

Failure Analysis of Hybrid Natural/Synthetic Fiber Composite Laminates in The Application of Hybrid Composite Pressure Vessel

D.V. Srividya^{1*}, Shaik Khadar Vali², B. Hadya³, S. Irfan Sadaq⁴

Abstract

Composite laminates are frequently utilized in multiple sectors. The growing complexity of composites in aircraft applications necessitates hybridization of these materials. These hybrid laminates consist the combination of one natural fiber and two selected synthetic fibers. This work investigates three different six-layer hybrid composite laminate combinations: Jute2/Carbon2/Jute2, Jute2/Glass2/Jute2, and Carbon2/Glass2/Carbon2, with helix angles of 0° and 90° and a volume fraction of 50% fiber content. Each specimen is fabricated utilizing hand layup process, and it is inspected in accordance with ASTM guidelines. The numerical analysis was conducted and the blend of natural/synthetic fibers functioned well, as evidenced by the outcomes from the deformation and stress analysis conducted on hybrid composite laminates. This finding aids in the material selection process for the construction of hybrid composite pressure vessels. The sandwich, of natural/synthetic fibers is beneficial for a range of mechanical and aeronautical applications. It was determined to be optimal with good agreement by comparing the experimental and numerical results. The hybrid laminates with the combination of glass and carbon shown excellent strength performance followed by the combinations jute/carbon & jute/glass. In terms of strength performance, jute/carbon hybrid laminate outperformed jute/glass hybrid laminate by 50%. In terms of compression strength, there is not much difference observed between jute/carbon & Carbon/glass laminates while the flexural strength of jute/carbon & jute/glass shown equal strength enhancement.

Keywords: Hybridization, hybrid composite laminates, static testing, helix angle, hybrid composite pressure vessel

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INTRODUCTION

The hybrid composites are lighter, more affordable, and more energy-efficient than traditional materials, they are typically utilized to replace conventional materials with hybrid ones. They also have a longer lifespan. They are therefore a cost-effective choice for a variety of applications [1]. The process of hybridization is among the most significant and effective methods to strengthen and improve the enactment of composite materials. As natural fibers biodegrade, they are affordable and environmentally friendly, but synthetic fibers are more rigid. In contrast to metallic materials, hybrid composites made of synthetic and synthetic fibers have the potential to produce composites with higher particular material qualities. Conversely, natural and natural fiber composites offer excellent attributes and help protect environmental resources. [2-3].

The differences in composition and structure induced by the several layers increases the intended characteristics of the laminates [4]. The modulus is independent of the stacking sequence, and the no. of plies increases both the tension and the failure strain increases [5]. Strength and stiffness both rise with increasing fiber volume percentages. As the fiber capacity increases, the specimen's damage behavior changes [6]. Under tensile and compressive stress, the optimal fiber angle is 0° because it causes the least amount of strain and deformation. Under tensile strain, 0° and 30° fiber angles possess greater resilience than other fiber angles [7]. When it comes to strength, the carbon and glass fiber composites perform best at 0 and 90 degrees [8–10]. Unidirectional laminate had the modulus & largest tensile strength, maximum flexural strength & modulus in the flexural mode [11]. The stacking sequence and ply orientation of composite laminates have a considerable impact on their strain rate sensitivity. The interface concerning the matrix & fiber is probably a ductile rupture mechanism at greater strain rates [12].

Numerous researchers' studies on polymer composite technology have confirmed that NFC (Natural Fiber Composites) is superior to SFC (Synthetic Fiber Composites) and equal to them. Instead of using synthetic fiber as polymer reinforcement, jute fiber might function effectively. It is possible to boost the characteristics of jute composite materials by using polypropylene, polyester, epoxy resin, and other suitable matrix combinations. Chemical treatments applied on the fiber can further improve the characteristics of jute fiber composites [13–14].

Shear cracking is mostly caused by the fiber's path. In conclusion, improving the combined shear stability of the fiber & matrix can aid the compression strength of composite made of unidirectional fiber and epoxy resin [15]. Glass/epoxy composite materials orientated at a 90° angle show the least degree of strain. When compared to jute and plain glass weave composites, the former's reinforcement shows noticeably superior flexural capabilities. Tensile resistance decreases when the fiber content of the glass/epoxy composite laminate increases [16–18].

The max. load was likewise seen at a high yield point, and the CFRP composite exhibits higher flexural, tensile & axial compression strengths at a 90° orientation [19]. The mechanical characteristics of the CF/epoxy resin composite are greater than the CF/phenolformaldehyde resin composite [20–22]. Better interlaminar & flexural shear capabilities are demonstrated by Plain Weave (PW) laminates with orientations of ($0^\circ/90^\circ$) & carbon with both matrices (F584, 8552) [23]. The interlaminar strength (ILS) of CFRP laminates is considerably greater than the other orientation [24]. Although the Mode II interlaminar fracture toughness of UD CF/Epoxy laminates is lower while the interface is stronger [25].

Jute with glass fiber incorporation has improved mechanical properties, that increases the use of natural fiber in a extensive series of applications [26]. The hybrid laminate Glass/Jute/Polyester had the highest values of storage modulus among the combinations of jute/polyester & glass/polyester, hence validating the flexural test [27].

The overall maximum hybrid effect is reached at 50% of V_{fc} and V_{fg} . The strength is improved in comparison to the arrangements of glass and entire carbon, respectively [28]. Tensile test findings for the glass/epoxy and carbon/epoxy composites show a drastic reduction with the final fracture load; these composites rise linearly for $\theta = 90^\circ$ and non-linearly for $\theta = 0^\circ$ until they reach their extreme value [29]. The highest flexural strength is provided by the hybrid laminate with the outer carbon fiber layer (C/G/G/C) [30–32]. The impact properties of carbon-glass fiber/epoxy hybrid composites are affected by temperature fluctuations, with a peak occurring at -20°C or 60°C [33]. Peak loads raised with the addition of carbon fibers to the face sheets for all impact energies that were considered. When carbon fibers were included in the skin portions of the composites, their strength rose and decreased when glass fibers were present [34–35]. In association with the carbon composite laminate, laminates of hybrid composite are more ductile and exhibit more brittle behavior [36].

