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RESEARCH

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Mechanical properties of interply and intraply hybrid laminates based on jute-glass/epoxy composites

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Abstract

Currently, hybridization of natural-synthetic fibers within a polymeric matrix has received wide attention owing to its promising properties. This study investigated the mechanical properties of interply and intraply hybrid jute (J)-glass (G) fiber/epoxy composites. The mechanical properties (i.e., tensile, flexural, and impact) of the pure jute, pure glass, and their hybrid composites were evaluated. The prepared composite samples consisted of five plies of woven fabrics. Interply hybrid composites comprised three layering sequences: G3JG, GJGJG, and 2GJ2G. Intraply hybrid composites of similar co-woven plies were fabricated by either the alternative replacement of a single glass yarn with a single jute yarn (G_1J_1) or two jute yarns (G_1J_2). The results showed that increasing the glass fraction in the interply hybrid composites improved their tensile properties. The two intraply hybrid composites provided almost similar tensile moduli, while the tensile strength of the G_1J_1 samples was approximately 41% higher than that of the G_1J_2 counterparts. The maximum flexural properties were provided by 2GJ2G composites, followed by GJGJG, and they were interestingly higher than those of pure glass composites. The G_1J_1 intraply hybrid composites offered a higher flexural strength and a lower flexural modulus than those provided by the pure glass composites. Compared to the pure glass composites, the impact strengths of the 2GJ2G and GJGJG samples decreased by 4% and 16%, respectively. In summary, the GJGJG hybrid composites exhibited the highest specific tensile, flexural, and impact properties compared to the other hybrid composites.

Keywords: Jute fibers, Glass fibers, Interply, Intraply, Hybrid composites, Mechanical properties

Introduction

Polymer matrix composites are widely used nowadays, especially in weight-sensitive applications that require high stiffness and/or strength relative to their weight, such as in the aerospace and automotive industries [1]. Man-made fibers (synthetic fibers) such as glass, carbon, and Kevlar have been extensively used for many years to construct composite parts in these applications as alternatives to those made from metal-based materials [2]. Although synthetic fiber-reinforced composites (FRCs) have successfully proven their ability to withstand externally applied loadings, they could negatively affect the environment, starting from their fiber manufacturing processes until the end of their service life or failure [3]. The high cost of some synthetic fibers is another significant barrier to their wider adoption as reinforcements for composite materials. Carbon fibers, for example, are expensive despite their outstanding mechanical properties [4]. Therefore, the use of these fibers has been restricted to certain applications [5]. In recent years, increasing concerns about the environment and human life have motivated scientists to find alternatives to synthetic fibers that are cheaper than synthetic fibers and do not harm the environment [6]. Therefore, plant-based natural fibers have been widely used as alternatives to synthetic fibers for reinforcing polymer matrix composites because they are abundant, sustainable, non-abrasive in nature, and biodegradable [7]. The most commonly used natural fibers for strengthening polymeric composites include jute, bamboo, kenaf, flax, and sisal [7, 8]. These natural fibers are characterized by their lower mechanical properties, a higher ability to absorb water, a higher tendency to flame, and more non-uniform properties along the fiber length than synthetic fibers [9]. Therefore, hybridizing natural fibers with synthetic fibers has recently attracted increasing interest, as it could reduce the overall cost of production and the undesirable harmful effects on human life and the environment as well [10]. A good balance between the mechanical and physical properties of the natural-synthetic hybrid fiber composites can be obtained if the hybridization is well configured and designed to withstand different external loadings [11, 12]. Generally, hybrid FRCs can be classified into three distinct types: interply (interlayer), intraply (intralayer), and intrayarn, which are referred to as layer-by-layer, yarn-by-yarn, and fiber-by-fiber hybridization, respectively [13].

The mechanical properties of hybrid natural-synthetic FRCs have been a subject of interest, particularly in the last decade. Increasing the fractional content of the fibers having the highest tensile properties within the interply hybrid natural-synthetic composites led to increasing the tensile properties of the hybrid composites [14–18]. On the other hand, the stacking sequence of the natural and synthetic plies within the interply hybrid composites can change the tensile properties of the composites. According to Zhang et al. [16] and Sezgin and Berkalp [19], the alternative lamination of natural-synthetic plies within the hybrid composites provided the highest tensile properties. They attributed this behavior to the presence of a higher level of interaction between the layers with different fibers. Therefore, it improved the tensile strength and strain-to-failure of the composites, whereas the tensile modulus was almost unchanged when compared with composites possessing the same fiber volume fraction, type of plies, and their number, but with different stacking sequences. However, other studies have shown that the best tensile properties can be obtained by inserting carbon fibers into the core of carbon-jute interply hybrid composites [19, 20]. This finding was attributed to the increased adhesion strength between the adjacent layers of similar carbon fabrics. The flexural and impact properties of the interply natural-synthetic hybrid composites showed that inserting the stronger fiber at the outermost layers while maintaining the weaker fibers in the core of the composite not only improved these properties but also made them higher than those of their pure synthetic composite counterparts [15, 19–26]. The main reason for this behavior was the loading nature and its effect on the individual layers that were laminated at different locations from the midplane of the laminated composites. Layers located at the farthest distance from the neutral axis of the composite beam thickness are exposed to the highest level of axial stress, according to the classical flexure beam theory.

The mechanical properties of intraply hybrid natural-synthetic fiber composites have not been widely studied as interply hybrid composites because of the difficulties in performing yarn-by-yarn replacements, which are time-consuming when performed manually. Ramnath et al. [27] investigated the tensile, flexural, and impact properties of intralayer hybrid abaca-jute-glass fiber/epoxy composites. The fabricated composite samples were prepared using a stacking sequence consisting of glass fabrics on the skin, and three other intralayers of jute with abaca fibers (in the form of strips) were inserted into the core of the composite. The results showed that samples with higher abaca content exhibited better tensile, flexural, and impact properties, as abaca fibers have higher stiffness, strength, and elongation to break than jute fibers. Rajesh and Pitchaimani [28] studied the tensile, flexural, and impact properties of intraply glass-jute-banana hybrid woven fabric polyester composites. Six different intraply hybrid composites were fabricated, in addition to those made from individual glass, jute, and banana composites. Natural fibers were inserted either along the warp or weft direction, while glass fibers were aligned in the other direction of the fabric to create an intraply hybrid lamina. Therefore, the fabricated samples consisted of only three weaving patterns. These included the glass-jute, glass-banana, and glass-jute-banana patterns. No significant effects on the flexural and tensile properties were observed when the intraply hybridized configuration was used. However, the intraply woven fabric hybridization significantly improved the impact strength, but these properties (tensile, flexural, and impact) were all lower than those of pure glass composites. Ouarhim et al. [29] studied the flexural and tensile properties of two different hybrid configurations: interlayer and intralayer of glass (G) and jute (J) fibers within the polyester matrix. Tensile tests were performed on three types of composites reinforced with only a single layer of woven glass, jute, or hybrid intraply glass-jute fibers (alternative replacement of glass yarns in both the warp and weft directions that make approximately 85 wt% glass and 15 wt% jute fibers). Intraply hybrid composites provided intermediate values of tensile properties when compared with those offered by pure jute and pure glass FRC counterparts. For the flexural properties, three-point bending tests were conducted on the composite samples fabricated from five intraply hybrid layers (85 wt% glass fiber with ply orientations of 0/22.5/45/67.5/0) and seven interply hybrid layers (GJGJGJG) with ply orientations of 0/15/30/45/60/75/0 and 74 wt% glass fiber. The results showed that the GJGJGJG configuration had higher flexural strength (approximately 63%) and modulus (around 40%) than the intraply hybrid composite samples. Islam et al. [30] studied the tensile and fatigue properties of intralayer hybrid flax (F) and carbon (C) fiber-reinforced epoxy composites and compared them with those prepared from interlayer hybrid flax-carbon composites. Interply hybrid composites were prepared using seven layers of different unidirectional fibers with a sequence of (C2FC2FC). Intraply unidirectional hybrid composites (co-woven flax and carbon fibers) were prepared with 14 plies of hybrid fabric (49% C and 51% F fibers by weight). The results showed that both the hybrid configurations had almost the same tensile strength. However, the F–C intralayer hybrid composites showed a prolonged fatigue life of approximately 2000% of that provided by the interlayer hybrid composite counterparts. This extraordinary behavior was attributed to the higher damping characteristics of the uniformly distributed flax fibers within the hybrid layer, which improved the fatigue life characteristics of such intralayer hybrid composites. Table 1 lists the most related published studies that investigated the mechanical properties of interply and intraply natural/synthetic hybrid composites with their main findings. Although hybridizing natural fibers with synthetic fibers has been widely studied concerning their FRC mechanical properties, few studies dealing with natural-synthetic intraply hybrid fiber configurations have been published. Further investigations of these hybrid composites should be achieved either by emphasizing the previous findings with more justifications or by finding new results that are still not known.

This study focused on the mechanical properties of interply and intraply hybrid jute-glass/epoxy composites. Three different lamination sequences of the interply and two co-woven intraply hybrid epoxy composites were fabricated under constant pressure using the hand layup method. The laminated hybrid composites were tested under tensile, flexural, and impact loading. The mechanical properties of the hybrid composites were compared to those of pure glass and jute composites.

Methods

Materials

Jute is the common name for fibers extracted from plant stems belonging to the botanical genus *Corchorus*. Jute plants grow well in warm and humid environments [9]. Jute fibers are inexpensive, eco-friendly, sustainable, and biodegradable. Figure 1 shows images of the woven jute and E-glass plain-weave fabrics. Tables 2 and 3 list the mechanical and physical properties of the jute and glass fibers, respectively. A low-viscosity epoxy resin, commercially known as Quickmast 105, with a density of 1.1 g/cm^3 was used in this work as the matrix phase.

