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Tensile strength evaluation of glass/jute fibers reinforced composites: An experimental and numerical approach

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ABSTRACT

Polymer-based composites have an exceptional perspective to replace traditional structural materials like steel and aluminium, owing to their low weight, high strength, and outstanding performance at elevated temperatures. However, the utilization of natural reinforcements for functional polymer composites is still in infancy. In this study, the tensile properties of natural and synthetic fiber-reinforced hybrid composites are reported. Glass-jute hybrid composites, prepared through hand layup technique, were used with different glass and jute fiber stacking sequences. The experimental results stipulate that the tensile properties of glass fiber reinforced polymer (GFRP) were merely affected at lower jute fiber concentration. The strength of composites consisting of single jute fabric lamina and four glass-fiber laminas were comparable with five-laminas GFRP composites. For validation of the experimental tensile testing results, a numerical simulation was also executed. Errors between experimental and numerical simulations were found for different stacking sequences due to non-uniformity in jute fiber diameter and the manufacturing process adopted for these hybrid composites. Fractographic analysis revealed the micro voids and adhesive failure at different joining layers of fibers as the primary cause of delamination.

1. Introduction

The significant advancements in materials science have diverted the attention of many researchers towards utilizing biodegradable materials in different engineering applications [1–3]. To be a potential eco-friendly candidate for functional applications, materials must exhibit biodegradability and significant mechanical properties [4]. Natural fibers (NFs) as reinforcement to polymers can serve this aim, as NFs possess good strength, low cost, abundant availability, and minimal effects in the environment [5]. They are now effectively utilized in many polymer composite materials as a reinforcement. Different natural fibers like banana, sisal, hemp, flax, bamboo, ramie, and jute are reported in the literature as reinforcement to polymers [6–9]. These natural fibers are mostly used in hybridization with any other synthetic fibers mainly due to two reasons. First, they have deficient mechanical properties compared to glass, carbon, and Kevlar fibers, and second, due to hydrophilic nature [10–12]. The hybridization technique overcomes these problems and simultaneously provides partially green and sustainable materials. The stacking sequence and the adopted manufacturing route have a significant impact on hybrid composites' mechanical properties. From all the natural fibers available, jute fiber has a strong potential to be used in ballistics armors applications due to significant impact properties [13–15]. Different studies have reported the impact resistance of jute fiber-reinforced composites [16]. Assis et al. [17] performed ballistic testing on polyester composites with a jute-fiber multilayer armor system (MAS). Results revealed that these composites have an excellent prospect in replacing Kevlar fiber in MAS. Furthermore, cost and weight reduction objectives were also achieved through these jute fiber polyester-based composites.

Bharath et al. [18] studied the mechanical properties of hybrid composites containing different stacking sequences of coconut leaf sheath/jute/glass fibers. The hand layup technique was employed for the manufacturing of these composites. The hybrid composite containing coconut leaf sheath and glass at the outer skin layer revealed optimum mechanical properties than all other combination and stacking sequences. In another work [19] using the same procedure, the mechanical

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Table 1
Mechanical and physical properties of fibers and adhesive resins.

Properties Materials	Density (kg/m^3)	Young's Modulus (GPa)	Elongation (%)	Poisson Ratio	Ultimate Tensile Strength (MPa)
E-Glass Fiber	2300	71–76	2.2–2.6	0.3	2000–2800
Jute Fiber	1400	20–30	1.5-1.7	0.32	390–770
Adhesive Resin	–	5–9	–	0.4	9–19

properties of jute/kenaf/E-glass hybrid composites were evaluated. The vacuum bagging technique was used for producing these hybrid composites. These hybrid composites can be used in roofing sheets, door and furniture panels, inner paneling, storage tanks, and household-based applications.

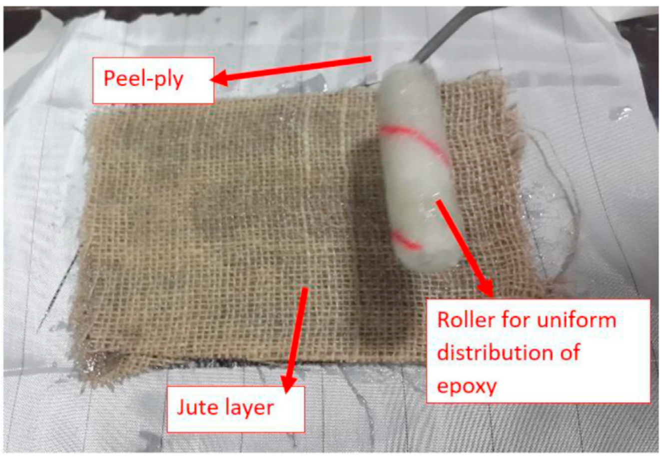

Fig. 1. Figure showing hand layup process employed for the preparation of composites.

