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ORIGINAL ARTICLE

Mechanical performance of laminated boards using polyester with jute and glass fabrics

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Abstract

Hybrid laminates are formed by layers of different reinforcements in a matrix to combine distinct properties. Hybridization aims to leverage the advantages of materials, creating a composite with greater mechanical performance and sustainability. This study investigates the replacement of synthetic reinforcements by natural ones. Six composite configurations are analyzed, using glass (G) and jute (J) fabrics with 145 GSM and 245 GSM, respectively, two pure (GGG and JJJ) and four hybrids (GJG, GVG, GGJ and JJG), produced by manual lamination followed by compression. The tensile strength tests (σ), according to ASTM D3039, revealed that the GJG (σ = 87.37 MPa) presented performance closer to the GGG (σ = 89.60 MPa), followed by the GGJ, JJJG, JGJ and JJJ. The resistance is mainly influenced by the sequence of layers, method of manufacture and volumetric fraction of reinforcements. Despite the manufacturing limitations, composites have demonstrated viability for applications with lower structural requirements.

Keywords: *fractography, hybrid polymer composites, mechanical properties, sustainability.*

Data Availability: All data supporting the findings of this study are available from the corresponding author upon request.

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1. Introduction

Synthetic materials, especially those derived from oil, are increasingly being replaced by natural and renewable options, driven by market trends that emphasize environmental protection across several industrial sectors. This transition has motivated research on composites materials, defined as mixtures of different elements combined to achieve specific properties[1,2].

Widely used in automotive and aeronautical industries for weight reduction and mechanical efficiency, composites have gained renewed attention with the sustainable appeal of plant-based natural fibers. This practice aims to produce alternatives to synthetic fibers, such as glass, which are widely used[3-11]. Therefore, plant fibers are evaluated as promising due to factors such as availability, biodegradability, low cost and interesting physical-mechanical properties[12-18].

Research with this bias has already been carried out globally. The use of additives such as nanoclay in synthetic and natural fiber hybrid polymer composites has already been investigated[19], resulting in improvements in mechanical and wear resistance. The authors proposed hybrid composites obtained from E-glass fiber mat, with a thickness of 1 mm and a density of 2.6 g/cm^3. In addition to the variation in the type of reinforcement, the influence of the addition of nanoclay was also considered, allowing discussion of how glass morphology, processing conditions, and the presence of additives can affect mechanical behavior.

It is known that in the case of hybrid laminates, the sequence of layer positioning can significantly alter stress transfer, stress distribution, and, consequently, the overall performance of the material. In this context, it is essential to assess how different structural configurations can contribute to mitigating losses in mechanical properties, while expanding the potential for partial replacement of synthetic reinforcements with natural fibers, aligning technical performance and sustainability.

In addition to the choice of constituent materials, the arrangement of layers in laminates is a determining factor for final performance. It has been shown that different stacking sequences between natural and synthetic fibers can significantly alter properties such as tensile and flexural strength, with alternating arrangements providing superior results[20].

Furthermore, the mechanical performance of polymer composites is strongly associated with three main factors: type of matrix, volume fraction of reinforcements and manufacturing method. The choice of matrix directly influences interfacial adhesion and tensile strength. Studies show that resins such as epoxy generally provide better mechanical results when compared to other matrices, such as polyester or polyethylene[21,22] although polyester is still widely used due to its cost-effectiveness[23].

The manufacturing process has a direct impact on the mechanical properties of composite materials[24]. Research shows that methods such as infusion and vacuum lamination provide better impregnation, less porosity and greater mechanical resistance than the hand lay-up method[25-27]. Despite this, the hand lay-up method has advantages due to its low cost and simplicity, still viable for medium-performance composite materials[28].

The volume fraction of the reinforcements is also decisive, as it has a direct impact on the stiffness, strength and energy absorption of the final material. Hybrid composites that properly integrate natural and synthetic fibers can optimize structural performance while reducing environmental impact compared to conventional materials of exclusively synthetic origin[29-32]. Table 1 shows the characteristics of hybrid composites with different glass (G) and jute (J) fiber stacking configurations found in academic literature.

Previous studies have described different failure modes depending on the stacking configuration. Figure 1 compiles the main highlights observed in the fracture regions in different types of hybrid composites with polymeric matrices reinforced by glass (G) and jute (J) fibers, according to various authors.

The present study aimed to contribute to the development of sustainable composites by investigating the feasibility of replacing synthetic reinforcements with natural fibers, prioritizing the analysis of the influence of layer arrangement in hybrid laminates. Six composite configurations laminated with polyester matrix reinforced with jute (J) and glass (V) fabrics in different positions are evaluated: two pure GGG and JJJ and four hybrid arrangements - GVG, GJG, GGJ and JJG. Combinations are identified that minimizes losses in mechanical performance compared to pure synthetic composite, while incorporating materials with a lower environmental impact.

Table 1. Mechanical properties of jute-glass hybrid laminates found in the literature.