From the aforementioned survey, hybrid laminates are made by hand layup method with a combination of two synthetic fibers glass & carbon with natural fiber jute, as a common ingredient. The helix angles of 0° and 90° are also taken into consideration from the literature study. Three hybrid combinations—jute/carbon, jute/glass, and carbon/glass—were made and contrasted with one another to determine which combination is best suited. Their mechanical characteristics are examined in order to ascertain the most effective way to employ the material in the building of a hybrid composite pressure vessel.

MATERIALS AND METHODS

One of the early methods utilized for fabrication of FRP composites is the simple and reliable hand lay-up technique. In the fabrication process, jute, carbon, and glass mat fibers were used as reinforcements. Epoxy resin with hardening agent is the type of resin used in the construction. The source of these fiber materials is Vruksha Composites (AP). The fiber to matrix ratio considered in the present work is 50:50. Table 1 displays the material properties of the composite fibers reinforced epoxy.

Experimental Analysis of Hybrid Composite Laminates

The fabricated Hybrid Composite Laminates (HCL) are cut and prepared in accordance with ASTM standards. The samples are then tested for their tensile, compression, flexural, impact, and ILSS properties. The Jute/carbon reinforced epoxy composite laminate is designated as (J2/C2/J2) or JC, whereas Jute/glass reinforced epoxy composite laminate is (J2/G2/J2) or JG, and the Carbon/Glass reinforced epoxy composite laminate is (C2/G2/C2) or CG. The JC, JG, and CG HCL specimens of tensile, compression, flexural, impact, and ILSS as per standard are displayed in the following Figure 1.

Hybridizing the composite pressure vessel (HCPV) without measuring the characterization on their material is quite crucial. With experimental observations of HCL, it is simple to understand how different fiber kinds interact with alignment. The way the different fibers are arranged, stacked, and directed, affects the laminate's ability to withstand stresses in tension, compression, flexural, impact, and ILSS. Figure 2 in bar diagrams below illustrates how each JC, JG, and CG HCL's strength is executed under various testing conditions.

Table 1. Material properties of composite fibers reinforced epoxy.

Type of composite	Jute fiber reinforced epoxy	E-Glass fiber reinforced epoxy	T700-12k carbon fiber reinforced epoxy
Young's modulus in X-direction (GPa)	12.57	56.75	115.6
Young's modulus in Y-direction (GPa)	5.633	12.27	6.311
Major poisson's ratio	0.339	0.225	0.295
Minor poisson's ratio	0.1008	0.0486	0.0161
Shear Modulus (GPa)	2.452	5.204	2.478

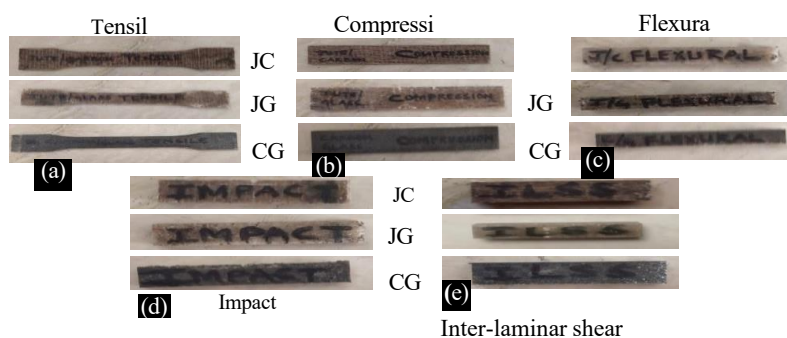
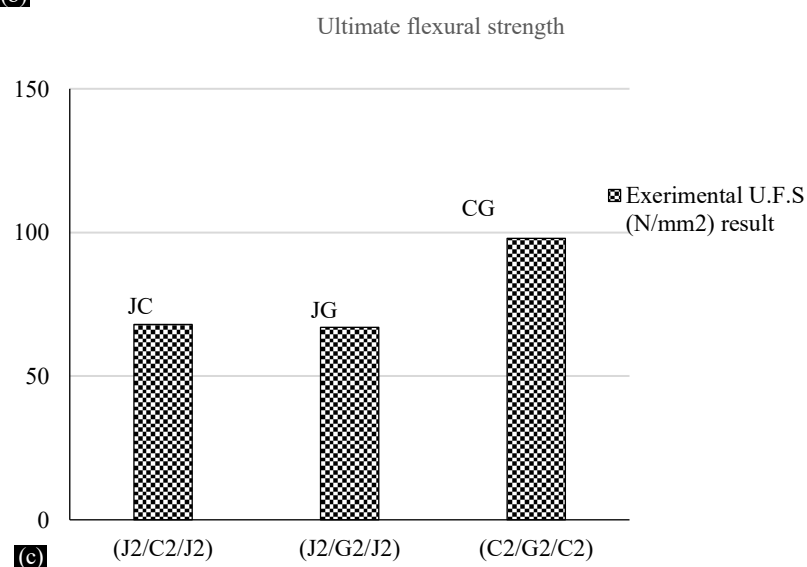
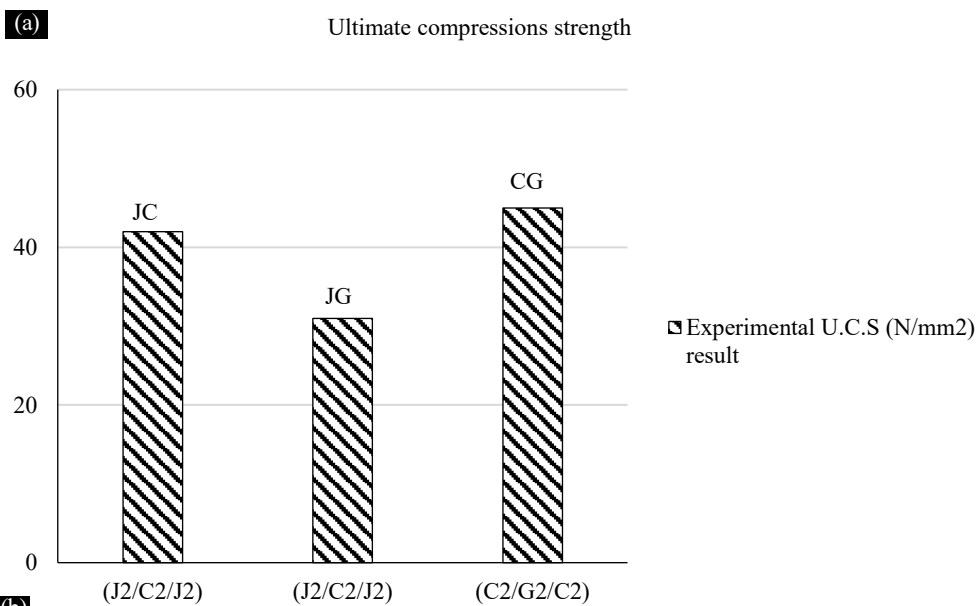
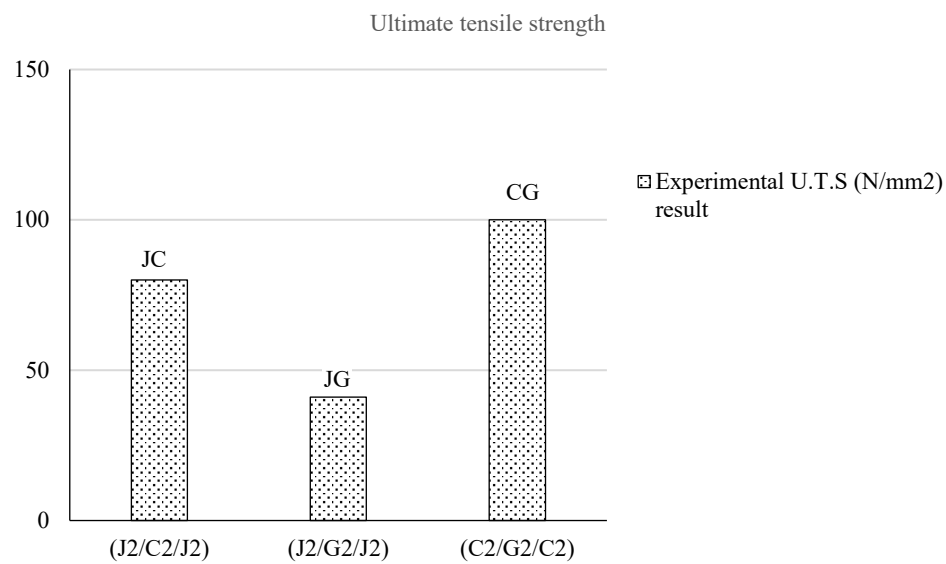