Jothibasu et al. [20] explored the mechanical properties of sheath fiber, jute fiber, and glass fibers-based hybrid composites. Numerical analysis was also performed for the deformation behavior using ANSYS software. Experimental and numerical analysis showed that jute fiber as discontinuous layers, areca sheath fiber as a center layer, and glass fibers as skin layer had improved mechanical properties for the "L" frame, which can be used in flower stand applications. Kumaran et al. [21] investigated the thermal and mechanical properties of seafood waste-based *Portunus sanguinolentus* shell and jute fiber-based hybrid composites using the hand layup technique. Different surface and chemical treatments were also employed on these natural fibers and residue. Reported results indicated that at 10 wt% treated hybrid composites possessed improved thermal and mechanical properties.

Athith et al. [22] examined the tribological and mechanical properties of jute, sisal, and glass-based hybrid composites. Furthermore, the effect of the addition of tungsten carbide (WC) as particulate fillers in different weight ratios was studied. Results proved that the addition of WC fillers improves both tribological and mechanical properties of jute/sisal/glass hybrid composites. A similar study [23] was performed on glass/sisal-based hybrid composites with different silicon carbide fillers. The addition of these silicon carbide fillers improved flexural properties by filling the voids that are usually present due to the hand layup technique. Yorseng et al. [24] conducted weathering studies on

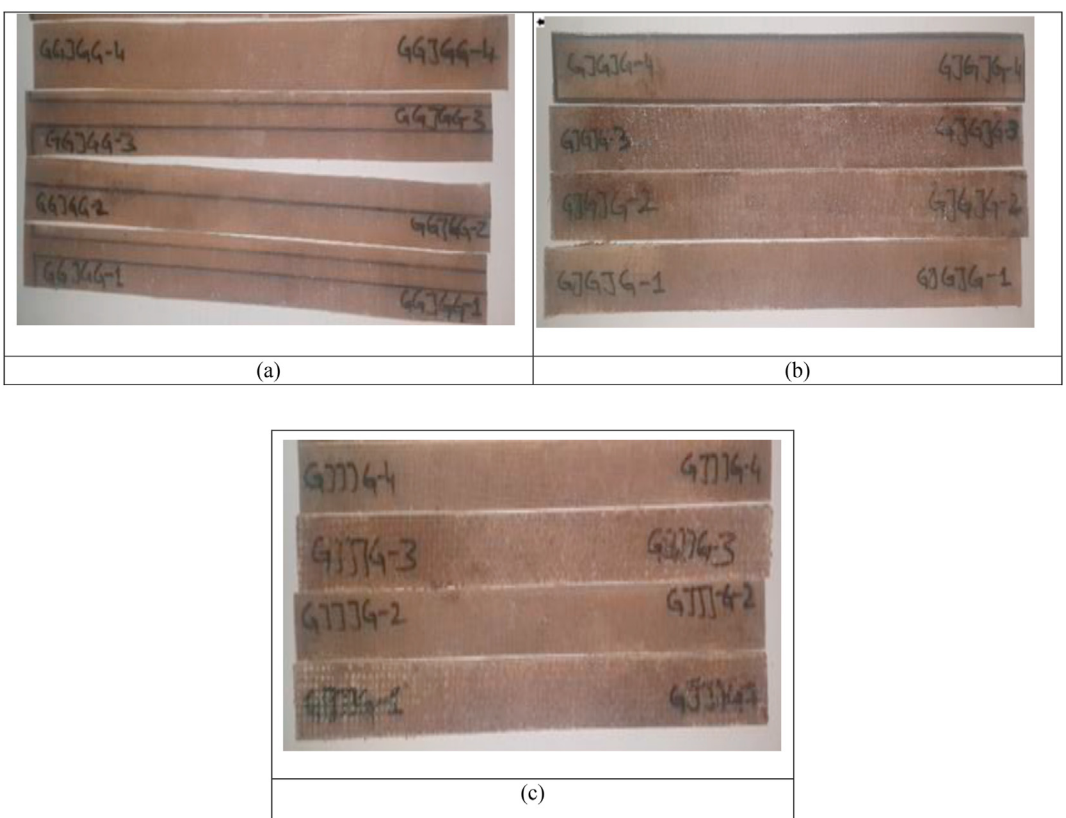

Fig. 2. Hybrid specimens after cutting (a) GGJGG, (b) GJGJG, (c) GJJJG.

Table 2
Testing conditions, sample's designations and details.