Author	σ (MPa)	Configuration	Matrix	Manufacturing method	Volumetric fraction (%) (GSM)	
					Jute	Glass
Souza et al.[33]	73.49 (± 6.20)	GGJ	Polyester	Hand lay-up	-	-(200)
	73.03 (± 3.58)	GJG				
	48.46 (± 4.16)	GJJ				
	67.13 (± 4.86)	JGJ				
Almeida et al.[34]	86.35 (± 2.25)	JGJ	Polyester	Hand lay-up	12.48 (m/m)	6.00 (m/m)
Varela[35]	40.88 (± 1.74)	GJGJGJGJ	Polyester	Compression molding	14.30 (m/m)	
Hasan et al.[36]	121.134	JGGJ	Epoxy	Vacuum infusion	46.18 (m/m)	
					46.03 (m/m)	
	115.284	GJJG				
					-	(400)
Queiroz et al.[37]	20.26 (± 1.44)	JJGJJ	Polyester	Hand lay-up	-(200)	-(306)
Mahmud et al.[38]	~50	JGGJ	Polyester	Hand lay-up	31.37 (285)	38.11 (360)
	50.00~100.00	GJJG			34,66 (285)	41,34 (360)
Gujjala et al.[39]	116.00	GGGG	Epoxy	Hand lay-up	18.50	
	52.00	JJJJ			16.60	
	76.00~80.00	GJGJ			17.50	
	72.00~76.00	JGGJ			17.50	
	84.00~88.00	GJJG			17.50	
Costa et al.[40]	18.53 (±3.49)	JJGJJ	Polyester	Hand lay-up	-	
Fontes[41]	40.10 (±2.70)	JJGJJ	Polyester	Hand lay-up	-	
					(306.00)	(600.00)
Alves[42]	199.70 (± 11.4)	GJJG	Epoxy	Vacuum infusion	31.30 (m/m) (450.00)	68.70 (m/m) (800.00)
Sezgin & Berkalp[43]	37.84	JJJJ	Polyester	Vacuum infusion	16.00	
	199.08	GGGG			44.00	
					(200.00)	(200.00)
	100.12	JGJG			21.00 (200.00)	12.00 (200.00)
	103.21	JGGJ			22.50 (200.00)	12.50 (200.00)
	84.84	GJJG			22.50 (200.00)	12.50 (200.00)
Mahmud et al.[44]	140.86	GGJJJJGG	Polyester	Compression molding	40.10(270)	47.40(605)
	114.16	JJGGGGJJ			36.30 (270)	43.60 (605)

2. Methodology

A polymer matrix unsaturated terephthalic polyester resin was used, supplied by Ara Química, under the trade name Arazan AZ 1.0 #34. The resin was cured by adding methyl ethyl ketone peroxide (MEKP), commercially identified as Permec D-45, in a proportion of 0.7% by volume, according to the manufacturer's recommendations. Table 2 shows the properties of the resin, which is widely used in industry due to its good mechanical performance, ease of processing and low cost.

Bi-directional glass fiber and jute fabrics were used as reinforcement materials, with weights of 145 GSM and 245 GSM, respectively. The fabrics were purchased from a local business and manually cut, 0.28 m x 0.32 m, to enable the reinforcement layers to be assembled in the configurations defined for lamination. Figure 2 shows how the fabric arrangements with laminated composites are arranged.

The experimental procedures used to produce the composites, from the preparation of laminated plates to the removal of specimens for tensile strength tests and fractographic analysis, are illustrated in Figure 3.