Chemical treatment of jute fibers

The jute fibers were cleaned and chemically treated before use in the composite fabrication process. They were washed three times using deionized distilled water to remove impurities and dust and then immersed in a 0.5 wt% sodium hydroxide solution for 24 h [7]. Subsequently, they were washed again using distilled water to remove the sodium hydroxide residues (i.e., the potential of hydrogen of the rinsing water becomes neutral). This alkali treatment of jute fibers removes wax and reduces the hemicellulose, lignin, and pectin contents [1, 7]. Consequently, many micro-voids, gaps, and wrinkles were created. After alkali treatment with sodium hydroxide solution, the surface of the jute fiber becomes cleaner and rougher. Therefore, it increased the adhesion strength with polymeric resins. On the other hand, the cellulose crystalline structure improved and the cellulose chains became more compact, which could improve the strength of the natural fibers [40]. The treated wet jute fibers were dried using two sequenced rounds of the drying process. The first drying round was employed using the effect of centrifugal force in which the wet jute fibers were dried using a domestic washing machine with a spinning speed of 1400 rpm for 30 min. The second drying round was conducted using an oven at 105 °C for four hours with air circulation. A suitable dose (charge) of the jute fibers was weighed using a high-accuracy digital scale (0.01 g) before mounting it inside the oven. During the oven drying step, jute fiber was taken out and weighed every 30 min.

Table 1 Some related studies of interply and intraply natural/synthetic hybrid composites

Natural/synthetic fibers composite	Types of fibers and hybrid configuration	Research area	Main finding(s)	Ref
Jute/glass	Woven (interply)	Tensile, flexural, and interlaminar shear strength	■ The G2JG hybrid composites exhibited the highest tensile properties among other tested hybrids ■ The GJGJ hybrid composites exhibited the highest flexural properties among other tested hybrids and they approached those provided by pure glass counterparts ■ The G2JG hybrid composites provided the highest interlaminar shear strength among other hybrid composites including pure glass counterparts	[6]
Jute/glass	Woven jute/plain-weave glass fabrics (interply)	Tensile, flexural, and interlaminar shear strength	■ The 3G4J3G provided the highest tensile and flexural properties among other hybrid composites ■ 2G6J2G provided the highest interlaminar shear strength among other hybrid composites	[15]
Flax/glass	Unidirectional (interply)	Tensile, fracture toughness, and interlaminar shear strength	■ Tensile properties are reduced with reducing glass weight fraction ■ Hybrid composites have higher fracture toughness and interlaminar shear strength than pure glass composites	[16]
Jute/glass and jute/carbon	Plain-weave (interply)	Tensile, and Charpy impact	■ Tensile properties are reduced by reducing the weight fraction of synthetic fibers ■ Best hybrid composites against tensile strength were JGJG and J2CJ ■ The G2JG and C2JC provided the highest impact resistance among other hybrids	[19]
Jute/carbon	Unidirectional (interply)	Tensile, flexural, and Charpy impact	■ The 3J4C3J and 2C6J2C provided the highest tensile strength and flexural strength among other hybrid composites, respectively ■ No significant variation in the impact strength with changing the stacking sequence of jute and carbon fiber plies	[20]
Jute/glass	Woven (interply)	Tensile, flexural, Charpy impact, and interlaminar shear strength	■ The hybrid stacking sequence of 2G4J2G was better than 2J3G2J	[21]

Table 1 (continued)

Natural/synthetic fibers composite	Types of fibers and hybrid configuration	Research area	Main finding(s)	Ref
Jute/glass	Woven jute/glass mat (interply)	Tensile, flexural, Charpy impact, and dynamic mechanical analysis	■ The GJGJG provided higher mechanical properties compared to other hybrids ■ Hybrid composites showed the highest storage modulus than neat jute and neat glass composites ■ Highest damping is provided by neat jute composites	[24]
Jute/glass and flax/glass	Woven (interply)	Low velocity drop weight impact	■ The impact test results showed that the natural or hybrid composites absorbed more impact energy than glass composites	[26]
Jute-abaca/glass	Strips of jute and abaca fibers in the core/woven glass on the skin (intraply jute/abaca)	Tensile, flexural, double shear, Charpy impact, and inter-delamination	■ No comparison with individual fiber composites ■ Samples made up of higher abaca content displayed better results and were found to be superior to other test samples	[27]
Jute/glass, banana/glass, and Jute-banana/glass	Woven (intraply with single mat consists of glass yarn in one direction and natural fiber yarn in the other direction)	Tensile, flexural, Izod impact, and dynamic mechanical analysis	■ Tensile and flexural properties were lower than pure glass counterparts ■ The intraply hybrid composites improved the impact strength and damping characteristics significantly	[28]
Jute/glass	Woven (interply and intraply)	Tensile, flexural, and moisture absorption	■ Tensile properties of a single layer of intraply jute/glass hybrid composites showed intermediate properties between pure glass and pure jute counterparts ■ The GJGJG interply hybrid composites exhibited higher flexural properties ■ Intraply hybrid composites presented higher resistance to moisture compared to the tested interply hybrid composites	[29]
Flax/carbon	Unidirectional (interply and intraply)	Fatigue life	■ Intraply hybrid configuration showed a very large increase in fatigue life (more than 2000%) compared to interply hybrid configuration for the similar mass of both fibers	[30]

Table 1 (continued)

Natural/synthetic fibers composite	Types of fibers and hybrid configuration	Research area	Main finding(s)	Ref
Jute/glass	Woven (interply)	Tensile, flexural, Charpy impact, and vibration characteristics	■ Hybrid composites with lower jute weight fraction provided the higher tensile, flexural, and impact properties ■ Hybrid composites with higher jute fiber fraction exhibited higher vibration characteristics ■ Hybrid composites showed better mechanical properties and vibration characteristics when they were related to their densities (i.e., specific properties)	[31]
Jute/glass and flax/glass	Plain-weave (interply)	Tensile, flexural, interlaminar shear, and vibration characteristics	■ No significant change in the tensile properties when layering natural fibers (i.e., jute or flax) in the core or on the skin of the hybrid composites ■ Putting glass fibers on the skin of the hybrid composites improved the flexural properties of hybrids with glass core reinforcement ■ The G2JG and G2FG exhibited higher interlaminar shear strength than their pure glass counterparts ■ Inserting glass layers in the core of the hybrid composite improved the damping by 155% and 100% for the J2GJ and F2GF, respectively, over pure glass counterparts	[32]
Curaua/aramid	Non-woven curaua mat/woven aramid (interply with non-alternating configuration)	Tensile and Charpy impact	■ Tensile and impact properties are reduced with increasing the content of curaua instead of aramid fibers (replacement of four to five layers of aramid by a single Curaua mat) ■ According to the novel proposed reduction maps, hybridization of curaua and aramid exhibited advantages if the replacement was for nine or more aramid layers	[33]
Curaua/aramid	Non-woven curaua mat/woven aramid (interply with non-alternating configuration) (interply)	Flexural and Charpy impact	■ Replacement of aramid fabrics by curaua fibers reduced flexural and impact properties while increasing the curaua content ■ Hybrid curaua/aramid composites exhibited lower delamination and transverse deformation	[34]

Table 1 (continued)

Natural/synthetic fibers composite	Types of fibers and hybrid configuration	Research area	Main finding(s)	Ref
Abaca/glass, Banana/glass, and abaca-banana/glass	Unidirectional (interply with alternating and non-alternating configurations)	Tensile, flexural, and Izod impact	■ Highest tensile strength was provided by abaca-banana/glass hybrid composite ■ Highest flexural strength was provided by Banana/glass composite ■ Abaca/glass composite provided the highest impact strength	[35]
Coir/Kevlar	Woven (intraply with replacing all Kevlar yarns in either the warp or weft direction by coir yarns)	Charpy impact and flexural	■ Intraply hybrid coir/Kevlar composites provided impact strength up to approximately 94% of the pure Kevlar counterparts ■ Flexural strength of intraply hybrid composites was higher than pure Kevlar counterparts (Note: no rupture occurred in these composites when the maximum lateral load applied was applied due to using a single ply of fabric in each composite)	[36]
Kenaf/glass	Unidirectional kenaf fibers/woven glass (interply)	Tensile, flexural, and Izod impact	■ Tensile and flexural properties were higher than typical bumper beam material, but impact energy was still lower	[37]

J jute, *F* flax, *G* glass, *C* carbon

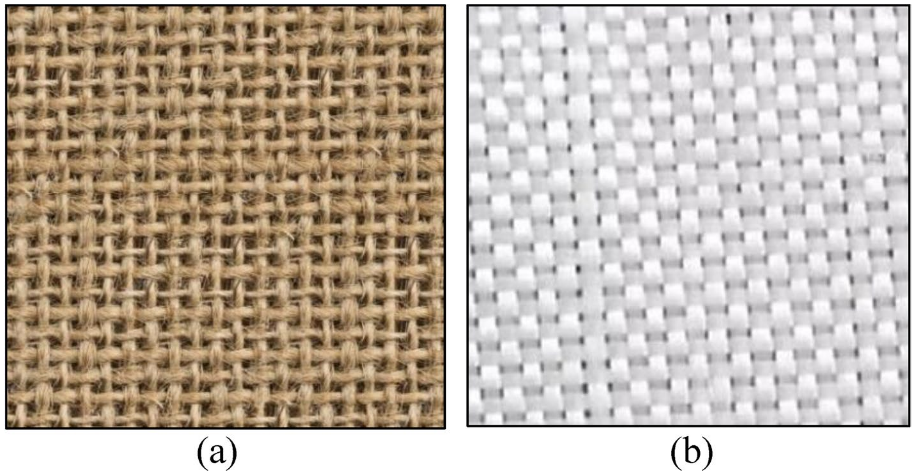

Fig. 1 Woven fabrics: **a** jute fabric, **b** plain-weave E-glass fabric

Table 2 Mechanical and physical properties of jute fibers [6, 38]

Properties	Value
Strain-to-failure (%)	1.1–1.5
Elastic modulus (GPa)	10–32
Tensile strength (MPa)	450–550
Density (g/cm^3)	1.5
Areal density (g/m^2)	225[a]
Warp density (end/cm)	4.18[a]
Weft density (end/cm)	4.18[a]

[a] Measured in this work

Table 3 Mechanical and physical properties of E-glass fibers [39]

Properties	Value
Strain-to-failure (%)	1.8–3.2
Elastic modulus (GPa)	72.4
Tensile strength (%)	3450
Density (g/cm^3)	2.56
Areal density (g/m^2)	600[a]
Warp density (end/cm)	2.4[a]
Weft density (end/cm)	2.4[a]

[a] Measured in this work

This step was repeated till the change in the weight of the jute fiber due to water evaporation had become almost negligible. This state happened at the seventh repetition (i.e., after 3.5 h). Adding another half-hour of drying was recommended to ensure complete evaporation of the remaining water. The dried jute fibers were kept inside zipped bags to keep them clean and dry until they were used in the composite fabrication processes.