Figure 1. Illustrates the JC, JG & CG specimens of (A)Tensile, (B)Compression, (C)Flexural, (D)Impact and (E)ILSS



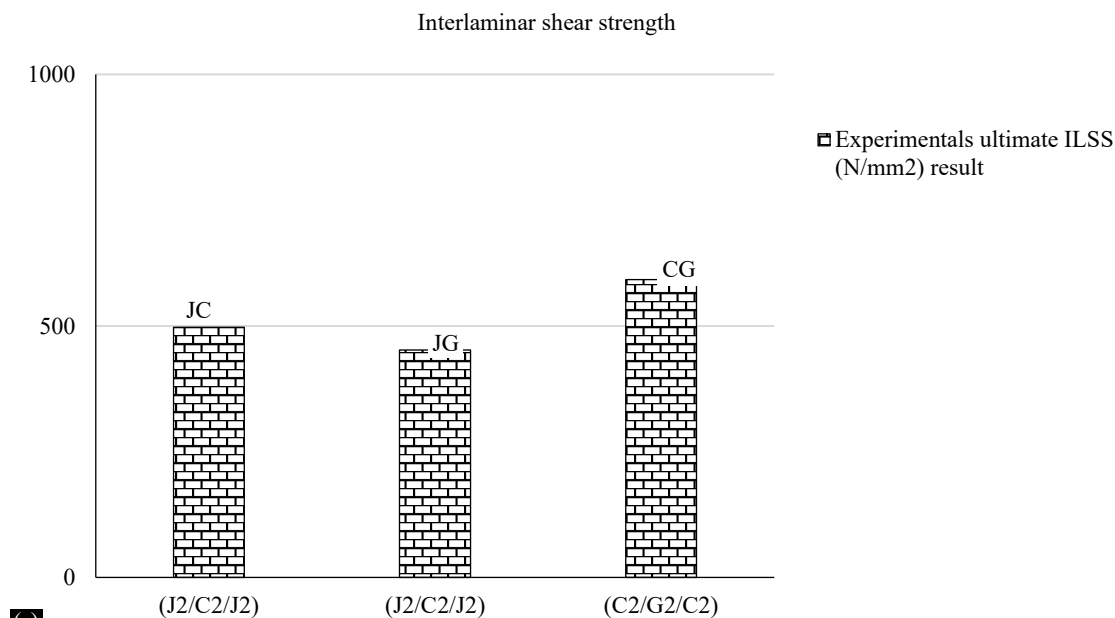
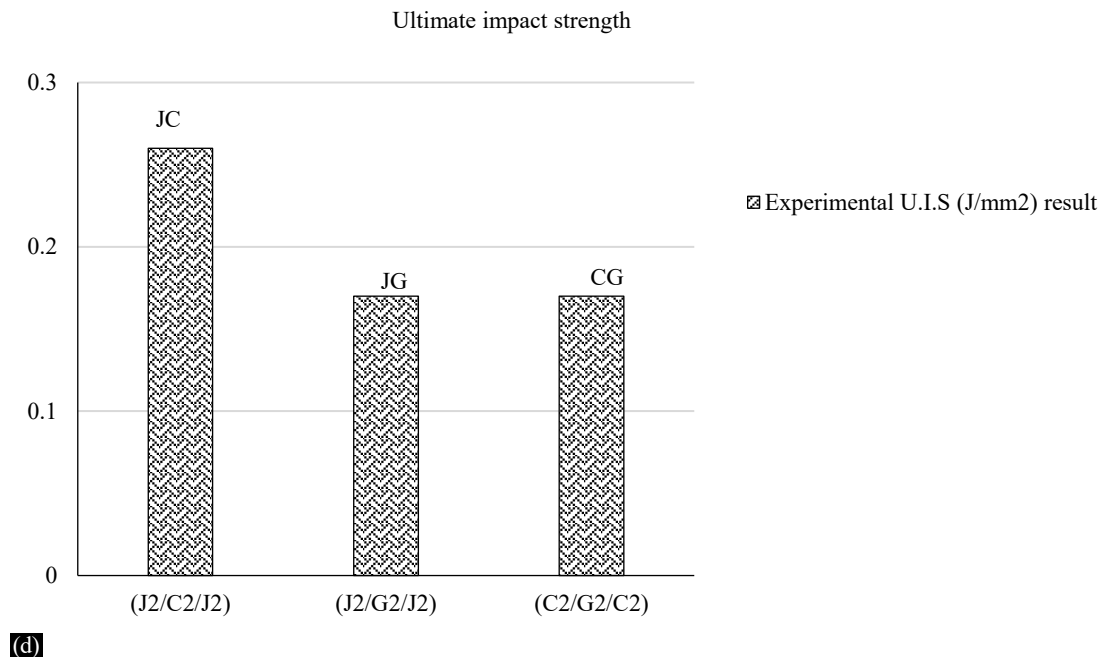


