, and WC laminate composite specimens under tree point bending loading. Strain distribution was observed to be strongly related to the microstructure (layer orientation) of GFRP. However, the uneven distribution showed the heterogeneous mechanical behavior of these composite materials when deformed [12]. Figure 5b shows the result of poor stress transfer from fibers to the epoxy matrix, causing severe damage to the matrix surface. Some mechanisms, such as pullout, debonding, or delamination, were shown in WR but less in CSM and WC [12], [28], [29]. This was also confirmed by the image analysis results, showing that CSM and WC surfaces had flatter and neater fractures than WR. The irregular fracture in WR was due to several voids between fiber and matrix that triggered the crack, showing low tensile strength. This phenomenon also occurred in ALF-Epoxy and IPPI composite, where the addition of carbon powder and fiber layers reduced the cracks in intra-layer composite [2], [5], [28]. Therefore, several solutions were offered, such as adding fillers or hybridizing fiber arrays to improve adhesion/bonding [12]. In shipping industry, adhesion played an important role in developing composite materials to improve structural performance, efficiency, and resistance to harsh environmental conditions. Due to the ability to combine various materials into a strong and lightweight whole, adhesion enabled continuous ship design and

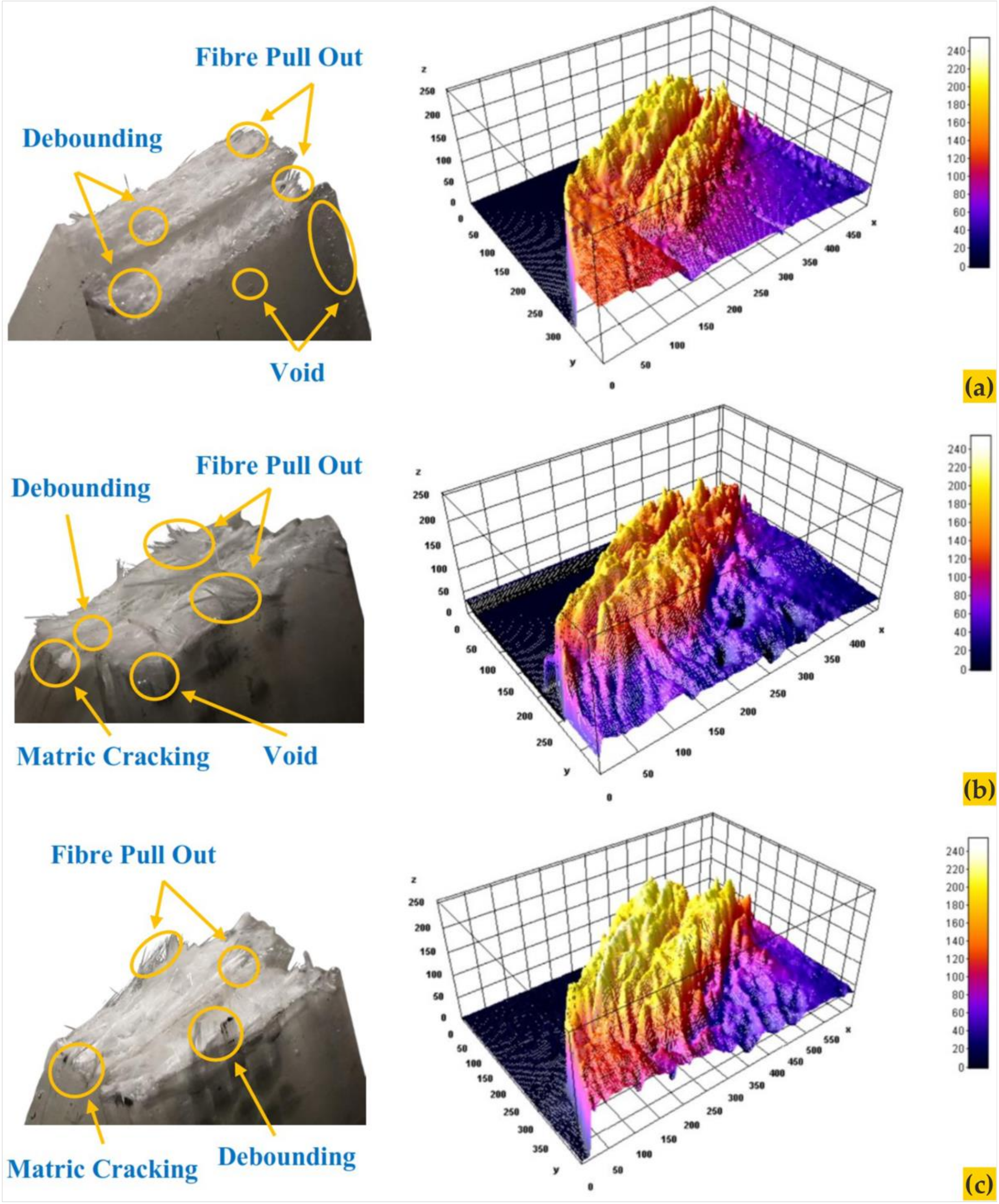


**Figure 8.** Fracture macro and imageJ analysis: (a) CSM; (b) WR; (c) WC

construction innovation [1]. In this research, mechanical dynamic analysis showed that the stacking sequence of fabrics with different weave types significantly affected the composite storage modulus, loss modulus, and loss factor [28].

WC and CSM tended to have a better fracture due to the tighter interlacing between yarn in the warp and weft direction. This allowed for even stress absorption and distribution, thereby reducing stress concentrations that could lead to fracture. WC restricted yarn movement more effectively than WR. In WC arrangement, yarn in the warp and weft directions interlock, reducing relative displacement and increasing resistance to deformation and fracture. However, fractures tended to occur in a more controlled manner in WC due to tighter weave structure. This allowed fractures to occur at a localized microscopic level, preventing the rapid distribution that could lead to complete structural failure. Some images show localized de-bonding or micro-cracking resulting in fracture.