Fabrication of composites

The hand layup method was adopted to fabricate composite sheets with dimensions of 200 mm $\times$ 300 mm $\times$ t mm. Where t denotes the thickness of the composite plate in a millimeter that are listed in Table 4. The applied compressive pressure and room temperature during the epoxy curing process were 7.5 kPa and 20 ± 2 °C, respectively. The fabricated non-hybrid composite sheets were either made from five glass woven fabrics that were designated as (5G) or five jute fabrics (i.e., 5J) reinforced with epoxy resin. The hybrid glass-jute/epoxy composite sheets were configured with either an interply or an intraply pattern. For the interply configuration, three layering sequences with five layers were adopted (i.e., G3JG, GJGJG, and 2GJ2G), as shown in Fig. 2. Meanwhile, intraply hybrid composite sheets were handwoven by either the alternative replacement of a single glass yarn with a single jute yarn in both warp and weft directions of the glass fabric or the alternative replacement of a single glass yarn with two jute yarns, as shown in Fig. 3. In this study, the former is designated as G_1J_1 and the latter as G_1J_2. The final intraply hybrid composite sheets (i.e., G_1J_1 and G_1J_2) also consisted of five similar co-woven layers. The handwoven method was used to prepare the alternative replacement of yarns to get intraply hybrid fabrics. First, jute yarns were carefully taken out from the jute fabric and humidified using a water spray to make them more flexible for the ironing step at a temperature of 110 ± 5 °C. These steps are important to reduce the pre-crimping (undulation) along the yarn length and get almost straight yarns. Second, a suitable piece of glass fabric was gently clamped by the magnetic embroidery hoop having a rectangular shape. Subsequently, alternatively selected yarns in the weft and warp directions were cut at their ends and gently pulled out of the fabric. The last step was weaving the jute yarns in the same places and orientations as the removed glass yarns. Finally, the intraply hybrid ply was released from the embroidery hoop and was ready for composite fabrication. Table 4 lists the specifications of the prepared composite sheets.

Tensile test

Tensile specimens were prepared according to the ASTM D3039 standard [41]. The dimensions of the fiber-reinforced composite samples were 250 mm (length) × 25 mm (width) × *t* mm (thickness). A universal testing machine (200 KN WDW-200E III) was used to conduct tensile testing at a constant head displacement rate of 2 mm/min. Five samples were tested and the average outcomes were considered.

Table 4 Specifications of fabricated different composite sheets

Designation	Thickness (*t*) (mm)	Weight of (0.06 m^2) composite sheet (g)	Density (g/cm^3)	Weight content of (J + G) fibers (g)	Fiber type weight fraction (J + G) (%)	Total fibers weight fraction (%)	Total fibers volume fraction (%)
5J	4.15	295	1.185	(67 + 0)	(100 + 0)	23	19
G3JG	3.34	272	1.357	(40 + 67)	(37 + 63)	39	26
GJGJG	3.26	263	1.345	(26 + 96)	(21 + 79)	46	30
2GJ2G	2.67	290	1.810	(13 + 130)	(9 + 91)	49	31
5G	2.80	290	1.726	(0 + 175)	(0 + 100)	60	40
G_1J_1	2.48	220	1.478	(21 + 81)	(21 + 79)	46	30
G_1J_2	3.74	275	1.225	(40 + 85)	(32 + 68)	45	31

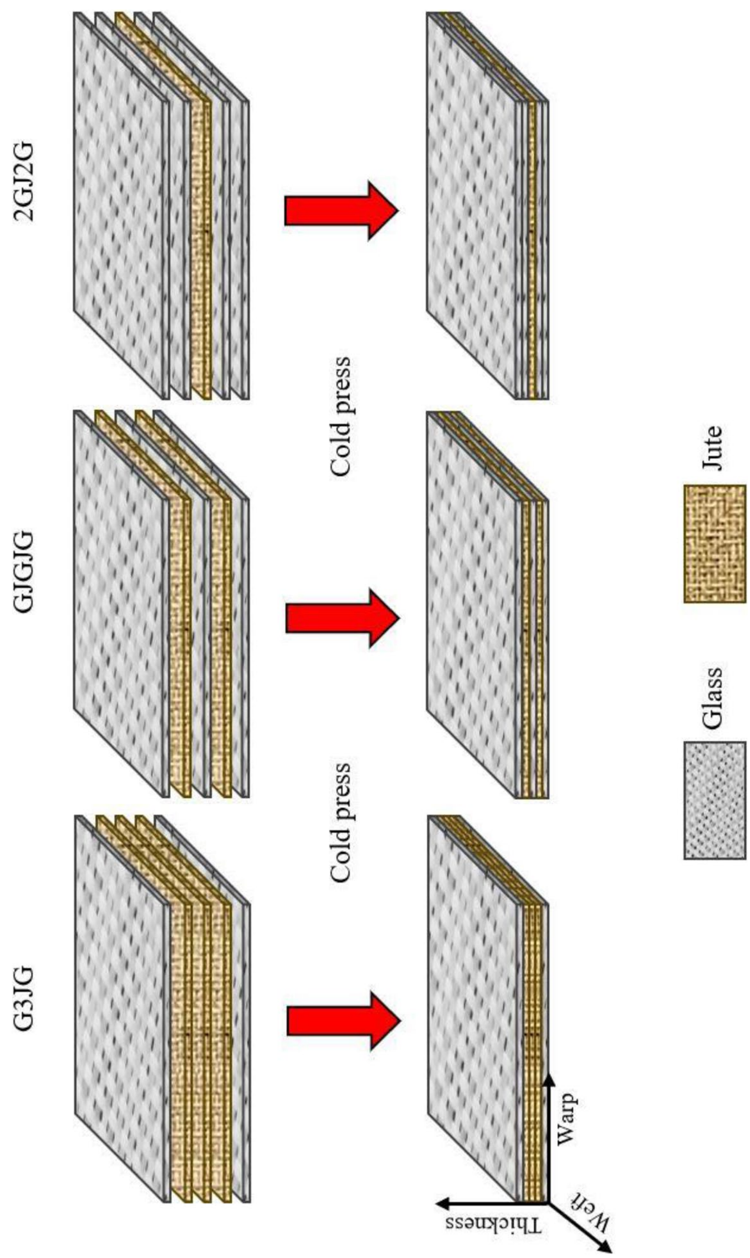

Fig. 2 Configuration of interply hybrid composite sheets

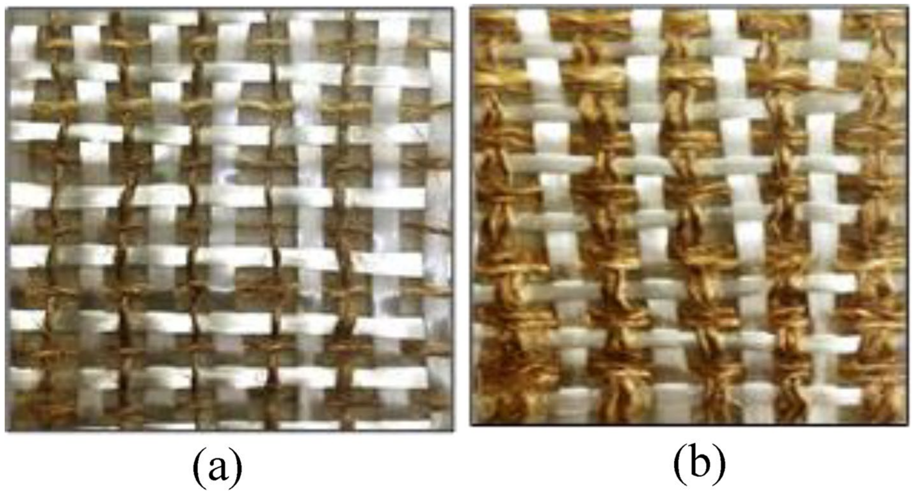

Fig. 3 Intraply hybridization methods: **a** yarn-by-yarn (G_1J_1), **b** yarn-by-two yarns (G_1J_2)

Flexural test

The flexural tests with a three-point bending setting were conducted according to ASTM D790 standard [42]. The dimensions of all composite sample types were 128 mm (length) × 12.7 mm (width) × t mm (thickness). The machine crosshead speed was held constant at 3 mm/min with a strain rate of 0.01 mm/mm/min. The results were obtained from the average of five replicates.

Impact test

Charpy's impact test was conducted to determine the energy absorbed by the composite materials when subjected to an impact load. The impactor weight and velocity were equal to 2.05 kg, 3.8 m/s, respectively. Unnotched Impact composite samples were prepared as per ISO 179 standard [43], with dimensions of 55 mm (length) × 10 mm (width) × t mm (thickness). Five samples of each type of composite were tested, and the average values were considered. The impact strength was calculated by dividing the absorbed energy by the cross-sectional area of the sample.

Morphological examination

Selected composite specimens after performing the tests were examined using a scanning electronic microscope (SEM; JSM-6100, Japan). The examined surfaces of the specimens were coated with a thin layer of gold. Images were taken by subjecting the surfaces to a voltage equal to 20 kV.