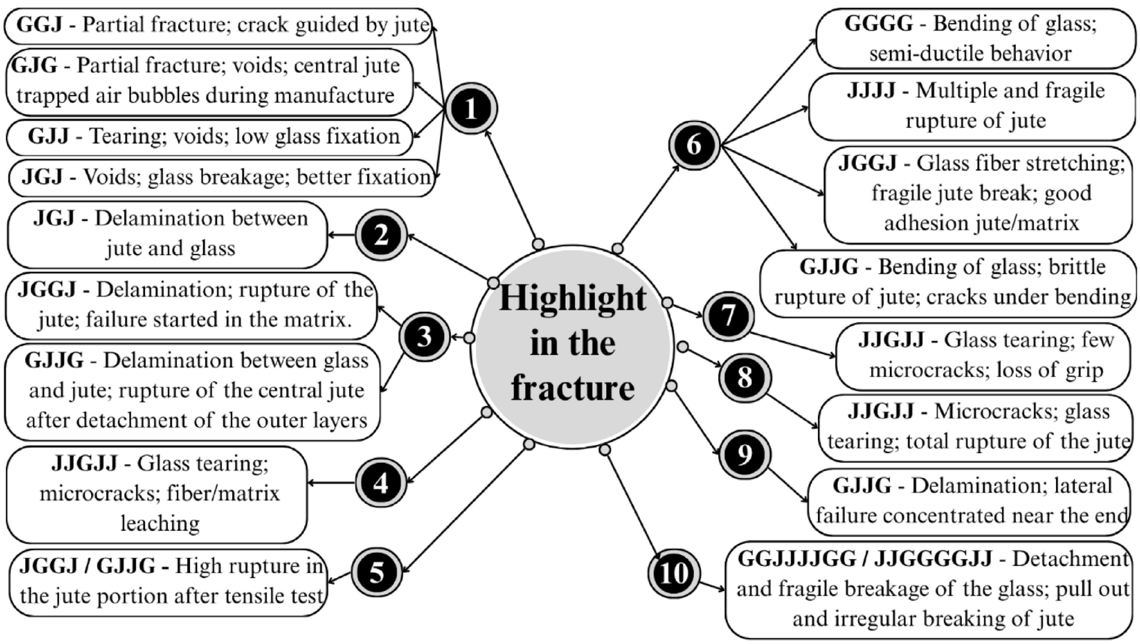

Figure 1. Analysis of fracture regions in different hybrid composite configurations. Legend: 1) Souza et al.[33]; 2) Almeida et al.[34]; 3) Hassan, Islam e Hassan[36]; 4) Queiroz Jr et al.[37]; 5) Mahmud et al.[38]; 6) Gujjala et al.[39]; 7) Costa et al.[40]; 8) Fontes[41]; 9) Alves[42]; 10) Mahmud et al.[44].

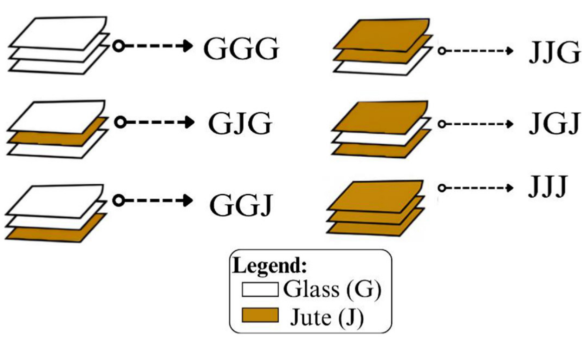

Figure 2. Stacking configurations of glass and jute fabrics in the proposed laminates.

Table 2. General properties of polyester resin.

Resin	Density (g/cm³)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation (%)
Polyester	1.2 – 1.5	40 – 90	2.0 – 4.5	2.0

Source: Hul and Clyne[45].

The jute and fiberglass fabrics were cut into 0.28 m × 0.32 m sections. A total of 24 fabrics, 9 of which are fiberglass (145 GSM) and 15 jute (245 GSM). After cutting, the process of manufacturing the laminated boards began to produce the six composites.

Four boards were made with hybrid reinforcement configurations and two with non-hybrid reinforcements. Before the lamination stage, the fabrics are weighed on a precision scale, and the jute fabrics were evaluated at two points: before and after drying in an oven for five minutes, to eliminate the moisture. The average loss of mass due to drying the jute is 10.24%.

Each laminated composite was molded using two plywood boards with dimensions of 0.36 m × 0.40 m × 0.013 m, previously coated with transparent polyester film (transparency for back projection) and adhesive tape, as shown in Figure 4a. The reinforcing fabrics (glass and jute) are positioned between the plywood sheets, according to the apparatus shown in Figure 4b.

Once the lamination process is complete, the assemblies are placed in a hydraulic press, where a load of 0.5 tons is applied for a period of two hours, allowing the materials to cure properly. At the end of the process, the final laminated plates are obtained.

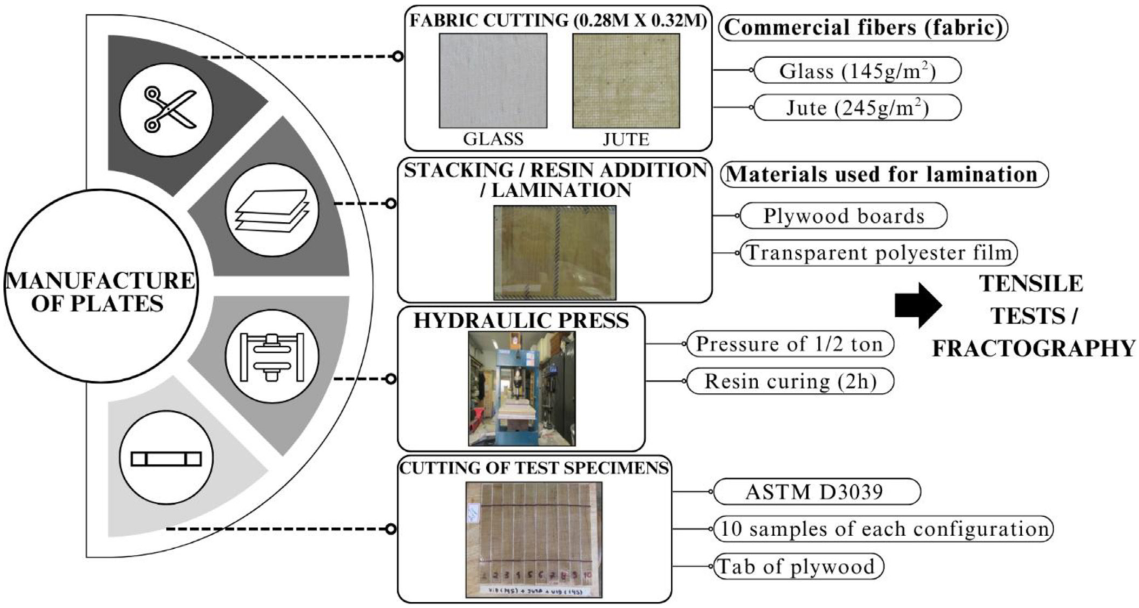

Figure 3. Flowchart of the stages for preparing the sheets and removing the specimens for the tensile tests.