# 4. Conclusion

In conclusion, this research successfully explored the effect of fiber arrangement on the mechanical behavior of glass fiber-epoxy composite laminates for ship structures. The results showed that WR arrangement excelled in various mechanical behaviors, which included flexural strength of 6992.6 Mpa, hardness of 75.66 HD, and impact of 0.1789 J/mm, although the tensile strength was weak. The high tensile strength value obtained for WC of 73.24 Mpa was higher than Glass/Polyester Balsa Sandwich and Carbon/Epoxy Nomex Sandwich Prepreg composite based on the Design Guide for Marine Applications of Composite. Fracture analysis showed that the composite experienced many pullouts, debonding, and delamination mechanisms. Furthermore, WC faults showed the result of poor stress transfer from fiber to the matrix, leading to a severely damaged and irregular composite. This phenomenon was also confirmed by the image analysis results, where CSM and WC surfaces had flatter and neater fractures compared to WR. The fracture was due to the tighter interlacing between yarn in the warp and weft direction, which allowed for even stress absorption and distribution, reducing stress concentrations. WC restricted yarn movement more effectively than WR. In WC arrangement, yarn in the warp and weft directions interlock reduced the relative displacement and increased resistance to deformation as well as fracture. This research showed that regular and tighter fiber arrangements provided better mechanical properties than random fibers. Therefore, fiber arrangement could be recommended when developing high-performance polymer composite materials, particularly in ship construction.

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# Authors' Declaration

**Authors' contributions and responsibilities** - M.R.G., W.A.W.: The authors made substantial contributions to the conception and design of the research; A.P., W.N.F., M.R.G., W.A.W.: The authors took responsibility for data analysis, interpretation, and discussion of results; M.R.G., W.A.W.: The authors read and approved the final manuscript.

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**Availability of data and materials** - All data is available from the authors.

**Competing interests** - The authors declare no competing interest.

**Additional information** – No additional information from the authors.

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