Results and discussion

Tensile properties

The stress–strain curves of the composites tested in this work are shown in Fig. 4. The strain to failure of the pure jute and pure glass composites indicated that failure occurred in the jute composites faster than in the glass composite counterparts. The strain-to-failure of the pure glass composites was more than three times that of the

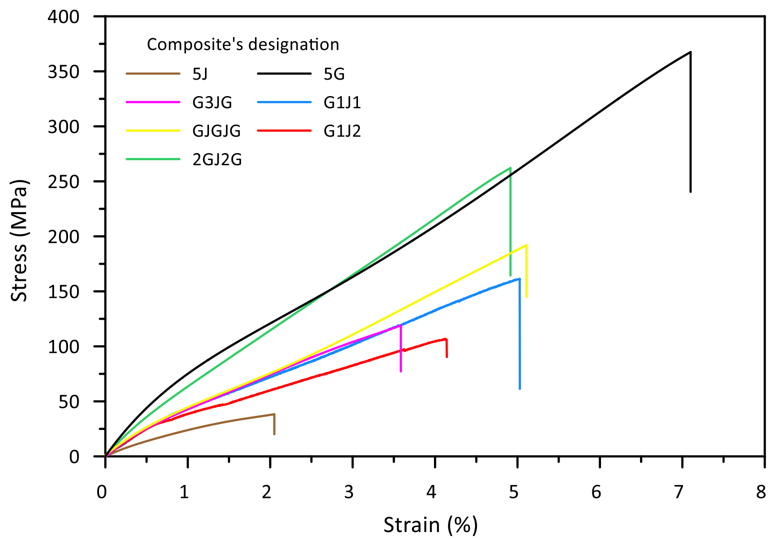

Fig. 4 Stress–strain relationships of pure glass/epoxy, pure jute/epoxy, and their hybrid composites

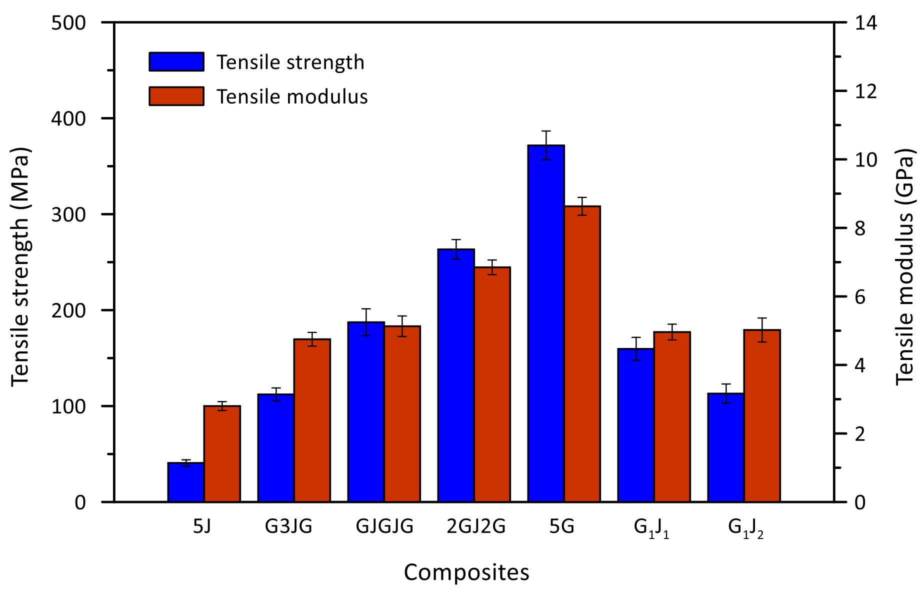

Fig. 5 Tensile properties of pure glass/epoxy, pure jute/epoxy, and their hybrid composites

pure jute composites. This means that the jute composites followed a brittle failure mode. Figure 5 shows the most important tensile properties of the composites, such as tensile strength and modulus. It is clear that composites reinforced with only glass fibers provided the highest tensile properties compared to the other types of composites prepared in this study. Accordingly, the tensile properties of the interply hybrid composites increased with increasing glass fiber weight fraction within the composite. The 2GJ2G hybrid composites exhibited the highest tensile strength among the interply hybrid configurations, approximately 71% of that obtained for pure glass composites. Meanwhile, the GJGJG and G3JG interply hybrid composites had tensile strengths of approximately 50% and 30% of those obtained for pure glass composites,

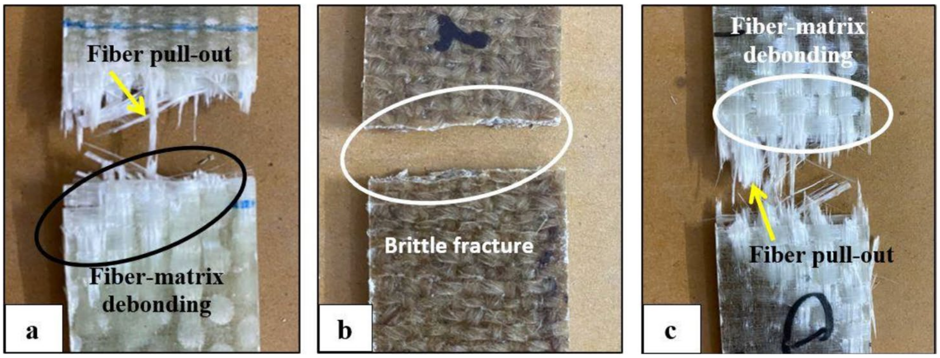

Fig. 6 Images of specimens after the tensile test. **a** 5G, **b** 5J, and **c** 2GJ2G

respectively. This behavior is logical as the tensile properties of the glass fibers are higher than those of the jute fibers, and their adhesion to the epoxy matrix is stronger. Therefore, increasing the glass fiber weight fraction within the hybrid jute-glass/epoxy composites would increase their tensile properties [31]. On the other hand, placing glass fibers on the composite skin is highly recommended when they are hybridized with natural fibers, such as jute, as they can make the composite harder, more durable, and more resistant to burning and humidity. The tensile modulus of the interply hybrid composites followed the same trend as the tensile strength. Increasing the volume fraction of the stiffer fibers (i.e., glass fibers) within the hybrid composites would increase the stiffness of the composite. Therefore, a higher stress is required to produce elastic deformation [21, 24, 31].

Figure 6 shows the failure modes of the pure glass, pure jute, and 2GJ2G interply hybrid composite samples after conducting tensile tests. The pure glass/epoxy composite sample, shown in Fig. 6a indicates that it suffered from fiber-matrix debonding near the fractured surfaces with fiber pull-out and fiber breakage during the tensile test. However, the dominant failure in the pure jute composites was the brittle fracture pattern in which the jute fibers were broken without any sign of jute fiber pull-out as shown in Fig. 6b. This does not necessarily mean that the adhesion strength between the jute fibers and epoxy matrix is strong; rather, it can be attributed to the low tensile strength of the jute fiber itself. Consequently, jute fibers fractured early during the tensile test before any sign of fiber-matrix debonding. In contrast, failure of interply hybrid laminates designated as 2GJ2G was caused by extensive glass fiber pull-out, glass fiber-matrix debonding, and breakage, as shown in Fig. 6c. Another reason for the weakest tensile properties of jute composites is that the percentage crimp (waviness) of jute yarns within the woven jute textile is relatively higher than that of the glass yarn within the woven glass fabric as shown in Fig. 7. It is well known that loosen and crimped jute yarns within the polymeric matrix cannot instantly carry the load transferred from the matrix [44]. Therefore, macrocracks are initiated early when tensile loading is applied to the pure jute/epoxy composite, and a sudden brittle failure occurs [45].

For intraply hybrid composites, the results indicated that this hybridization method could produce a material with intermediate tensile properties between those of pure glass and pure jute composites, which was also indicated by Ouarhim et al. [29] as

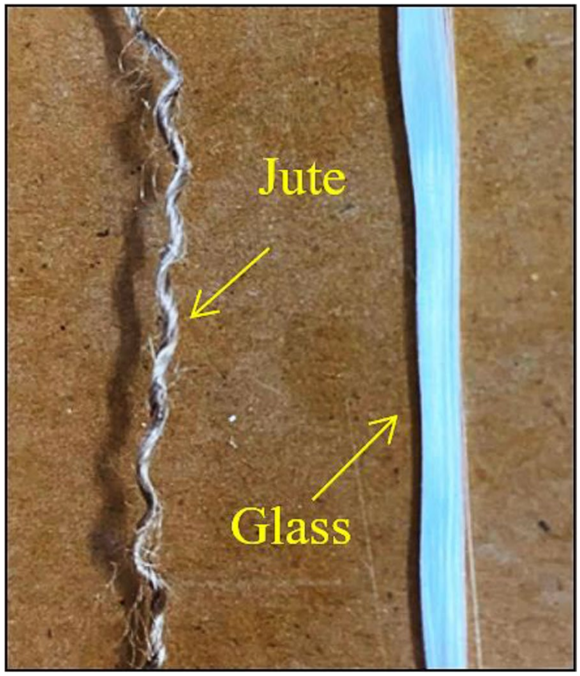

Fig. 7 Waviness in the jute and glass yarns

shown in Fig. 8. The hybrid composites G_1J_1 and G_1J_2 exhibited approximately the same results for the tensile modulus, but their tensile strengths were different. The G_1J_1 samples had a tensile strength approximately 41% higher than that of the G_1J_2 samples, although they had approximately equal weights of glass fibers. The presence of two jute yarns within the interply G_1J_2 hybrid composites played a weakening effect when they were subjected to tensile loading. Jute fibers were broken earlier than glass fibers when undergoes a certain tensile strain. This would leave many severe defects within the intraply hybrid composites (G_1J_2) in the form of longitudinal pores. These empty pores cannot sustain any tensile stress and only act as local regions surrounded by relatively higher stress levels due to the stress concentration. The fractured

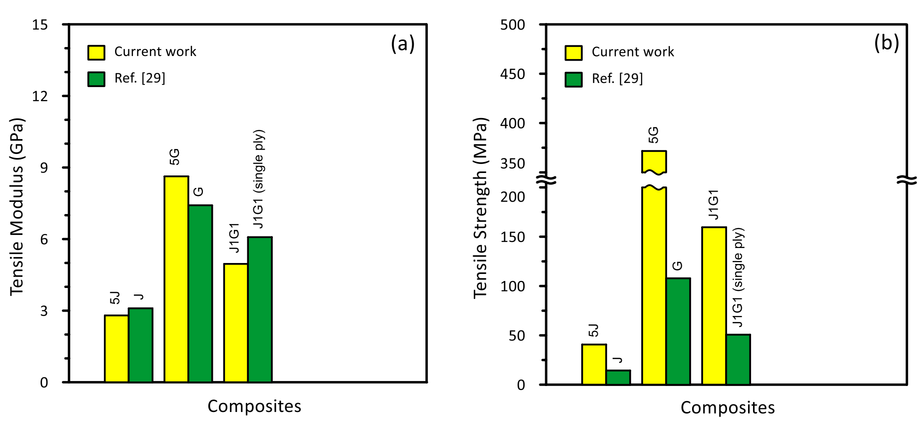

Fig. 8 Comparison of tensile properties obtained in the current work with those obtained by Ouarhim et al. [29]. **a** Tensile modulus. **b** Tensile strength

intraply hybrid specimens are shown in Fig. 9. Regarding the tensile modulus, G_1J_2 has a tensile modulus slightly higher than that of G_1J_1. It was noted that the G3JG and GJGJG interply hybrid composites have tensile moduli very close to those of G_1J_1 and G_1J_2 intraply hybrid composites, although they have different fiber type contents (i.e., hybridization ratio). This behavior could be attributed to the good mechanical compatibility between the two different fibers (i.e., glass and jute) at a relatively low-strain stage in which the elastic modulus was calculated. There is no sign of any failure pattern in the composite in this stage between their constituents (i.e., fiber pull-out and fiber-matrix debonding) and/or between their components (i.e., fiber breakage and matrix cracking). Notably, although GJGJG and G_1J_1 have similar jute-glass fiber hybridization ratios, the tensile properties provided by the GJGJG interply hybrid composites were slightly higher than those of their intraply G_1J_1 counterparts. This could be attributed to the hand-weaving preparation of the co-woven jute-glass hybrid plies, which is not perfect because it could leave some unwanted yarn waviness within the fabrics. Accordingly, non-compacted fabrics were obtained.