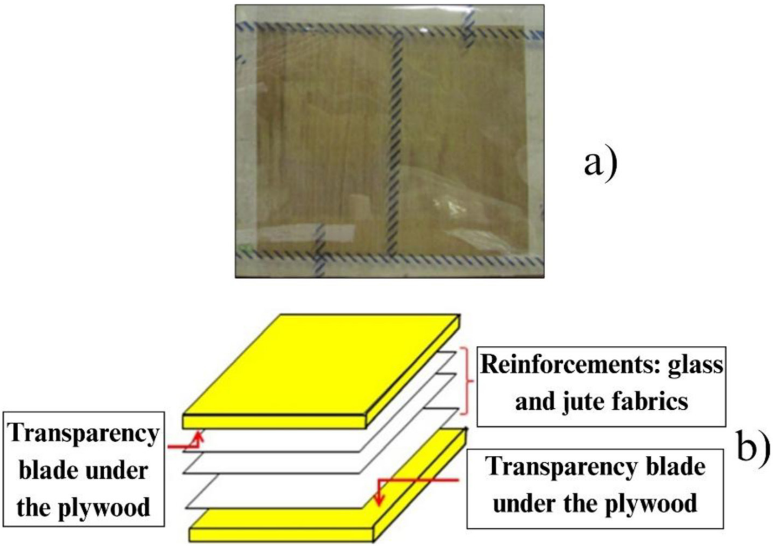

Figure 4. Laminate manufacture: a) Plywood board covered with transparency and adhesive tape; b) Schematic illustrating the manual lamination process.

After the manufacturing stage of the plates, they were subsequently sectioned to obtain the test specimens, according to the dimensions standardized by ASTM D3039. Each plate allowed an average of 10 specimens to be made. Figure 5a shows an example of a plate after making the necessary cuts to extract the specimens. To prepare these samples, reinforcement tabs (Tabs) are glued at the ends using Tek Bond structural adhesive no. 725, as shown in Figure 5b.

Three types of materials are evaluated for making the Tabs: plywood, glass and 180 granulation sandpaper, with plywood being the preferred material adopted in most samples tested. The tensile tests were carried out in accordance with the procedures established in the ASTM D3039 standard, at the Materials Engineering Laboratory of the Federal Institute of Pará (IFPA), located in Belém-PA.

The tests were performed on an Arotec universal testing machine, model WDW-100E, operating at a load application speed of 2 mm/min and a load cell with a capacity of 5 kN, under room temperature conditions. Once the tensile strength tests had been completed, the fracture surfaces of the specimens were analyzed to identify the main failure mechanisms involved. A visual analysis was carried out using a stethoscope.

3. Results and Discussions

The manufacturing process produced boards with uniform geometry and good surface finish, ensuring consistent tensile behavior. Polyester sheets during pressing improved surface leveling, resin impregnation, and handling, while the pressure applied during the first 24 h of curing was crucial for the final composite quality.

3.1 Tensile mechanical properties

The tensile tests were satisfactory, as the specimens failed in the region of the useful length. The use of tabs to protect the ends of the specimens was efficient, as no crushing or slipping occurred during the tests. Table 3 shows the properties stress at maximum load (σ [MPa]) and modulus of elasticity (E [GPa]).

It is found that from the increase in the volumetric fraction of jute, there are losses of stiffness and mechanical strength. Figure 6 shows the characteristic Stress x Strain curves of the composites reinforced by the combination of jute and glass to evaluate the mechanical behavior of the materials produced.

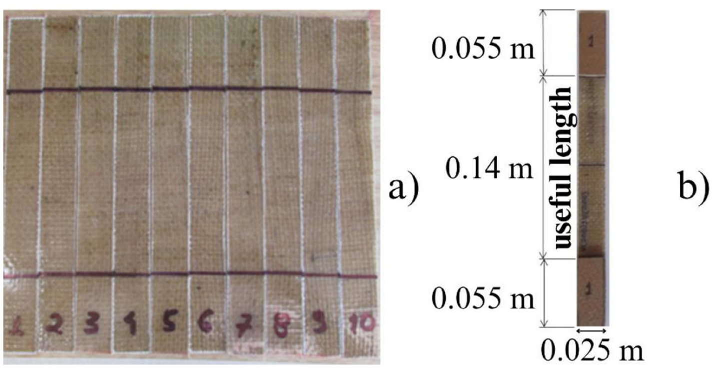

Figure 5. Preparation of test specimens: a) sectioned test samples; b) final dimensions of representative sample.