Scheme	Designation	Strain rate (mm/min)	Temperature (°C)	Specimen Length (mm)	Average Thickness (mm)	Width (mm)
Glass/Glass/Glass/Glass/Glass	GGGGG	2	23	150	1.9	25
Glass/Glass/Jute/Glass/Glass	GGJGG				2.1	
Glass/Jute/Glass/Jute/Glass	GJGJG				2.4	
Glass/Jute/Jute/Jute/Glass	GJJJG				2.8	

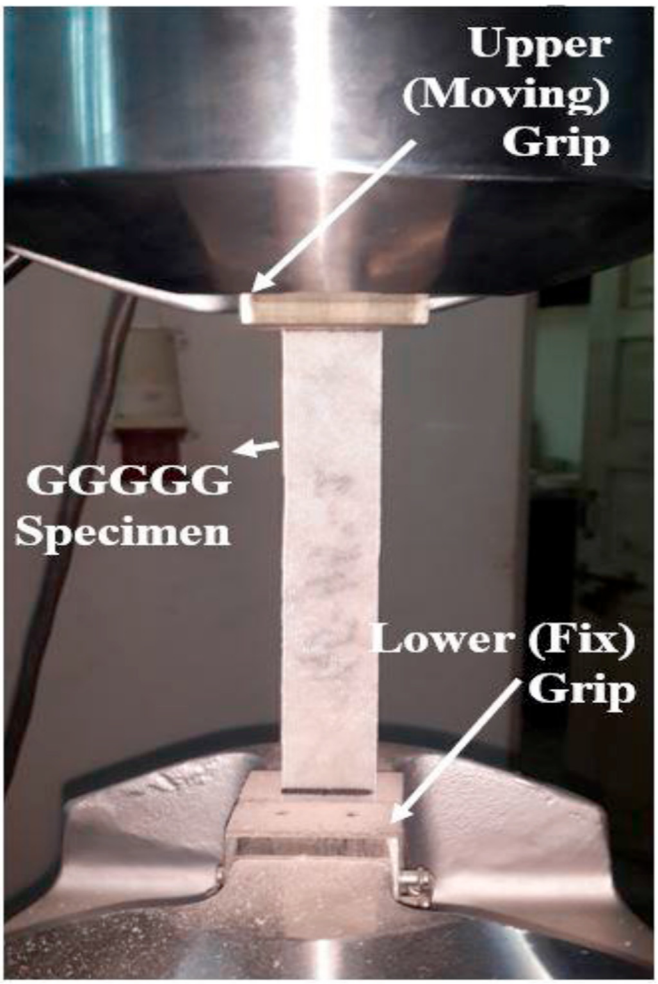

Fig. 3. GGGGG tensile specimen during testing.

Table 3
Engineering constants that are applied in numerical study.

Engineering Constants	Glass/Epoxy lamina	Jute/Epoxy lamina	Source
Density (kg/m^3)	1286.5	826.07	Experimentally
$E_1 = E_2$ (MPa)	7890	3400	Experimentally
E_3 (MPa)	4953	3200	Analytically (ROM)
G_{12} (MPa)	2850 [26]	1574	G/epoxy (Literature), J/epoxy(analytically)
$G_{23} = G_{13}$ (MPa)	1795	1536	Analytically (ROM)
ν_{12}	0.03	0.08	Experimentally
$\nu_{23} = \nu_{13}$	0.3	0.32	Analytically (ROM)

sisal/kenaf fibers-based hybrid composites. Different mechanical testings were performed on these hybrid composites. The moderate decrease in properties were seen after exposure to different environmental conditions, and thus, sisal/kenaf hybrid composites proved to be excellent materials for partial structural applications. Ganesan et al. [25] elaborated a comparatively new passement technique on jute fiber mat and eggshell hybrid composite mechanical properties. The eggshells were used as powder/nano clay. The incorporation of these nano clays in different percentages improved the tensile and flexural properties of hybrid composites.

From the above literature survey, it can be concluded that most of the works on natural fibers are related to their experimental testing; however, more focus should be made on numerical simulations of these materials. Thus, this study reports tensile testing of glass/jute hybrid composites through the ASTM D3039 standard. Later these experimental results were compared with numerical simulation results. A fractographic analysis was also performed on tensile specimens.

2. Materials and methods

2.1. Materials

Both plain-woven E-glass fiber and jute fiber were utilized in this study. The complete information about these fabrics and adhesive system are reported in Table 1.

2.2. Preparation of composites

The hand layup technique was adopted due to its wide range of advantages like simple manufacturing setup and low cost. Four different types of composites, including one non-hybrid laminate and three hybrid laminates, were produced. First, mold releasing wax was applied on the glass mold surface, then peel-ply and different fibers were placed one by one according to the desired stacking sequences. Excess epoxy resulting from roller movement comes out of the specimen sides and usually sticks with the glass mold surface. Thus, the function of peel ply is to remove the final prepared specimen easily from the glass mold surface. It provides roughness between the skin layers of fibers and the glass mold surface. It also protects glass mold from damage during the extraction of final composites from the glass mold surface. The necessary arrangements of different tools and materials used in the hand layup technique are shown in Fig. 1.