Flexural properties

Figure 10 shows the flexural strength and modulus of the pure jute, pure glass fiber-reinforced epoxy composites and their various hybridizations, including the interply and intraply hybrid configurations. It is well known that flexural loading develops an axial strain within the beam through-thickness, except in the neutral plane location. The outermost layers experienced the highest tensile and compressive stresses depending on the direction of the developed bending moment along the length of the beam. Accordingly, failure occurs when the stress becomes higher than the allowable stress of the material. Hence, the flexural strength and stiffness of the layered composites are mostly controlled by the properties of the external layers of the reinforcement. Failure begins with the

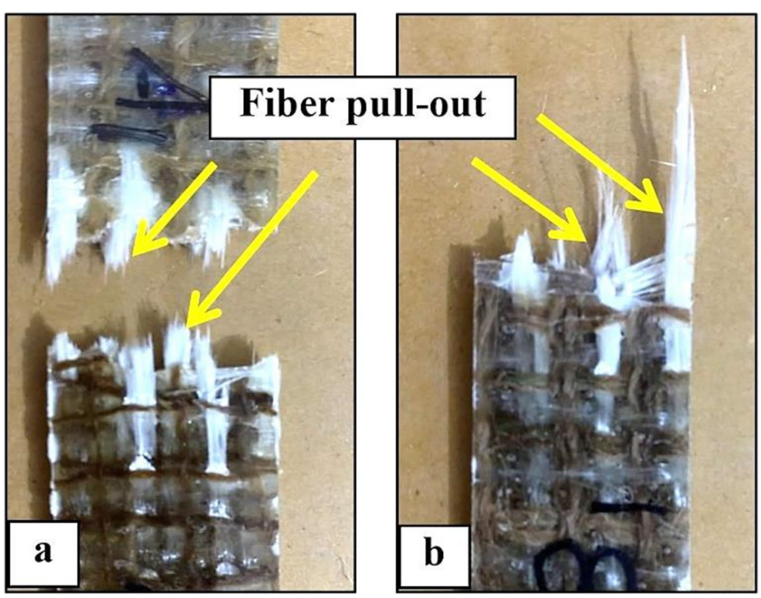

Fig. 9 Images of fractured intraply hybrid specimens after the tensile test. **a** G_1J_1. **b** G_1J_2

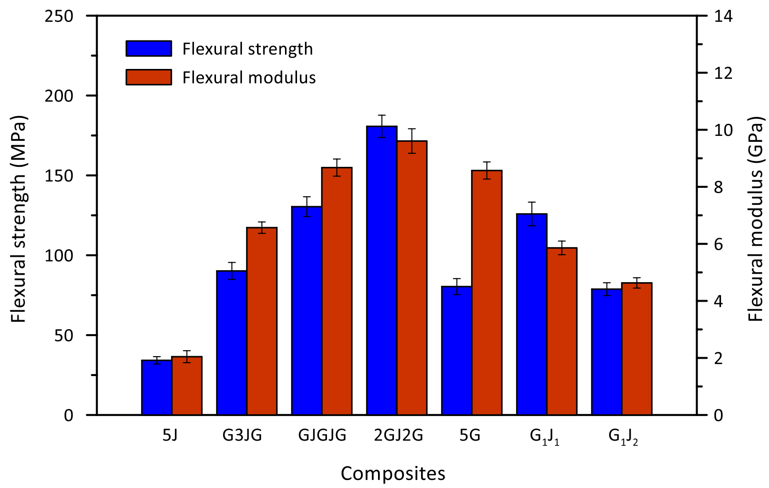

Fig. 10 Flexural properties of pure glass/epoxy, pure jute/epoxy, and their hybrid composites

development of microcracks and macrocracks on the tensioned side. Introducing glass layers on the skin of the laminated composites would significantly increase their flexural strength. This behavior has resulted from the higher strength and resistance exhibited by glass fibers against crack propagation than jute fibers.

The flexural strength and modulus of the pure jute fiber composites were lower than those of the pure glass/epoxy composites as shown in Fig. 10. This result is mainly attributed to the inferior mechanical properties of the reinforcement phase (i.e., jute fibers) and its weaker adhesion strength with the epoxy matrix than that of glass fibers. Additionally, interply hybrid composites designated as 2GJ2G, GJGJG, and G3JG provided flexural strengths equal to 2.25, 1.62, and 1.12 times than those provided by pure glass composites, respectively. Regarding the flexural modulus, the 2GJ2G samples provided an average flexural modulus that was approximately 12% higher than that of their glass composite counterparts. The improvement in the flexural modulus gradually decreased for the GJGJG and G3JG samples. The flexural properties of the tested interply hybrid composites were compared with those obtained by Ahmed and Vijayarangan [15], as shown in Fig. 11. Good agreements in the general trend of the results were obtained although using different number of plies, matrix material, and manufacturing conditions.

For the two intraply hybrid composites, the G_1J_1 specimens exhibited higher flexural strength and modulus than G_1J_2, although the latter had a higher jute fiber weight fraction and composite beam thickness than the former. The flexural strength of the G_1J_1 composite was approximately 60% higher than that of G_1J_2, whereas its flexural modulus was only 27% higher than that of G_1J_2. This behavior could be related to the elongation ability or what is called strain-to-failure of the composite constituents. Jute fibers fractured earlier than glass fibers when they were tensioned beyond their highest limit. Consequently, intrinsic defects were introduced within the intraply hybrid composite layer in the form of pores (longitudinal voids) that weaken the composite by increasing the developed stress in two ways. The first is due to decreasing the cross-sectional area that sustains the load, while the second is by increasing the stresses due to the stress concentration that develops around these pores.

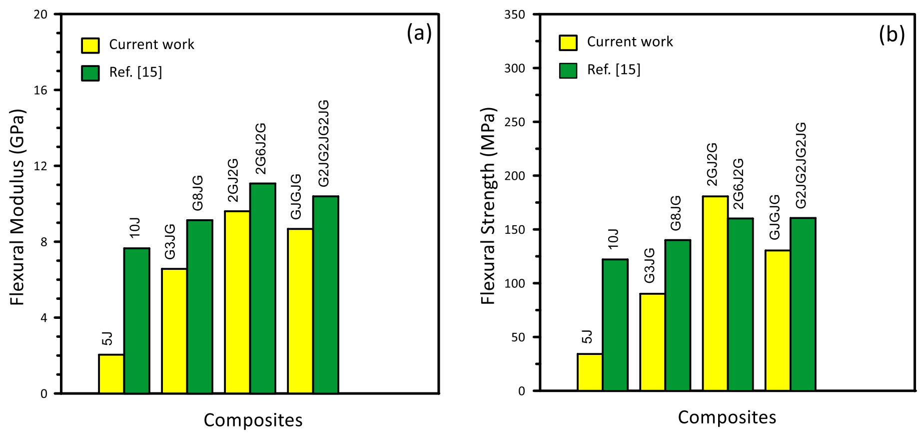

Fig. 11 Comparison of flexural properties obtained in the current work with those obtained by Ahmed and Vijayarangan [15]. **a** Flexural modulus and **b** flexural strength

Accordingly, the G_1J_2 samples would fracture earlier than G_1J_1 counterparts, as they would contain higher and/or larger pores after jute yarn breakage. Concerning the flexural modulus, the degradation in the G_1J_2 stiffness was lower than that of what happened in the strength when compared with the G_1J_1 samples, possibly because of the small weakening sources at the early stage when performing the bending test. The impressive result is that although the GJGJG and G_1J_1 samples have almost similar fiber type weight fractions, the interply hybrid composite designated by GJGJG exhibited a slightly higher flexural strength than that of the intraply hybrid composite G_1J_1 (around 3.6%), which cannot be considered an improvement from the statistical and engineering point of view. However, the flexural modulus of the GJGJG interply hybrid composites showed a clear difference (around 48% higher) when compared with the G_1J_1 counterparts. The GJGJG composite contains fully and well-compacted glass fabric layers on both the compressed and tensioned external sides of the composite specimens, which makes them stiffer, as illustrated by Ouarhim et al. [29]. It is interesting to mention that the majority of hybrid composites prepared in this work have a flexural strength higher than that of pure glass composites. Meanwhile, the flexural modulus did not follow the same trend. Only the 2GJ2G and GJGJG interply hybrid composites exhibited better flexural stiffness than their pure glass counterparts. However, the other hybrid composites give encouraging overall results if they are related to environmental concerns.