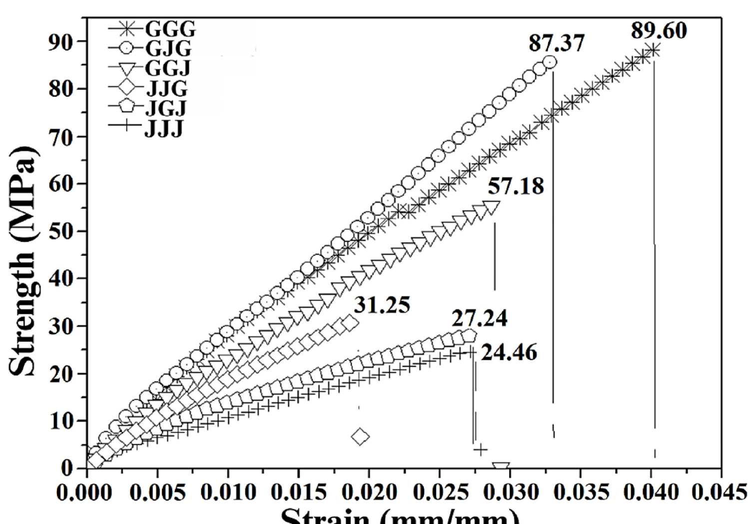

Figure 6. Characteristic curves of the composites with the configurations: GGG, GJG, GGJ, JJG, JGJ and JJJ.

Table 3. Mechanical properties of hybrid laminates with different configurations.

Laminated composite	Volumetric fraction (%)		σ (MPa)	E (GPa)
	Jute	Glass		
GGG	-	15.35	89.60 ± 3.04	2.35 ± 0.00
GJG	10.43	7.49	87.37 ± 5.05	2.43 ± 0.12
GGJ	10.57	7.36	57.18 ± 5.88	1.89 ± 0.19
JJG	15.20	2.96	31.25 ± 3.09	1.44 ± 0.17
JGJ	14.63	3.06	27.24 ± 2.46	1.06 ± 0.12
JJJ	18.09	-	24.46 ± 0.74	1.01 ± 0.15

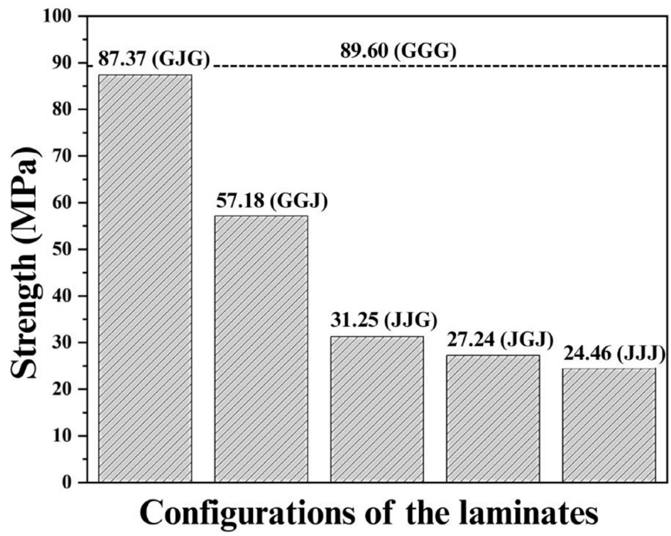

Figure 7. Comparative graph of the tensile strength of hybrid composites in relation to pure glass laminate.

The graph, based on the mean curves of each stacking configuration, shows that laminates with more fiberglass layers (GGG, GJG, GGJ) present greater deformations. Replacing one glass layer with jute in the GJG configuration slightly reduces tensile strength (≈2.5%) but increases stiffness (≈3.4%). However, positioning jute at the laminate end (GGJ) causes larger losses (≈36.2% in strength and 19.6% in stiffness). The JJG hybrid, with two jute layers, reduces strength and modulus by 65.12% and 38.72%, respectively, while the JGJ configuration shows even greater losses (≈69.6% and 54.9%). Full replacement with jute (JJJ) leads to the most significant reduction, with strength and stiffness 72.70% and 57.02% lower than GGG. Figure 7 compares these results with the purely synthetic laminate.

Relating the results presented to values obtained in the literature, it can be seen that although polyester resin has inferior mechanical properties compared to epoxy[21,23], the efficiency of stacking and the synergy between the reinforcements, especially in the GJG configuration, compensate for its limitations, as reinforced by Jiang et al.[22], who highlighted the importance of the matrix-reinforcement interface in load transfer and mechanical performance.

The limitations of manual lamination, such as greater porosity and lower impregnation quality[25,26], justify the lower resistance compared to vacuum infusion[27,28]. Even so, pressure applied with a hydraulic press reduced defects, improving performance and showing that layer arrangement optimization can offset process limitations, as in GJG. Although GGG had the highest strength, hybrids with less glass fiber (GJG and JJG) also performed well, confirming that combining natural and synthetic fibers allows good mechanical properties with lower cost and environmental impact[29-31].

Almeida et al.[34] that explored the configuration JGJ in polyester matrix through the technique of manual lamination obtained a superior tensile strength, even using less efficient manufacturing method with regard to obtaining better mechanical properties of the composites produced, as the authors used continuous and longitudinally aligned fibers in relation to the application of the tractive load, sense that gives the material greater mechanical strength. However, in the present study, bidirectional woven fabrics were employed, whose discontinuous yarn structure and higher heterogeneity reduce the efficiency of stress transfer, which may justify the lower tensile strength observed in comparison.

Higher jute fabric contents, as reported by Queiroz Jr.[37] and da Costa et al.[40], led to lower tensile strength across all configurations analyzed. Fontes[41] also obtained lower resistance than the present GJG and GGJ hybrids, while Mahmud et al.[44] reported superior results, associated with a higher number of glass fiber layers. The asymmetrical stacking sequence also influences mechanical behavior.