2.3. Mechanical study

After the successful preparation, samples were cut according to ASTM D3039 on the cutting machine, as shown in Fig. 2. Four types of hybrid composites were tested, as reported in Table 2. The tensile testing was done according to ASTM D3039. Loading and environment conditions were considered according to the standard for tensile tensing. Specimen dimensions were 250 mm × 25 mm, and thickness was in the range of 1.8 mm–2.8 mm. Sample during testing is shown in Fig. 3.

3. Numerical analysis

Numerical simulations were performed using ABAQUS software. 3D tensile specimen geometry-based part was modeled in the first step using 3D mesh element. Glass and jute laminas were defined in material definition by assigning them orthotropic properties, as reported in Table 3. There are mainly three sources for orthotropic properties used in the composite layup. First, engineering constants for fibers (glass and jute) and (adhesive resins) epoxy from technical data sheets provided by the

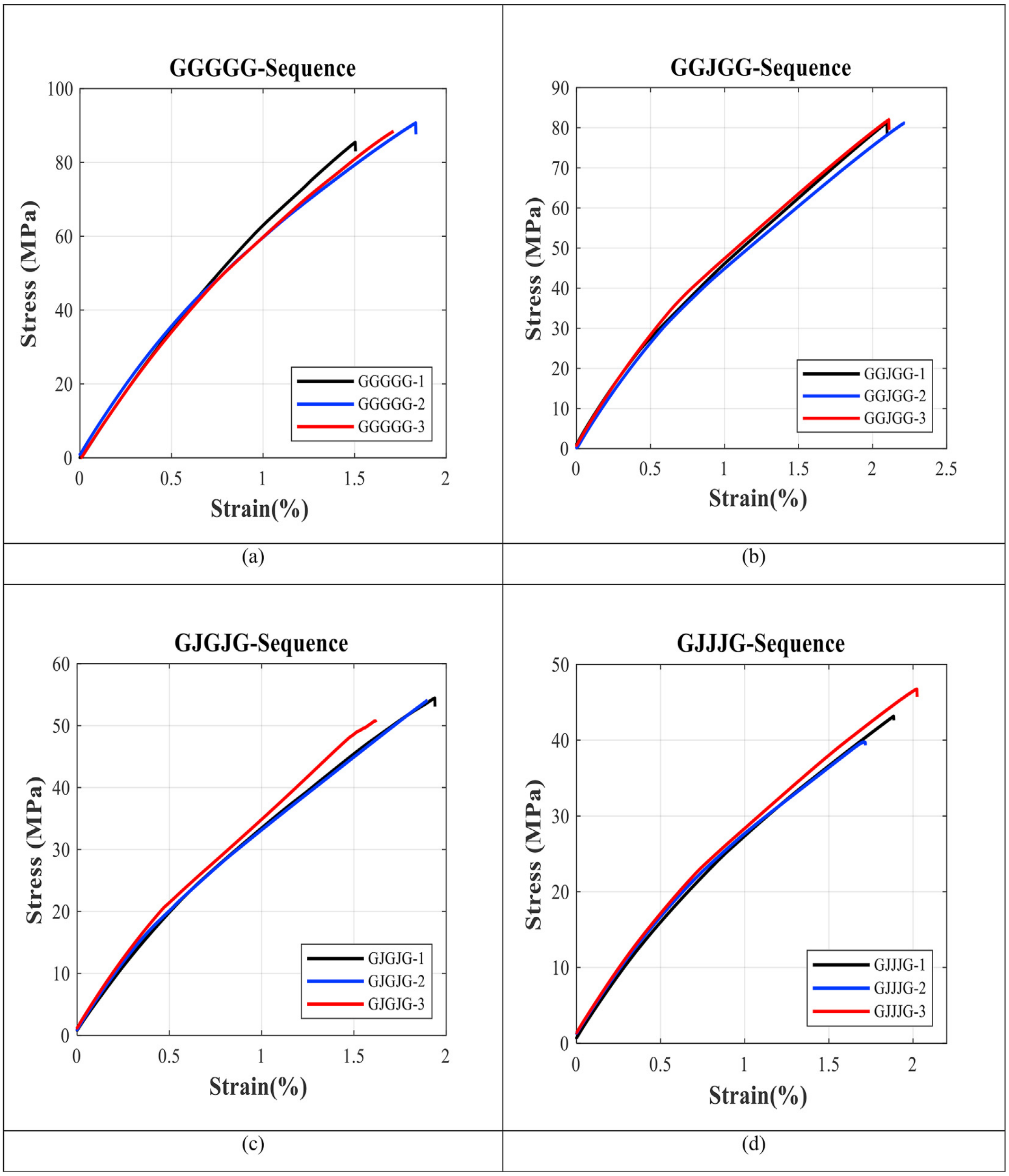

Fig. 4. Tensile stress vs strain graphs of different sequences (a) GGGG sequence (b) GGJGG sequence (c) GJGJG sequence (d) GJJJG sequence.