Figures 12 and 13 show the failure of different interply and intraply hybrid specimens after the flexural test. The overall brittle fracture was the most dominant failure mode of the pure jute composite samples because of the early breakage of the jute fibers during the bending test. Meanwhile, the pure glass composites exhibited fiber-matrix delamination and debonding close to the broken surfaces with a considerable fiber pull-out mode. Therefore, hybridizing jute fibers with glass fibers would improve the flexural properties with a reduced effect on the environment if compared with pure glass composites. Indeed, 2GJ2G interply hybrid specimens (with approximately 91% glass fiber weight

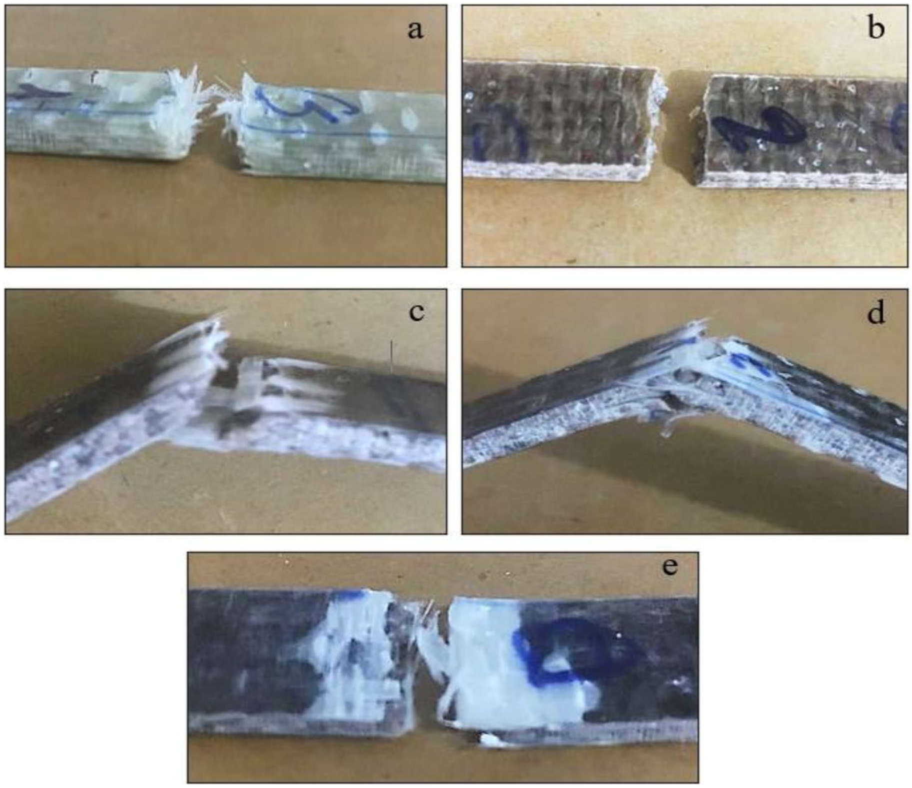

Fig. 12 Images of pure glass, pure jute specimens, and their interply hybrids after the bending test. **a** 5G, **b** 5J, **c** G3JG, **d** GJGJG, and **e** 2GJ2G

fraction) showed the highest flexural strength and modulus among the hybrid specimens, as they contained the highest weight content of glass fibers located at the farthest distance from the neutral axis of the composite beam or what is called the midplane, while a single layer of jute was inserted in its core.

Impact properties

The loss of energy that occurred during the impact test was the energy absorbed by the specimen during the impact event. Figure 14 shows the impact strengths and their specific values for various samples using Charpy's impact test. Pure glass composite samples exhibited the highest strength against impact, whereas pure jute composites showed the lowest strength among the composite configurations. Increasing the glass

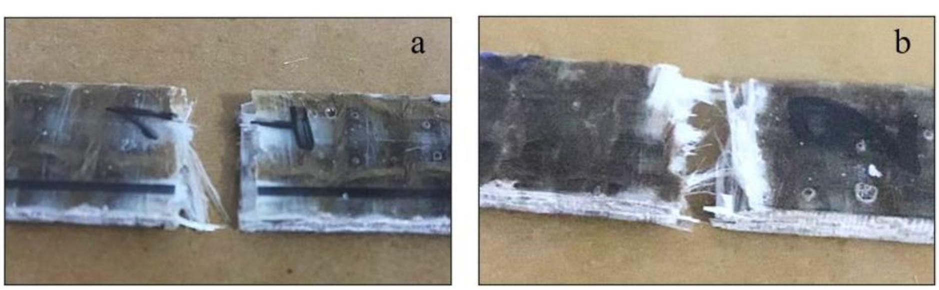

Fig. 13 Images of fractured intraply specimens after the bending test. **a** G_1J_1. **b** G_1J_2

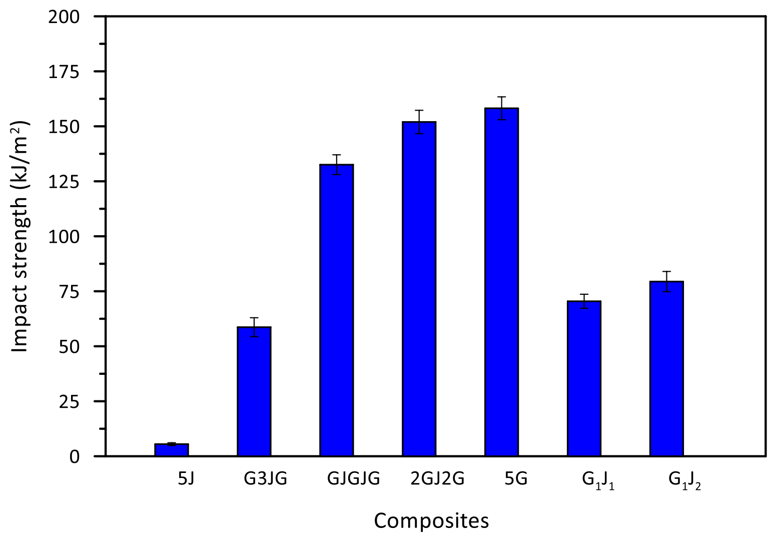

Fig. 14 Impact strengths of pure glass/epoxy, pure jute/epoxy, and their hybrid composites

fiber content within the hybrid composite relative to the jute content would increase its impact strength, as glass fibers are more durable and can sustain more energy prior to undergoing fracture. However, this event is not always true because the impact strength of the composites depends on several parameters, such as the lamination sequence of different materials, the location of the higher strength layers (innermost or outermost), the compatibility between various fiber properties, and their adhesion strength with the polymeric matrix.

The impact strength of the GJGJG and G_1J_1 samples exhibited that although these different hybrid composites have similar fiber type weight fractions, the GJGJG interply hybrid composites could withstand a higher impact load (almost twice that of G_1J_1) as they comprise higher content of glass fibers (around 18%) than those of G_1J_1 samples. If one considers the environmental concern, the GJGJG hybrid configuration is the best among the types of interply hybrid samples prepared in this work, with only a 16% reduction in the impact strength in comparison with the 5G counterparts, which is in agreement with the results obtained by Das et al. [24]. Meanwhile, the 2GJ2G hybrid composites exhibited the highest impact strength among the interply hybrid configurations, with an impact strength approximately 4% lower than that of the pure glass/epoxy composite. This result is attributed to the higher flexural stiffness provided by glass fibers than jute fibers, which increases the resistance against deformation. Glass fibers have a higher stiffness, strength, and toughness than jute fibers. Hence, glass fibers can absorb more energy than jute fibers can. It is noteworthy that placing glass fabric layers at the outermost layer in the composites also had a positive effect on the impact properties as mentioned by Selver et al. [26]. It has been reported that increasing the glass fiber volume fraction increases the impact properties of hybrid composites. Moreover, inserting a stronger fiber type at the farthest distance from the composite midplane would increase its ability to absorb more impact energy. Concerning the two intraply hybrid fiber configurations, it was noted that a relatively slight increase in the impact strength could be obtained by increasing the jute fibers content relative to the glass fibers. This result is not encouraging because the content of the glass fiber in the G_1J_2 samples is almost the same as that used in the G_1J_1 counterpart. The only difference is that the former contains more jute fiber content relative to the glass fiber (i.e., percentage of jute fiber content). Another drawback is the higher thickness and weight of the G_1J_2 samples than those of the G_1J_1 samples. Consequently, it can be considered just as a depletion of the resin and natural fiber without a considerable improvement in the impact resistance. The results of the interply hybrid composites prepared in this work were compared with the most similar studies as shown in Fig. 15. The trend of the results was in agreement with those obtained by Das et al. [24] and Mostafa and Hunain [31].

Figures 16 and 17 show the composite samples after the impact test. The dominant failure mode of pure glass composite samples was the fiber-matrix debonding in a limited region without any separation in the specimen body. No clear signs of the glass fiber fracture were observed. Only matrix cracking and fiber-matrix debonding close to the impacted area were detected. However, the 5J specimens showed a brittle failure mode with full separation in the specimen body without any clear signs of fiber pull-out and fiber-matrix debonding. The 2GJ2G interply hybrid specimens exhibited almost the same failure mode as their pure glass composite counterparts. Increasing the jute fiber fraction in the GJGJG and G3JG hybrid composite specimens resulted in the breaking of the outer plies (i.e., glass fibers) close to the broken surfaces. The presence of a glass layer in the alternative sequence, as in the GJGJG samples, would expose the adjacent jute fibers to a lower level of impact energy. The intraply hybrid composites exhibited mixed failure modes, as shown in Fig. 17, which includes the fiber-matrix debonding of glass fibers, glass fiber pull-out, and partial glass-jute fiber breakage. It is noteworthy that samples containing a high fraction of glass did not show any separation of the specimen body as their bending stiffnesses (i.e., the member resistance against bending deformation) were relatively lower than those provided by the pure jute composites or hybrid composites having low content of glass fibers. Accordingly, composite samples with relatively low bending stiffness were partially

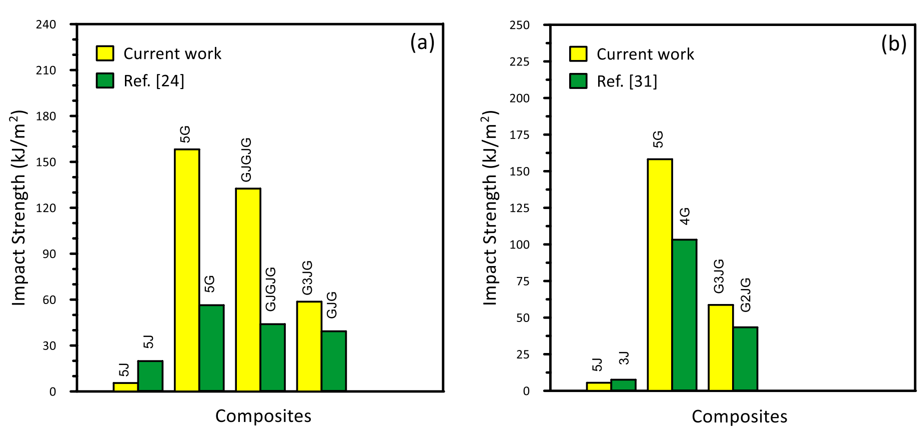

Fig. 15 Comparison of impact strengths obtained in the current work with other studies. **a** Das et al. [24], and **b** Mostafa and Hunain [31]