Figure 2. Shows (a) ultimate tensile strength (b) ultimate compression strength (c) ultimate flexural strength (d) ultimate impact strength & (e) ultimate interlaminar strength of JC, JG, and CG HCL.
[Note: JC-Jute/Carbon HCL, JG-Jute/Glass HCL, CG-Carbon/Glass HCL]

Numerical Analysis of JC, JG, and CG HCL's

Hybrid composite laminates JC, JG, and CG based on various material combinations are modeled and analyzed in accordance with ASTM standards. ANSYS APDL, a commercial software package, is utilized to analyze the strength of various HCLs. Every laminate model has six layers, each with a different helix angle of $[0^\circ-90^\circ]$ and by considering the properties of the materials from Table 1. Shell 3D 4node 181 element type is used for the FEA model. Here, the stress analysis for JC, JG, and CG is completed for various testing situations, including tensile, compression, flexural, impact, and ILSS. Figure 3 provides a graphic representation of the strength analysis of different HCL during various testing scenarios using FEA. Figure 3 illustrates the meshed model of the HCL. The figures from 4-6 displays the tensile strength distribution of jute/carbon, jute/glass & carbon/glass HCL's

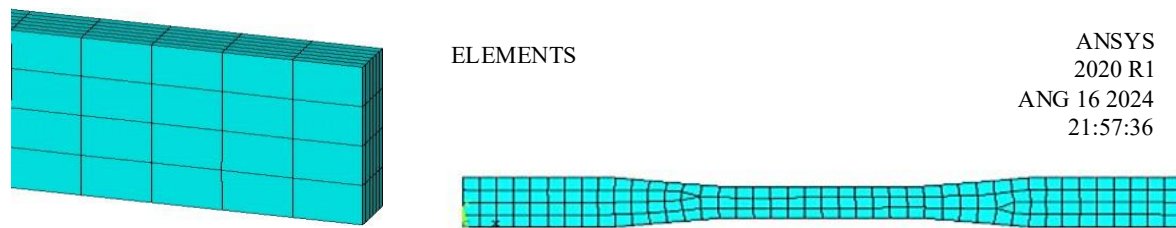


Figure 3. Meshing model of hybrid composite tensile test laminate according to ASTM D3039.

Nodal solution
 STEP-1
 SUB-1
 TIME-1
 SEQV (AVG)
 DMX = 5.47719
 SMX = 76.4236

ANSYS
 2020 R1
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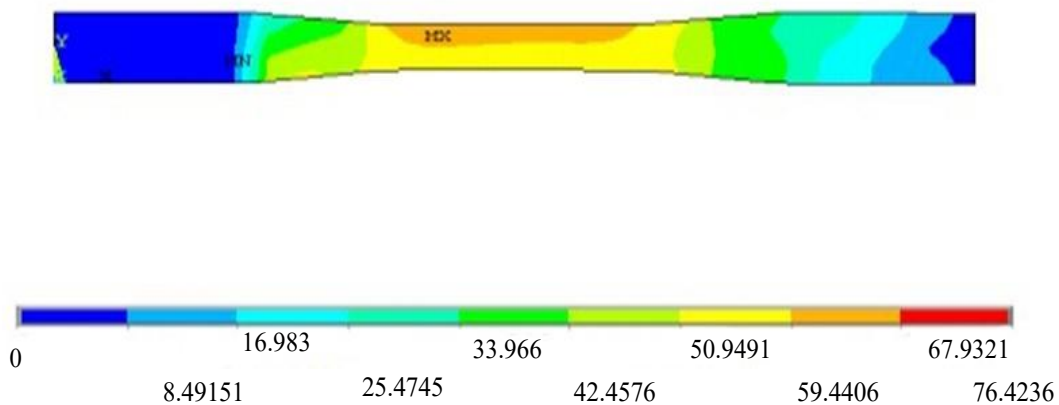


Figure 4. Tensile strength of jute/carbon HCL.

Nodal solution
 STEP-1
 SUB-1
 TIME-1
 SEQV (AVG)
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 SMX -38.2762

ANSYS
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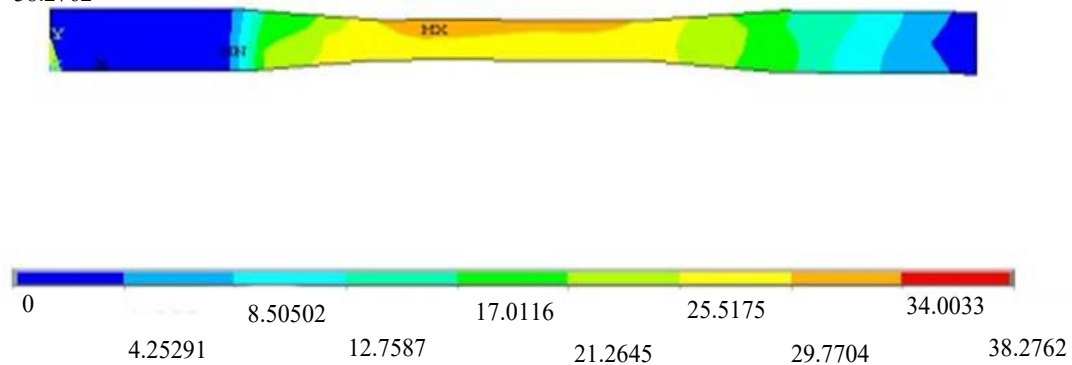


Figure 5. Tensile strength of Jute/Glass HCL.