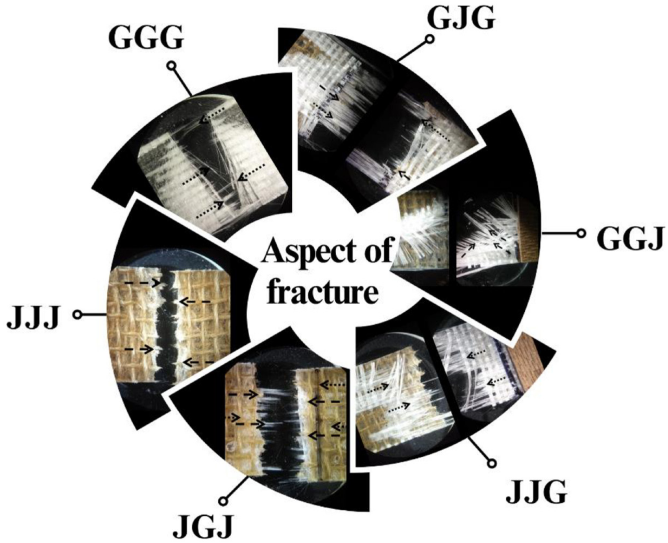

Figure 8. Fracture surface of the test specimens.

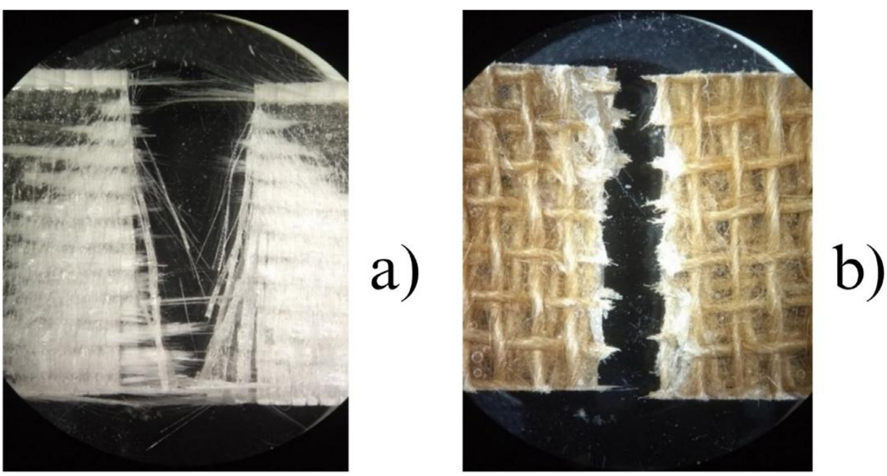

Figure 9. Fracture aspect of the composites (a) GGG and (b) JJJ.

Varela[35] proposed the GJGJGJGJJ laminate, which showed inferior performance compared to GJG and GGJ of this study, indicating that alternating natural and synthetic layers does not benefit composite strength.

3.2 Analysis of fracture surfaces

For the understanding of the variation of the composite's properties, the fractographic analysis of the region, where the failures occurred is fundamental. Figure 8 shows the failure surface of the test samples with all stacking configurations to be assessed.

After testing, the total fracture samples is observed for all stacking configurations, without partial ruptures. Figure 9 exposes the fracture surface of the purely synthetic (a) (GGG) and natural (b) (JJJ) composites.

A linear fracture is verified for the configurations (GGG) and natural (JJJ) with rupture of the warp wires, in the direction of longitudinal alignment, in relation to the applied loading. The JJJ break can be described as fragile and multiple, consistent with the pattern described above for pure jute laminates, Gujjala et al.[39] Such failure modes are attributed to the discontinuous structure of jute yarns, which results in lower energy absorption capacity before rupture. Figure 10 shows the fracture aspect of the samples manufactured with stacking (a) GJG and (b) GGJ.

In GJG (Figure 10a), both jute layers fractured in the weft and warp regions (dotted arrows), along with glass fibers (pointed arrows), which broke in the longitudinal loading direction, resulting in symmetric fracture without fiber orientation variation, consistent with reports of central jute rupture in intermediate laminates[36,38,44]. In GGJ (Figure 10b), the jute fabric detached earlier than the glass reinforcement, and only the glass fibers fractured (dashed arrows), showing post-failure orientation variation, a mechanism also previously observed[33].