Table 4
Calculated engineering constants from stress-strain curves.

Specimens Type	Scheme	Ultimate Tensile strength (MPa)	Average Elastic Modulus (MPa)	Average Strain (e) at failure (%)
Glass/Glass/Glass/Glass/Glass	GGGGG	87	7890	1.6
Glass/Glass/Jute/Glass/Glass	GGJGG	83	5516	2.0
Glass/Jute/Glass/Jute/Glass	GJGJG	54	3947	1.7
Glass/Jute/Jute/Jute/Glass	GJJJG	43	3193	2.1

manufacturer. Second, the literature for those materials whose simulations are already done by many researchers with similar adopted material, design of experiment, and manufacturing process. Third, the experimental testing of these materials. For example, the "v_{12}", (Poisson ratio) was calculated before and after the experimentation of broken tensile specimen by measuring the shape changes in longitudinal and transverse direction of the woven fibers through visual inspection. Both linear and lateral strains in the longitudinal and transverse direction of fibers of broken samples were measured. The reference point in the upper grip was coupled with all nodal points in the tensile test model. Finally, displacement was applied on the upper node by maintaining fixed boundary conditions at the lower end. Results were visualized through output plots of ABAQUS, and force vs displacement data was obtained.

4. Results and discussions

4.1. Tensile testing results

Four samples of each composite laminate were tested. Only three sample results for each laminate are presented in stress-strain graphs. The results showed that non-hybrid laminate GGGGG possesses the highest tensile strength of 87 MPa. At the same time, the hybrid laminate GGJGG, which contains a single jute fiber lamina in place of glass fiber lamina, shows a comparable tensile strength of non-hybrid laminate, i.e., 82 MPa. The difference between these two values is relatively small, justifying

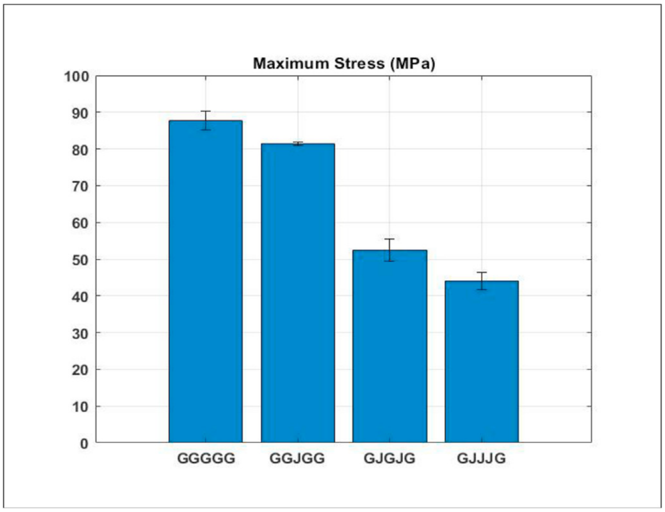

Fig. 5. Bar chart of maximum tensile strength.

that supplanting one jute fiber layer with one glass fiber layer didn't influence its tensile strength. Similar types of results were reported previously by many researchers [27,28] mainly with the hybridization technique utilizing jute fiber with any other synthetic fibers.

In contrast, sequence GJJJG possesses poor tensile strength among all the tested laminates. This behavior is because these hybrid laminates contain a more significant percentage of jute fibers and the mechanical properties of jute fiber are significantly lower than glass fiber. Furthermore, the conceivable justification of higher tensile strength GGGGG and GGJGG is the lesser number of interface layers; however, the GJGJG has many interface layers, resulting in lower tensile strength. Experimental stress-strain plots for all non-hybrid and hybrid laminates are shown in Fig. 4. The complete details of engineering constants which were calculated from these curves, are reported in Table 4. The comparison of tensile strength of all sequences through a bar graph is shown in Fig. 5.

4.2. Tensile simulation results

The hand layup approach is considered the most convenient in polymer composites manufacturing. A large variety of epoxy (matrix) and fibers (reinforcements) can effectively be utilized on small and industrial scales. Other advantages include low cost, fewer labor skills, and reuse of experimental setup and tools. A difference between experimental and numerical results was observed as the mechanical properties of manufactured specimens deteriorated due to several factors. Micro voids and