Nodal Solution
 STEP-1
 SUB-1
 TIME-1
 SEOV (AVG)
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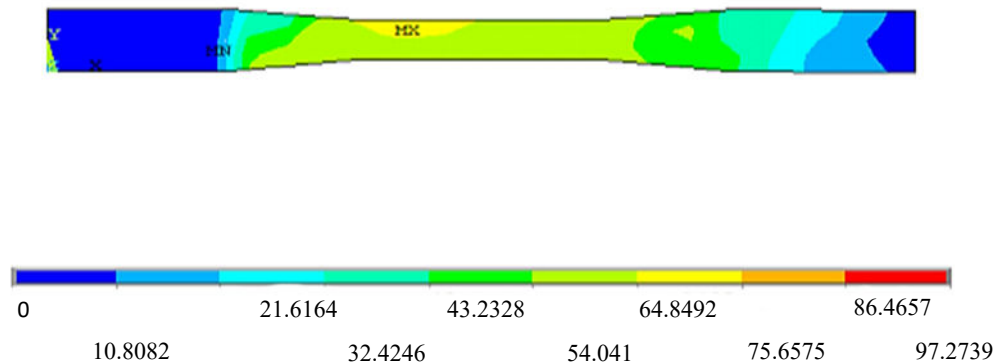
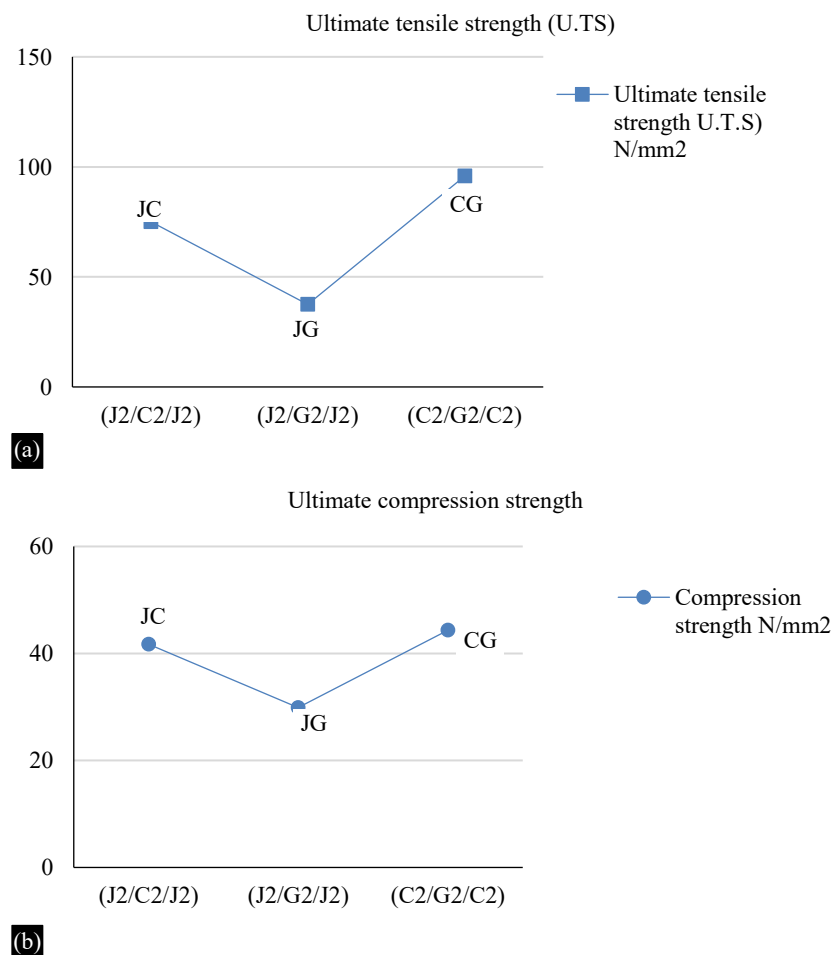
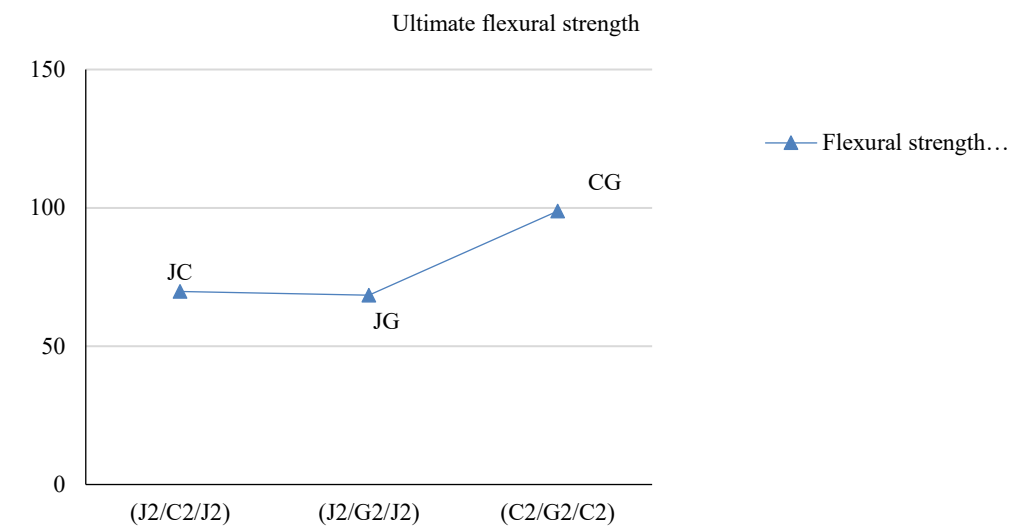