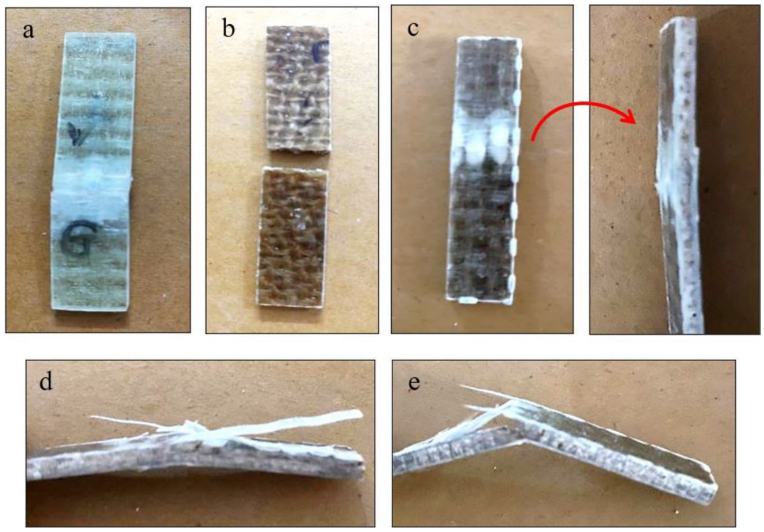

Fig. 16 Images of pure glass, pure jute specimens, and their interply hybrids after the impact test. **a** 5G, **b** 5J, **c** 2GJ2G, **d** GJGJG, and **e** G3JG

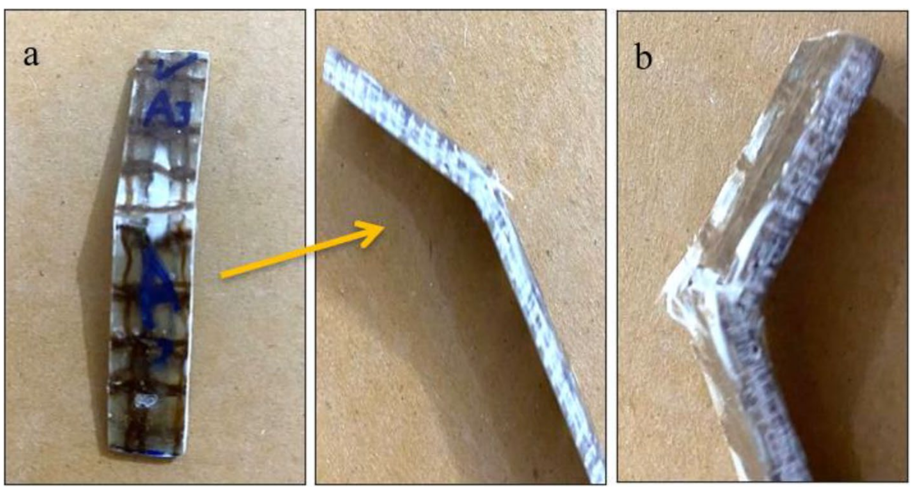

Fig. 17 Images of intraply hybrid specimens after the impact test. **a** G_1J_1 hybrid composite and **b** G_1J_2 hybrid composite

broken during the impact event as they could deflect in the same direction as the impact load. This behavior could release the sample from its supports (simply supported) and be flung out from the impact device frame, which was also observed by Erklig et al. [46] and Mostafa and Hunain [31].

Specific mechanical properties

It is well known that strength and stiffness-to-weight ratio are the most important characteristics of composite materials. Therefore, the specific mechanical properties of different composites were investigated by dividing the mechanical properties of the composites by their densities to compare their specific properties, taking into account their weight and volume, as listed in Table 4. Figure 18 reveals that additional

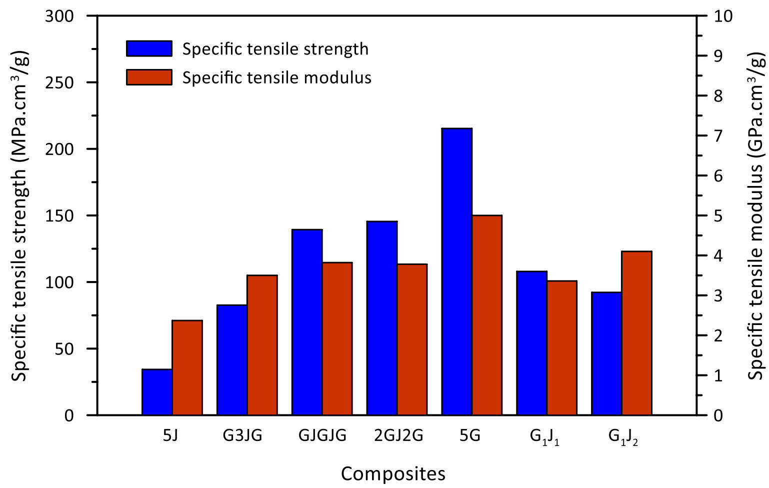

Fig. 18 Specific tensile properties of pure glass/epoxy, pure jute/epoxy, and their hybrid composites

improvements in tensile properties can be obtained when considering the specific tensile properties. For example, the tensile strength of the G3JG interply composite was approximately 30% of that provided by pure glass/epoxy composites (5G). The specific tensile strength of this type of hybrid composite was slightly improved to 38% of that provided by the 5G composites. Concerning the tensile modulus, the incorporation of 63% of glass fiber weight fraction within the G3JG hybrid composite gives a tensile modulus of approximately 55% of that offered by glass composite counterparts. However, it reaches up to 70% when using the specific values of elastic modulus. The same behavior of the GJGJG hybrid composite was observed when compared with that of pure glass composites. The tensile strength and modulus of the GJGJG hybrid composite were approximately 50% and 59% of those obtained for glass composite counterparts, respectively. However, the corresponding specific tensile properties were 65% and 76% of those introduced by the glass composite specimens. This interply hybrid configuration (i.e., GJGJG) offered the greatest improvement in the specific tensile modulus among the composite counterparts. Hybrid composite samples with higher glass fiber weight fraction, such as the 2GJ2G configuration, gave tensile strength and modulus of approximately 71% and 79% of those provided by pure glass/epoxy composites, respectively. These values were slightly reduced when considering their specific properties, in which they were equal to 68% and 76%, respectively. Notably, the specific tensile properties of the GJGJG hybrid composites were almost equal to those of their 2GJ2G counterparts. This means that the GJGJG composite is the best hybridizing configuration, as it uses minimal layers of glass fabrics to give specific tensile properties equivalent to another hybrid composite with a higher weight fraction of glass fibers. Regarding the two intraply hybrid composites, the G_1J_2 samples offered more improvement than their G_1J_1 counterparts when their tensile properties were calculated relative to their densities. This result was expected, as the G_1J_2 samples contained more jute fibers and were lighter than the G_1J_2 composites. Therefore, they have a lower average density than G_1J_1 composites.

With respect to the specific flexural properties, Fig. 19 shows the exceptional performance of GJGJG samples when their flexural properties are related to their

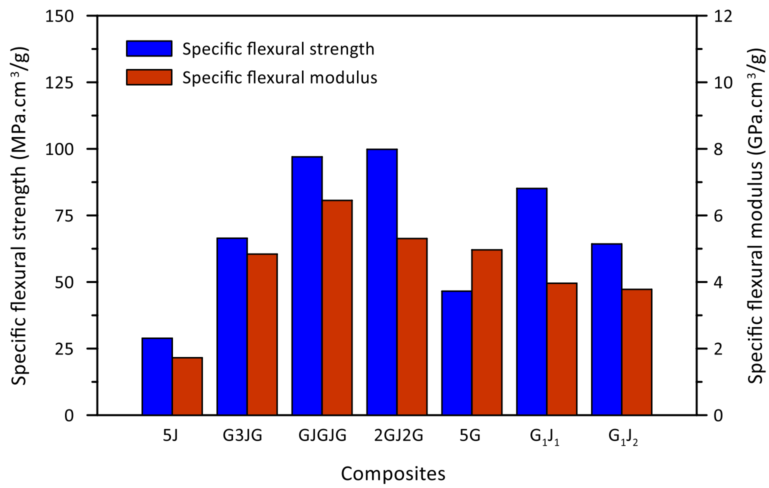

Fig. 19 Specific flexural properties of pure glass/epoxy, pure jute/epoxy, and their hybrid composites

densities. The specific flexural modulus of the GJGJG hybrid composite was the highest and its flexural strength was the second highest among the composite samples. GJGJG composites are lighter but thicker than their 2GJ2G counterparts, and this might make them the best configuration against flexural loading if the preservation of the environment is the main concern. Intraply hybrid composites designated as G_1J_1 showed good performance against bending, and they can fairly compete with their GJGJG counterparts as the former has a lower average thickness with a similar total fiber weight fraction as mentioned in Table 4. The G_1J_1 composite configuration has a lower sample thickness than GJGJG and a lower weight content of jute and glass fibers than GJGJG. This advantage could make it preferable for applications that require more compact dimensions.

Figure 20 shows the specific impact strengths of different composites. The impact strength of the G3JG interply hybrid composite was approximately 37% of that introduced by the glass/epoxy composite, while it increased by up to 47% when compared with their specific impact strengths. The impact strength of the GJGJG hybrid composite was 84% of the pure glass/epoxy composites. This proportion increased to 108% when specific impact strengths were used. Meanwhile, the 2GJ2G composites offered 96% of the impact strength of glass/epoxy composites, which decreased to 92% when specific impact strengths were used. For the two intraply hybrid composites, the G_1J_1 hybrid composites provided an impact strength of approximately 44% of that offered by glass/epoxy composites. Meanwhile, it increased to 52% when considering their specific impact strength. The G_1J_2 hybrid composite provided around 50% of the glass/epoxy composite, whereas it improved by up to 71% with respect to the specific properties. This confirms that GJGJG is the best hybrid configuration among the composites prepared in this study. However, the intraply hybrid composite designated as G_1J_2 exhibited a considerable increase when the specific impact strength was considered.