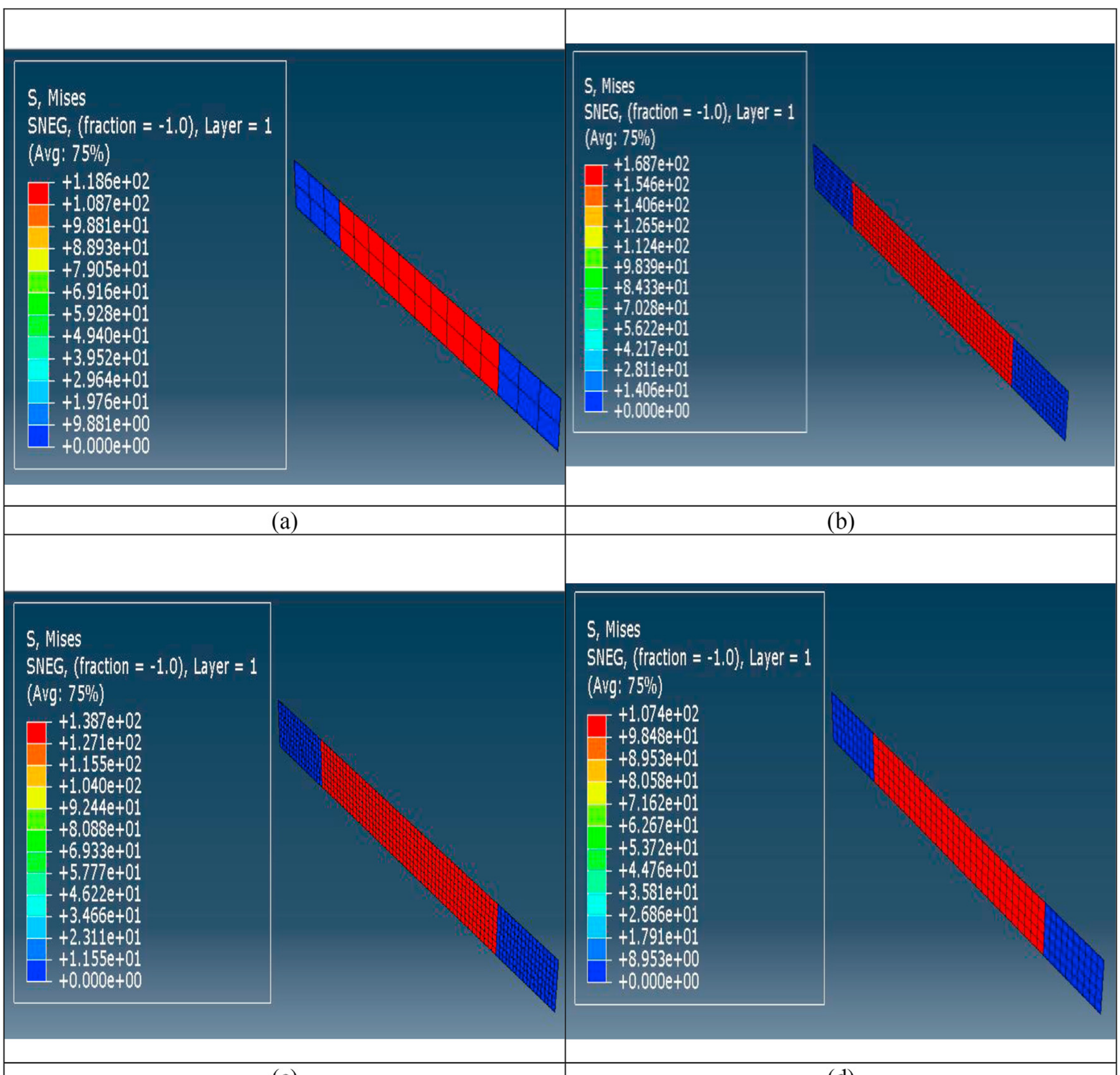

Fig. 6. Contour plots for von-Mises stress (a) GGGGG (b) GGJGG (c) GJGJG (d) GJJJG.