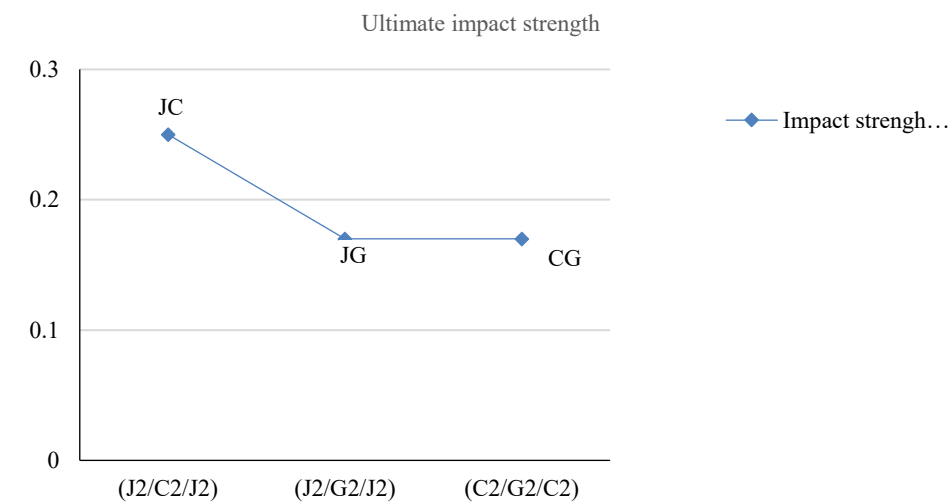
Figure 6. Tensile strength of Carbon/Glass HCL.

Similarly like above the analysis on the models of Compression, flexural, impact and interlaminar shear strength are carried out. The results have been depicted below in graphical representation in figure 7.

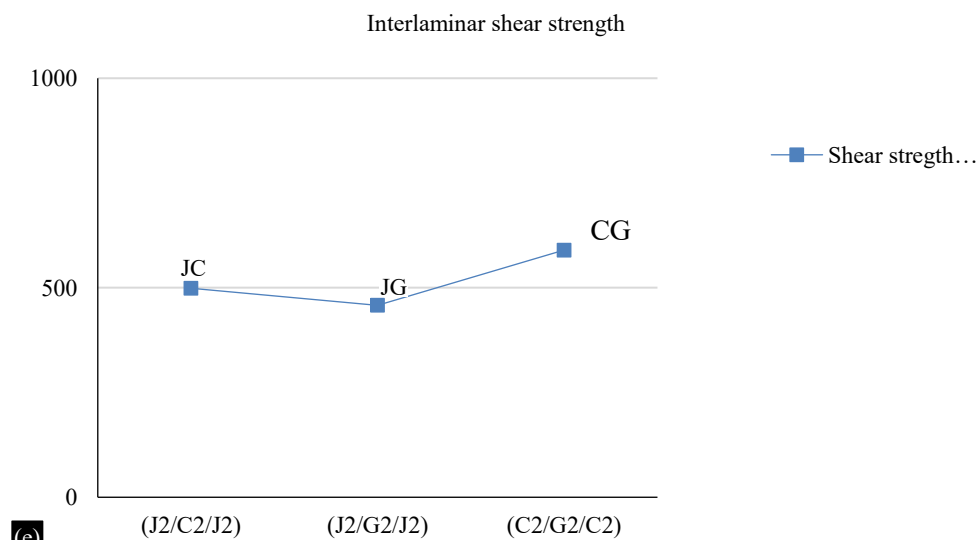




(c)



(d)



(e)

Figure 7. Graphical illustration of (a) tensile strength (b) compression strength (c) flexural strength (d) Impact strength & (e) interlaminar shear strength Vs JC, JG, and CG.

RESULTS AND DISCUSSION

The simulated outcomes show good accordance with experimental result in terms of all mechanical aspects. The bar diagrams from the Figure 8-12, demonstrate that there is a slight difference in either analysis.

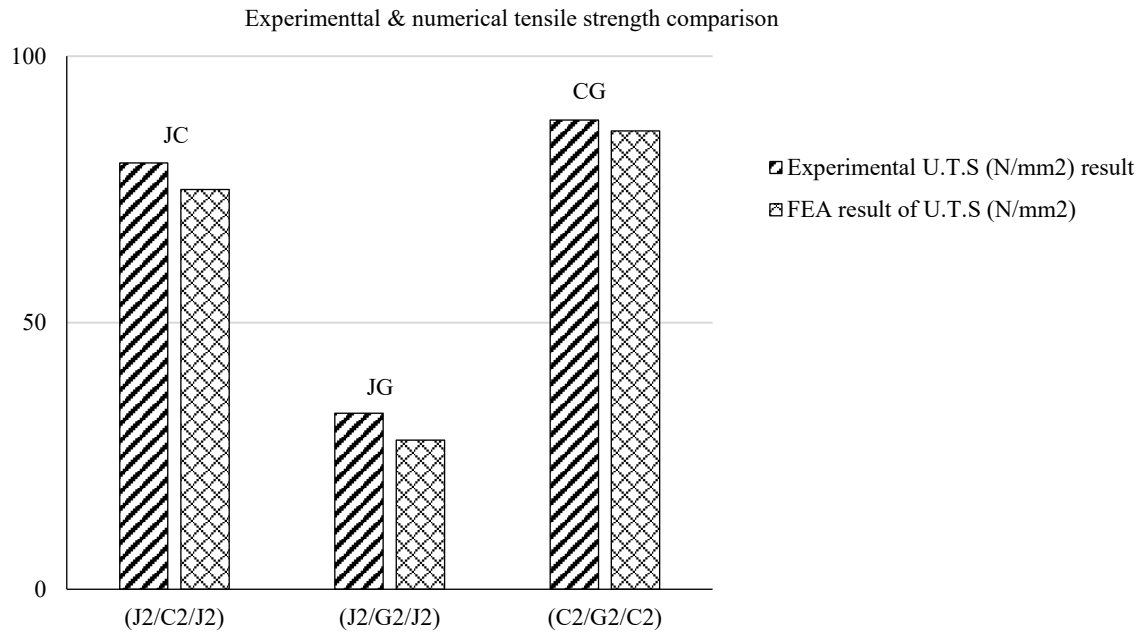


Figure 8. Experimental & numerical ultimate tensile strength comparison of JC, JG, and CG.