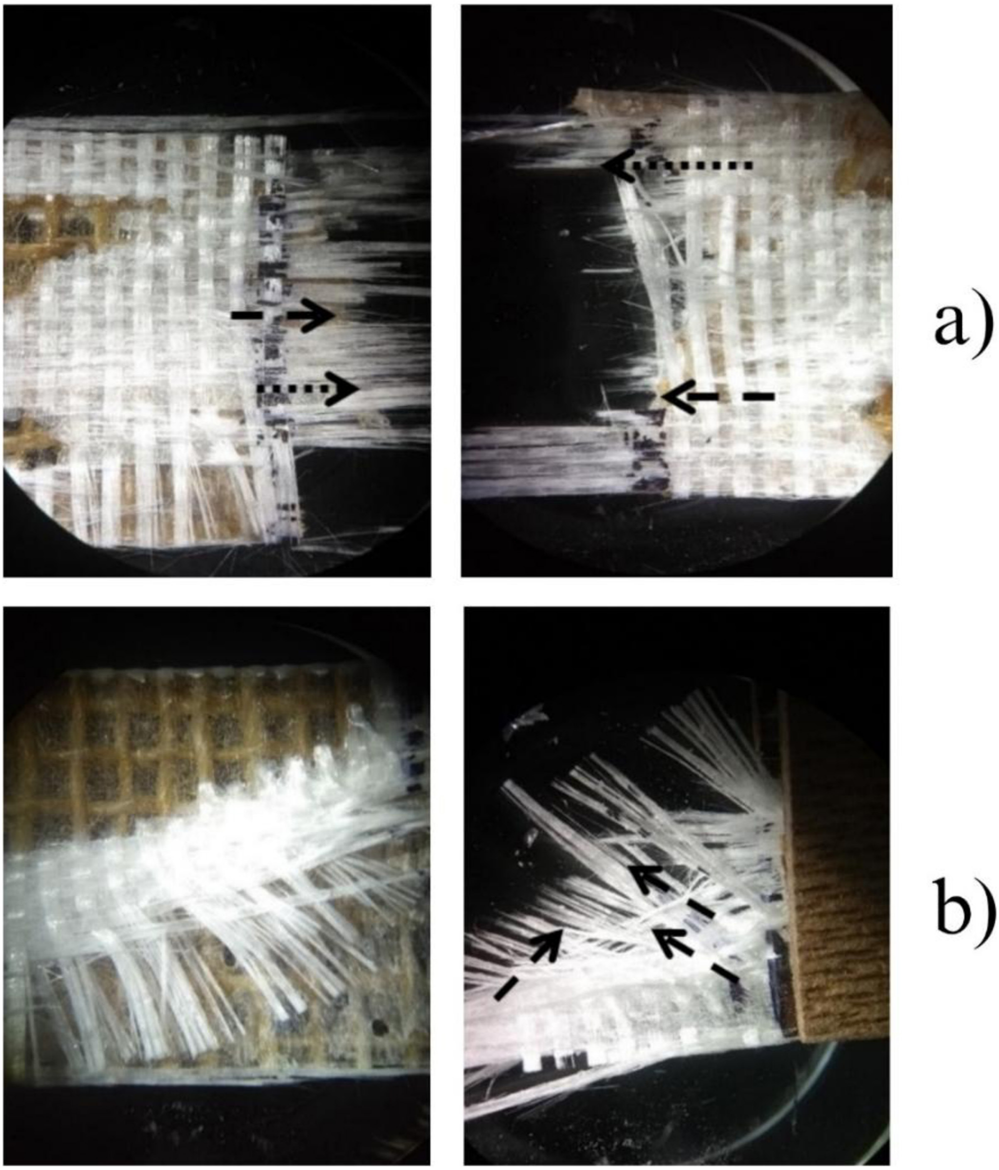

Figure 10. Fracture aspect of the composites (a) GJG and (b) GGJ.

Therefore, if one layer of the synthetic reinforcement GGG composite is replaced by natural reinforcement, GJG and GGJ configurations, different property values are found due to the influence of the material layer. The symmetrical aspect of GJG configuration provided greater mechanical strength due to greater effectiveness of the synthetic reinforcement in resisting the longitudinal load without change in orientation of the warp wires. Figure 11 shows the fracture aspect of test samples (a) JJG and (b) JGJ.

For the hybrid laminates JJG and JGJ, fracture mainly affected the glass fibers due to their higher resistance, with rupture aligned to the fabric warp. In JJG (Figure 11a), the glass layer detached (dashed arrows), explained by material heterogeneity and the two consecutive jute layers, which increased the natural fraction's response under tensile loading, ensuring good resistance. In JGJ (Figure 11b), jute and glass fibers fractured similarly, indicating balanced stress distribution. This effect results from placing the glass layer at the core, improving its fixation[33].

Thus, replacing two glass fabric layers with two jute layers causes greater mechanical performance loss than replacing only one. This occurs due to the fabric constitution: jute yarns are formed from short, randomly sized macerated fibers, while glass yarns consist of aligned continuous fibers, which better resist tensile load along the warp direction. It should be noted that, while most of the studies available in the literature present representative images or point micrographs with generic descriptions of fracture aspects, even of different hybrid configurations, this study opted for a more targeted approach, focusing individually on the failure modes observed in each of the six laminate configurations.