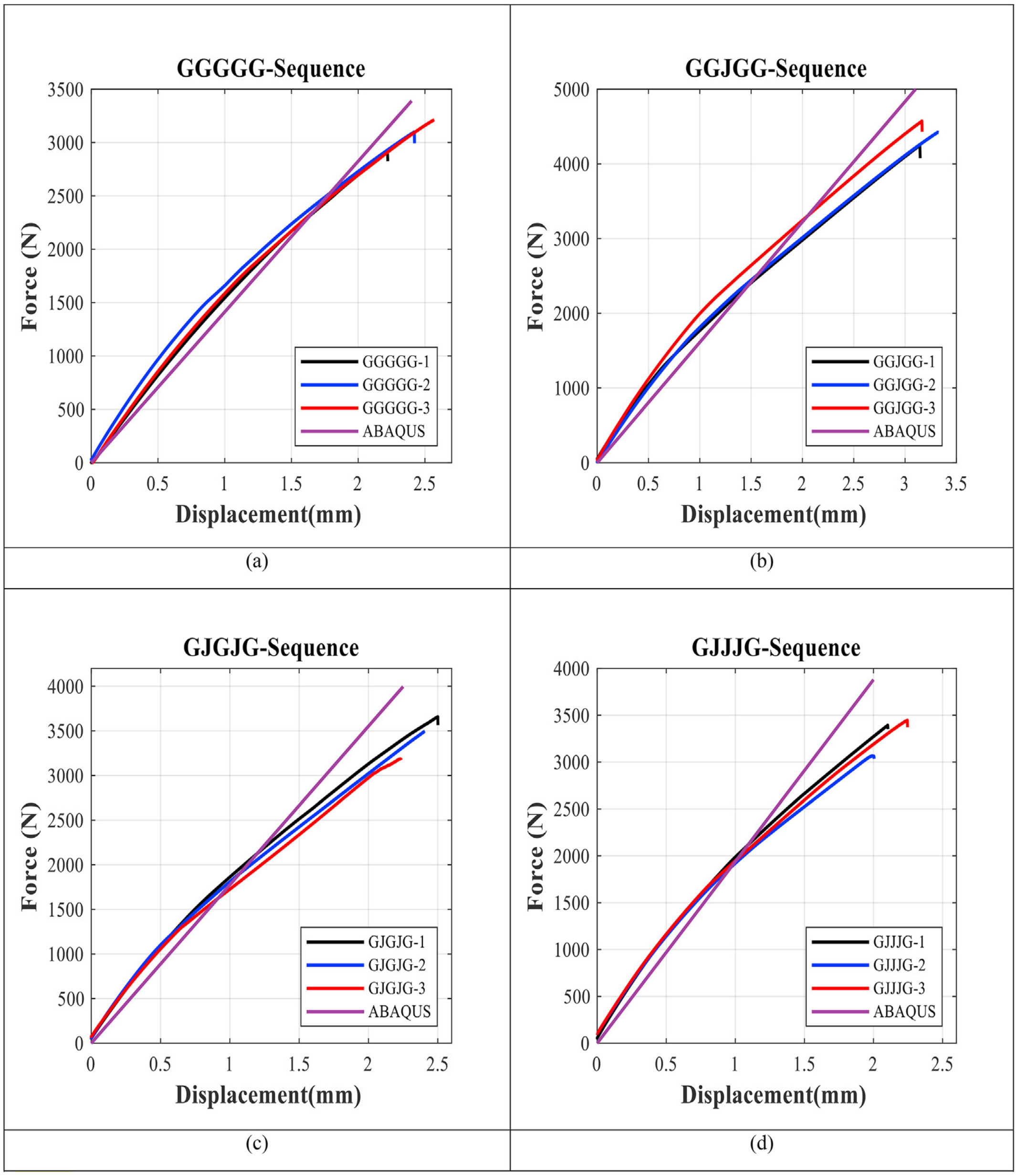

Fig. 7. Tensile force vs displacement graphs of different sequences (a) GGGG sequence (b) GGJGG sequence (c) GJGJG sequence (d) GJJJG sequence.

delamination between the laminas, especially when different fibers laminas are placed (GGJGG, GJGJG, and GJJJG sequences), are the prime causes of this behavior.

Furthermore, it is evident from previous researches that the hand layup technique often provides the composite with a higher ratio of the matrix (epoxy) [29], which results in lower mechanical properties of composites than expected. Different percentages of errors exist between experimental and numerical results for each of the stacking sequences. The stress contours plots for different sequences and force vs. displacement curves are presented in Figs. 6 and 7, respectively.

4.3. Fractographic assessment

Fractographic analysis was performed using OLYMPUS microscope BX51. This study aims to validate the different experimental results for each of the stacking sequences and underline the possible physical mechanism for failure. In the GGGGG sequence, as shown in Fig. 8a, the failure occurs mainly due to matrix failure. Fig. 8b illustrates jute fiber pull out in the GGJGG sample. This is because the single jute layer at the center of sequence pulls out from both glass fibers and matrix due to tensile loading. Different layers of glass and jute fibers can be visualized in Fig. 8c, fractured specimen of GJGJG sequence. The maximum number of interfaces in the GJGJG sequence is the possible reason for the lower tensile strength. Scattered glass fibers in the GJJJG sequence can be observed in Fig. 8d. This is because of the poor adhesion of glass fibers with multiple jute fiber layers, resulting in lowers tensile properties than the other sequences.