- a. The discrepancy among the experimental & numerical analysis for tensile strength is depicted in the bar diagram of Figure 8. We can see the percentage error of JC at 4.71%, JG at 5.26%, and CG at 2.77%. When compared to JG, the combination of JC & CG produced positive outcomes. There is a 21.48% percentage difference in strength between the CG and JC HCL's.

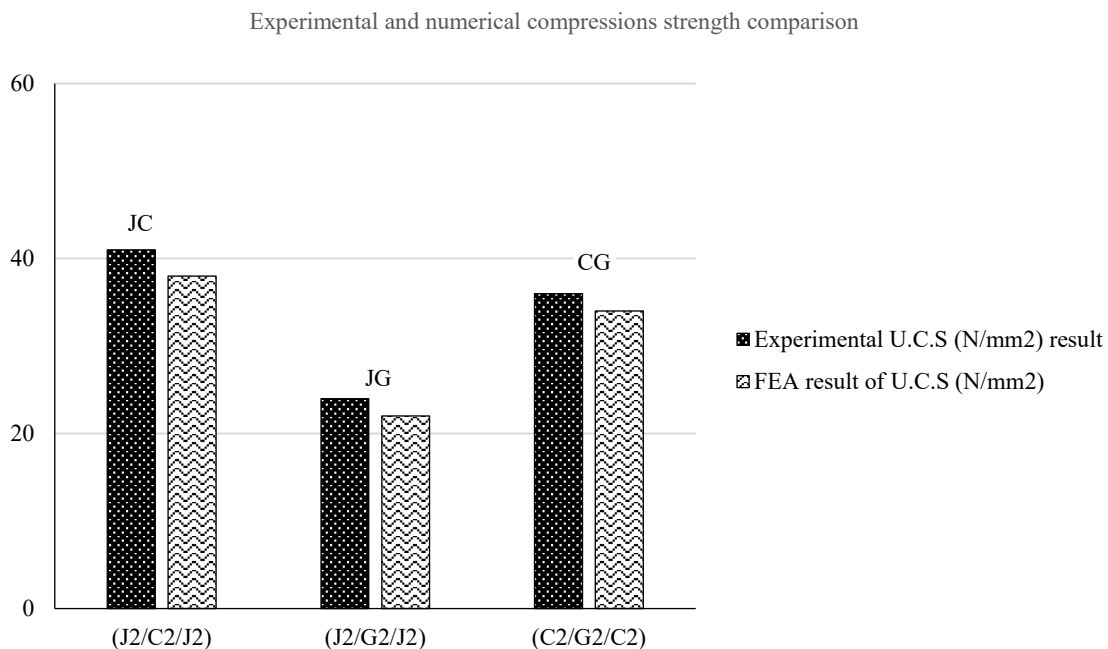


Figure 9. Experimental & numerical ultimate compression strength comparison of JC, JG, and CG.

- b. The difference between the experimental and FEA analysis for compression strength is displayed in the bar diagram 9, where we can see that JC HCL percentage error is 0.96%, JG is 3.39%, and CG is 0.67%. When compared to JG, the combination of JC and CG produced positive outcomes. The percentage difference in strength between the CG and JC is 6.94%.

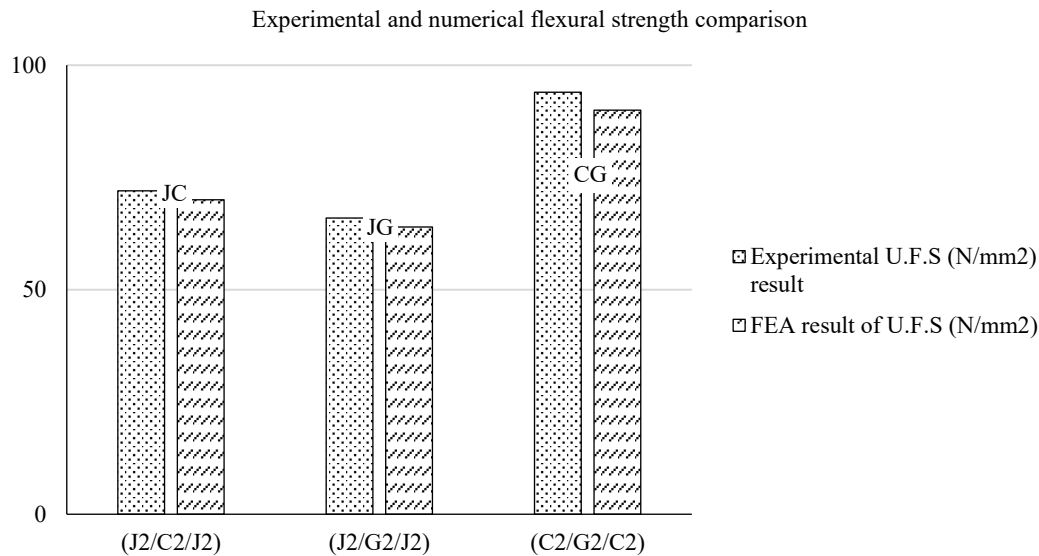


Figure 10. Experimental & numerical ultimate flexural strength comparison of JC, JG, and CG.

- c. Figure 10 illustrates, the discrepancy between the numerical and experimental analyses for flexural strength. It shows the percentage error for JC at 1.59%, JG at 1.74%, and CG at 1.52%. While CG laminate had stronger strength than JC and JG, the combination of JC and JG demonstrated the same strength performance. In percentage terms, there is a 30% strength difference between the CG and either JC or JG. By observations, CG performs better than JC and JG, whereas JC and JG are comparable. Glass & carbon fibers are them self of high strength, as they unite with one another they undergo greater strength and stiffness.