Figure 21 shows the percentage changes in the specific mechanical properties of pure jute/epoxy and different jute-glass/epoxy hybrid composites when they were related to those of the pure/epoxy composites. The specific flexural properties of the

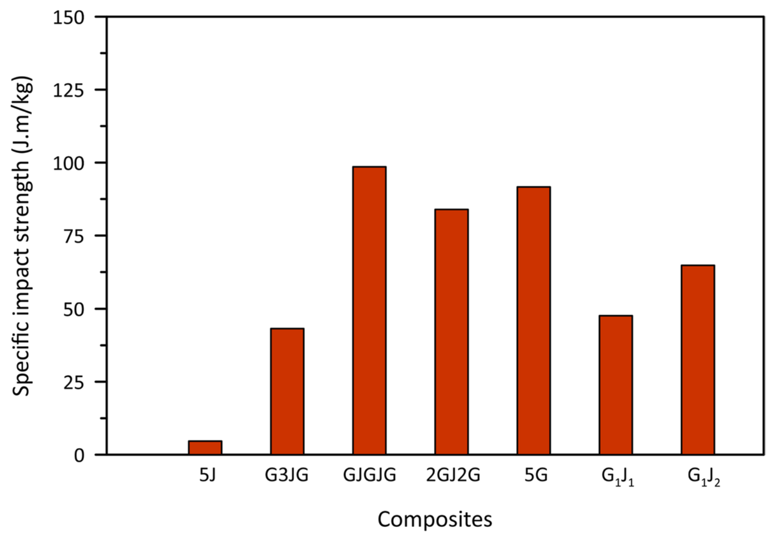

Fig. 20 Specific impact strength of pure glass/epoxy, pure jute/epoxy, and their hybrid composites

jute-glass/epoxy hybrid composites, especially the flexural modulus, exhibited the greatest improvement among the properties due to the jute-glass fiber hybridization. Obviously, GJGJG composites are the best hybrid among the tested specimens in which they introduced the highest improvement in the most mechanical properties, with a good reduction in the glass fiber content.

Morphological analysis

Figure 22 shows the SEM images of some composite specimens after the tensile test. The fractured surfaces of the specimens shown in Fig. 22a–d exhibited different patterns of failure. Breakage of fibers, fiber-matrix debonding, fiber pull-out, matrix dislocation, matrix cracking, and fiber-matrix delamination were noticed. The pure glass/epoxy composites failed by fiber breakage, fiber pull-out, and delamination of glass fibers from the epoxy matrix as shown in Fig. 22a, b. However, pure jute composites showed a dominant

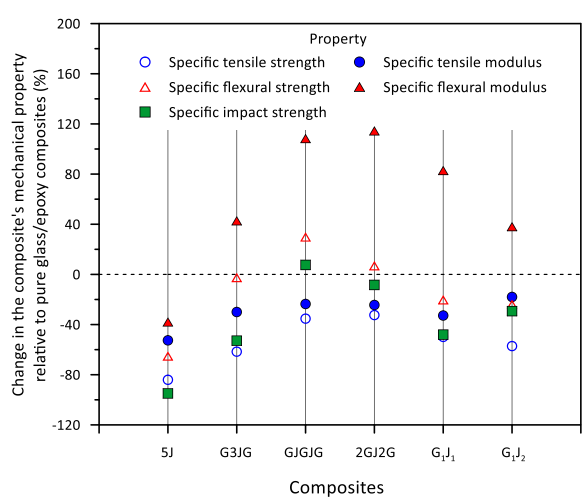

Fig. 21 Percentage variation of specific mechanical properties for pure jute/epoxy and hybrid jute-glass/epoxy composites relative to pure glass/epoxy composites

fiber breakage pattern as shown in Fig. 22c. The image shown in Fig. 22e was taken close to the fractured region from the lateral side of the G_1J_2 specimen after the tensile test. The presence of interfacial and inter-bundle cracks especially around the jute fiber interfaces was very clear. This suggests that the bonding strength between the jute fibers and the epoxy matrix is weaker than that of glass fibers with epoxy matrix. Accordingly, the fiber-matrix debonding would take place under large shear stress at the weaker interface regions. Interfacial cracks propagated between the epoxy and glass fiber ply close to the fractured surface led to severe delamination between the reinforcement and matrix phases.

Potential applications

The hybrid composite materials presented in this study have mechanical properties that can potentially be used in a variety of applications. Depending on the hybrid configuration, some of these hybrid composites showed the best performance against certain external loadings without significant loss of their durability and strength because of the

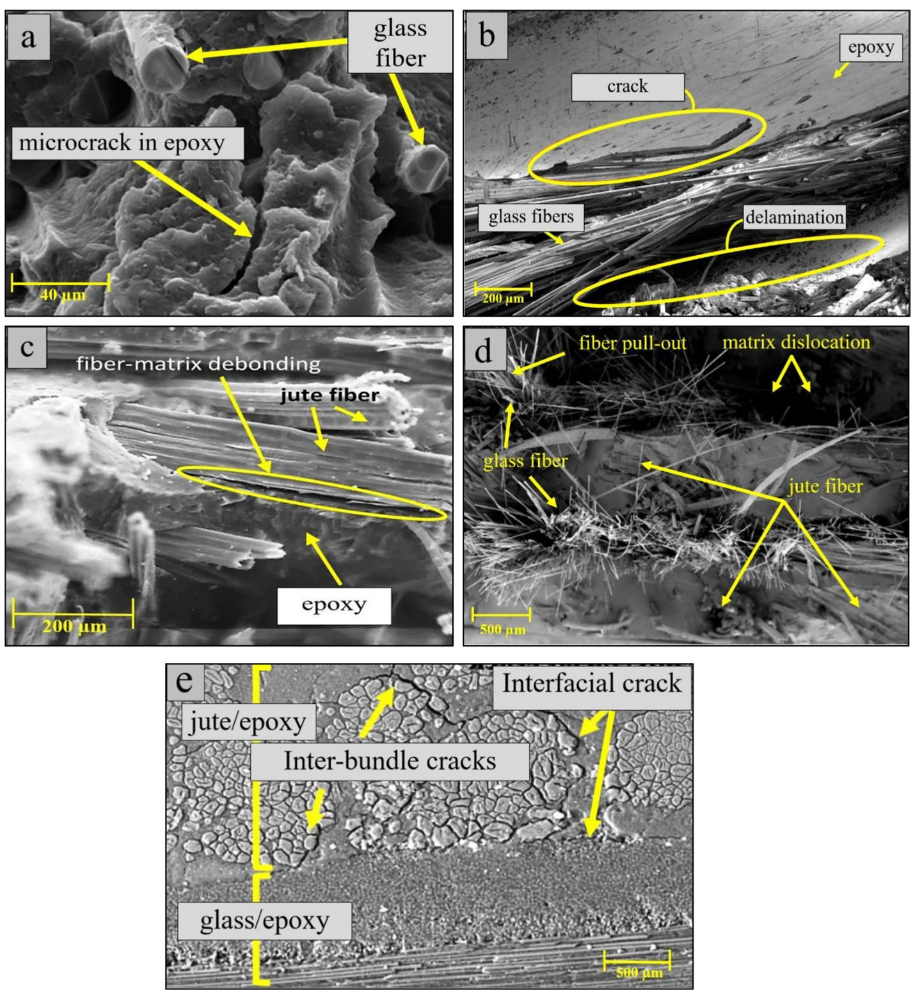

Fig. 22 SEM of composite specimens after tensile test. **a-b** 5G, **c** 5J, **d** GJGJG, and **e** G_1J_2

reduction in the content of the stronger fibers (i.e., glass fiber). Therefore, they could find applications in the structures that are exposed to medium loads, as they significantly reduce the problems related to environmental concerns and the relative cost of raw materials. Another advantage of including natural fibers in natural-synthetic hybrid composites, such as jute fibers, is their viscoelastic nature, which is useful for applications in which damping of vibration and absorption of sound are priorities [30, 47, 48]. Accordingly, these hybrid composites may be suggested for applications in the automotive field, such as the manufacturing of car interiors, car doors, trim panels, dashboards, headliners, seat backs, decking, pallets, parcel shelves, covers of spare tires, and spare-wheel pans.

Conclusions

In this study, the mechanical properties such as tensile, flexural, and impact properties of pure glass and pure jute fibers-reinforced epoxy composites and some of their hybridizations were experimentally investigated. Two main methods of fiber hybridization, namely interply and intraply, were used to observe the influence of the stacking sequence and yarn replacement on the mechanical properties of the hybrid composites. The following conclusions were drawn:

1. The tensile properties of the interply hybrid composites increased with increasing the glass fiber fraction within the composite. The 2GJ2G hybrid composites exhibited the highest tensile strength among the interply hybrid configurations, followed by GJGJG and G3JG. For intraply hybrid composites, G_1J_2 and G_1J_1 showed almost similar tensile moduli. The G_1J_1 samples had a tensile strength higher than that of the G_1J_2 samples by approximately 41%. The highest specific tensile modulus was provided by G_1J_2 when compared with other hybrid composites.
2. The 2GJ2G interply hybrid composites exhibited the highest flexural properties, followed by GJGJG. Meanwhile, the G_1J_1 specimens provided flexural properties higher than G_1J_2. The G_1J_1 intraply hybrid composites exhibited higher strength but lower flexural modulus than those provided by pure glass/epoxy counterparts. In general, hybridizing jute with glass fibers has a clear positive impact on the flexural properties especially the interply configuration with alternative successive lamination of glass and jute fabrics (i.e., GJGJG composites).
3. The highest impact strength was obtained for pure glass/epoxy composites. It decreased with increasing the fraction of jute fibers within the interply hybrid composites. The GJGJG hybrid composites provided a competitive impact strength compared to pure glass/epoxy composites. The G_1J_1 intraply hybrid composites could be considered better than G_1J_2 counterparts against impact loads when the conservation of natural fiber resources is the concern. However, the GJGJG provided the highest specific impact strength, followed by the 5G, 2GJ2G, G_1J_2, G_1J_1, G3JG, and 5J composites, respectively.

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Authors' contributions
MA contributed to the investigation, conducting experimental tests, data curation, formal analysis, and establishing methodology, and she was a major contributor in writing the manuscript. NH contributed to writing the manuscript, discussion, and justification of results. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets generated and/or analyzed during the current study are available from the corresponding author upon request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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