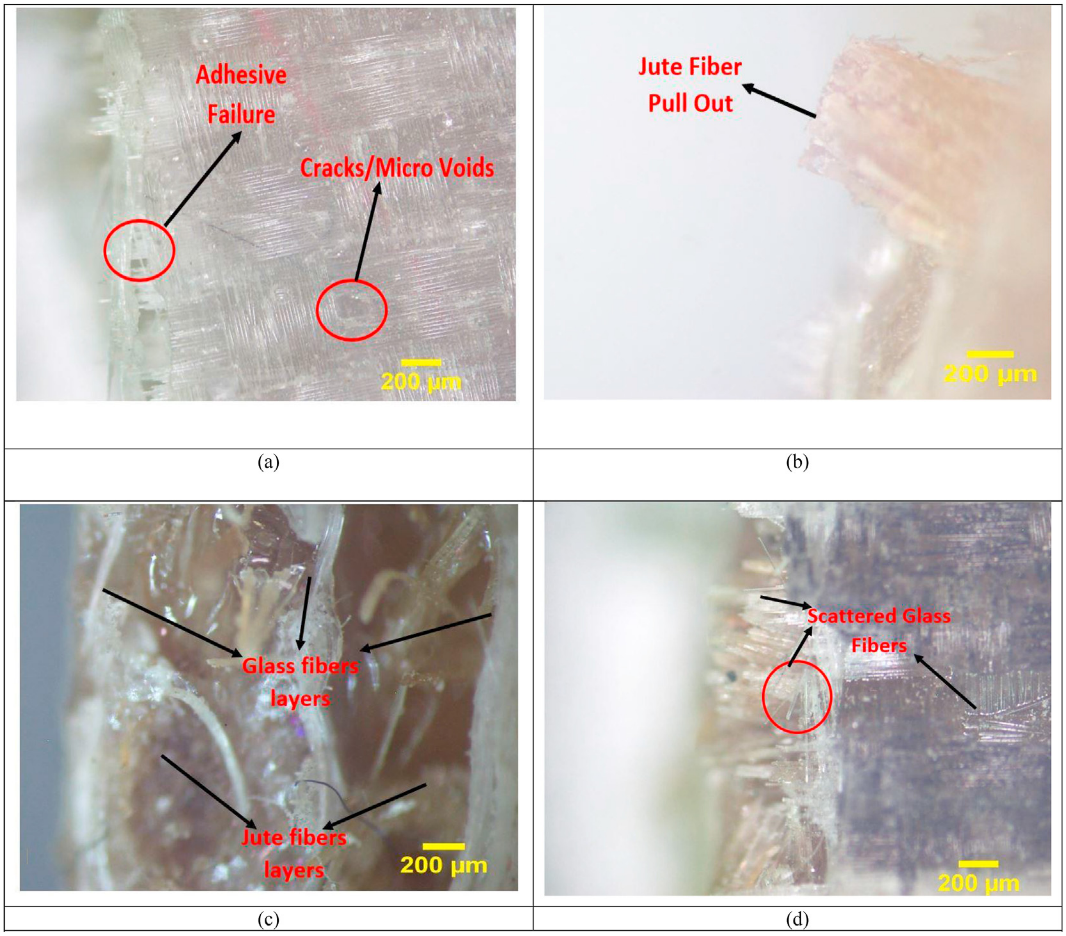

Fig. 8. Fractographic studies on different tensile specimens (a) GGGGG specimen (b) GGJGG specimen (c) GJGJG specimen (d) GJJJG specimen.

5. Conclusions

In this study, the hand layup technique was utilized to manufacture non-hybrid and hybrid composite laminates. The tensile testing was done as per the ASTM D3039 standard. The experiment revealed that incorporating a single jute fiber does not seriously influence the tensile properties of glass fiber reinforced composites. While maintaining the tensile properties, the use of jute fiber lamina lowers the overall cost of hybrid composite material to a significant amount. Experimental results were also validated through numerical simulations, which complemented the experimental results with some errors. The error resulted due to the non-uniformity in the diameter of jute fiber. Micro voids and adhesive failure between different fibers laminas causing delamination are the main findings of fractographic studies of these composites.

A potential scope exists for future researchers to implement and expand the current study for further analysis like thermal and dynamic mechanical properties. Further investigation will also be performed to evaluate mechanical parameters using other natural fibers with different manufacturing techniques like resin transfer molding (RTM) and injection molding under different strain rates.

Credit author statement

Conceptualization, Muhammad Yasir Khalid, Ans Al Rashid and Muhammad Ali Nasir.; methodology, Zia Ullah Arif., Ans Al Rashid and Muhammad Yasir Khalid.; software, Hassan Arshad and Muhammad Fahad Sheikh; formal analysis, Ans Al Rashid, Muhammad Yasir Khalid and Zia Ullah Arif.; investigation, Ans Al Rashid, Hassan Arshad and Muhammad Fahad Sheikh.; writing—original draft preparation, Muhammad Yasir Khalid and Muhammad Ali Nasir.; writing—review and editing, Muhammad Yasir Khalid, Ans Al Rashid and Zia Ullah Arif.; supervision Muhammad Ali Nasir.; project administration, Muhammad Ali Nasir.; funding acquisition, Ans Al Rashid. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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