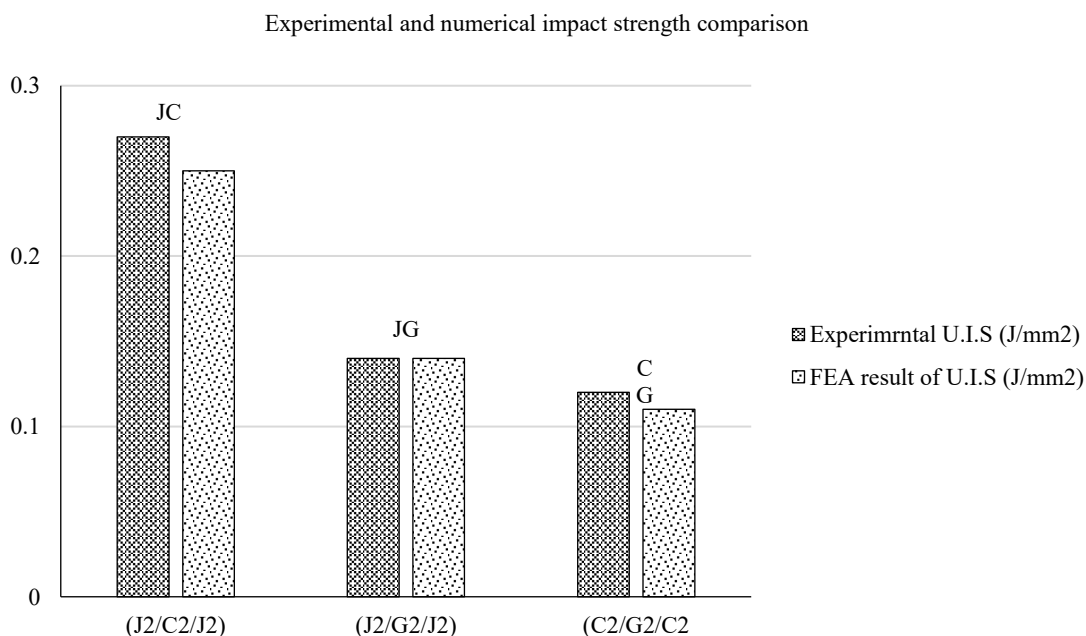


Figure 11. Experimental & numerical ultimate impact strength comparison of JC, JG, and CG.

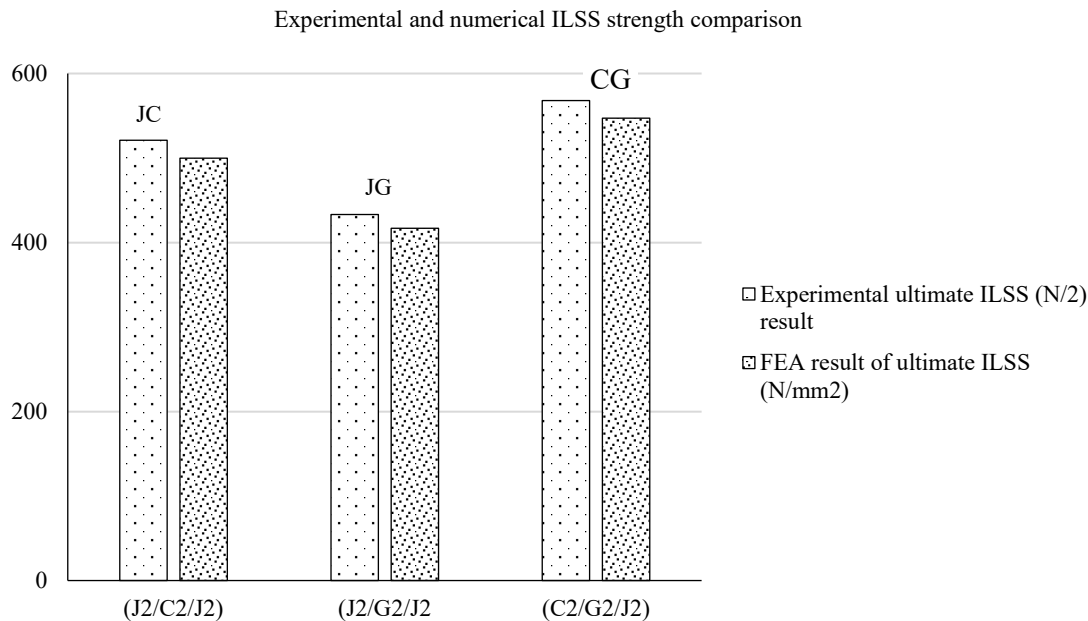


Figure 12. Experimental & Numerical ILSS Strength comparison of JC, JG, and CG.

- d. The difference between experimental and numerical analysis for impact strength is shown in figure 11, where we can observe the percentage error of JC having 3.85%, JG & CG of 1.17%. The combination of JG and CG shown same strength performance while JC laminate shown greater strength compared to JG & CG. The strength difference between the CG or JG and JC in percentage is 34.62%. JC outperforms the equivalent JG and CG in terms of impact strength. Although jute fiber is lightweight, flexible, biodegradable, and environmentally benign, it exhibits more impact strength when combined with carbon fiber than when combined with glass fiber.
- e. In Figure 12, we can observe the percentage error of JC at 0.51%, JG at 0.40%, and CG at 0.29%, illustrating the discrepancy among the experimental & numerical analysis for interlaminar shear strength. When compared to JG, the blend of JC and CG produced positive outcomes. 16.28% is the percentage difference in strength between the CG and JC.

In general, JC and CG combinations perform better than JG combinations in terms of tensile, compression, and interlaminar shear strengths. This is due to the hybridization of glass and jute fibers with carbon fiber; whilst jute exhibits modest strength, when it combined with carbon yields remarkable strength performance.

CONCLUSION

- The strength difference between CG & JC is 21.48%, whereas the strength difference between CG & JG is 60.9% (which is not acceptable). Therefore it is validated that the overall strength performance JC & CG undergoes best suitable for the hybrid composite pressure vessel (HCPV) application.
- In comparison to JC and JG, CG laminates consistently exhibits reduced percentage errors across a variety of strength tests suggesting a generally better alignment with numerical analysis. The difference in percentages for compression is 0.67%, flexural is 1.52%, impact is 1.17% & ILSS is 0.29%.
- The JC combination of material is suited for the optimum use of HCPV that requires low cost, low weight, and biodegradable. If the HCPV is requiring for ideal high-performance application requiring maximum strength, stiffness, weight reduction despite the higher cost the CG combination of the material can be applicable.

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Not applicable.

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