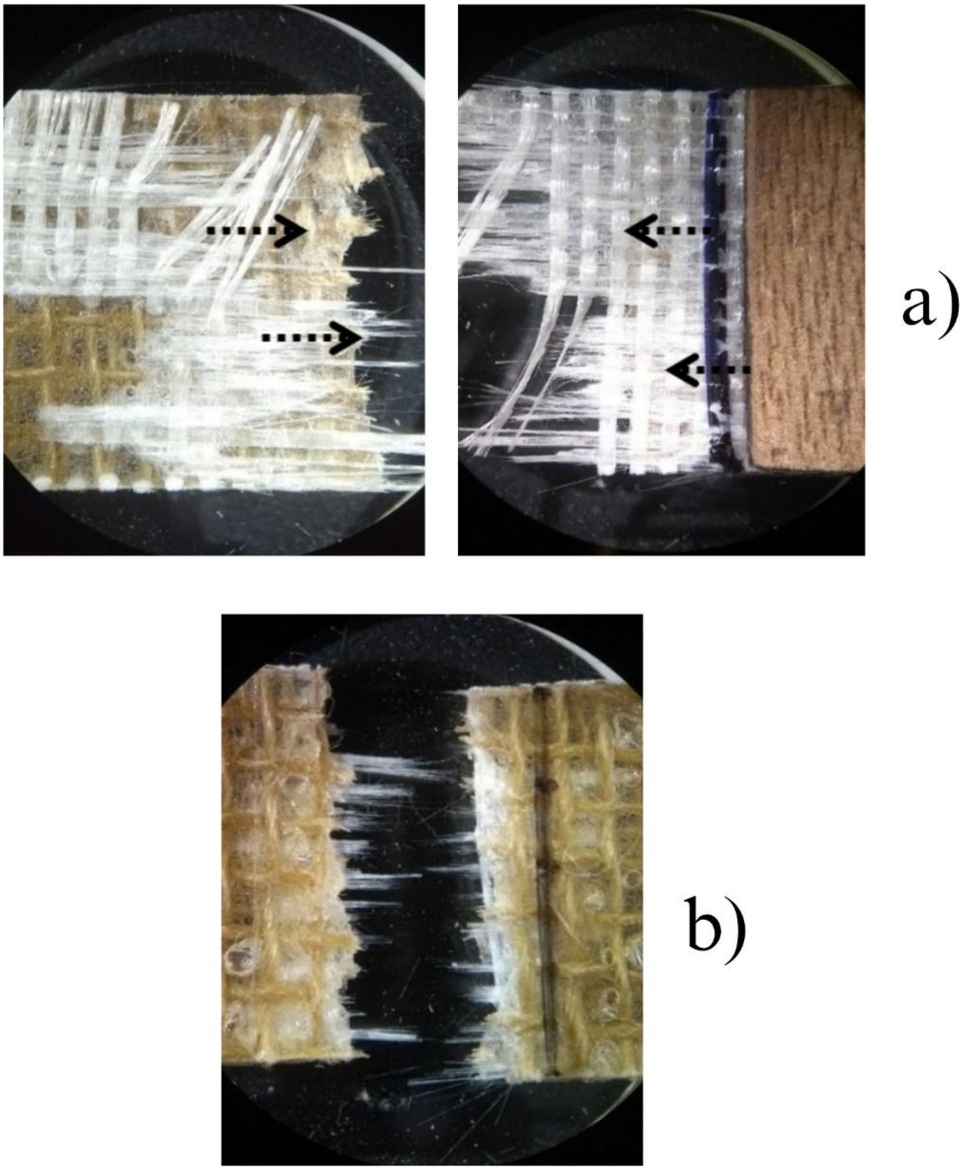

Figure 11. Fracture aspects of the composites (a) JJG and (b) JGJ.

4. Conclusions

Based on the adopted procedures and results, replacing synthetic reinforcements with natural fibers, combined with suitable stacking, can yield hybrid composites with satisfactory performance. The GJG configuration showed tensile behavior similar to the purely synthetic laminate (GGG), indicating that jute as an intermediate layer does not significantly reduce strength. Layer sequence, volumetric fraction, and manufacturing process directly affect behavior, and although manual lamination limits uniformity, the hybrids proved viable for low to medium structural applications. Thus, jute incorporation appears as a sustainable alternative, reducing environmental impact and enabling use in less critical sectors. Additionally, the detailed fractographic analysis of the six laminate configurations, uncommon in the literature, revealed specific failure mechanisms related to stacking, providing technical insights for future optimization of hybrid composites.

5. Author's Contribution:

- **Conceptualization** – Jair Francisco Souza Magalhães; Larissa dos Santos Borges; Roberto Yuri Costa Dias; Roberto Tetsuo Fujiyama.
- **Data curation** – NA.
- **Formal analysis** – Jair Francisco Souza Magalhães.
- **Funding acquisition** – Jerson Rogério Pinheiro Vaz; Roberto Tetsuo Fujiyama.
- **Investigation** – Jair Francisco Souza Magalhães; Larissa dos Santos Borges; Roberto Yuri Costa Dias.

- **Methodology** – Larissa dos Santos Borges.
- **Project administration** – Roberto Tetsuo Fujiyama.
- **Resources** – Jerson Rogério Pinheiro Vaz; Roberto Tetsuo Fujiyama.
- **Software** – NA.
- **Supervision** – Roberto Tetsuo Fujiyama.
- **Validation** – Roberto Yuri Costa Dias.
- **Visualization** – Larissa dos Santos Borges; Roberto Yuri Costa Dias.
- **Writing – original draft** – Jair Francisco Souza Magalhães; Larissa dos Santos Borges; Roberto Yuri Costa Dias; Jerson Rogério Pinheiro Vaz.
- **Writing – review and editing** – Jerson Rogério Pinheiro Vaz; Jair Francisco Souza Magalhães; Roberto Tetsuo Fujiyama.

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