Experimental Investigation of Pseudo-Ductile Behavior in Hybrid Sisal–Carbon Fiber Reinforced Epoxy Composites

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Abstract: **Fiber-reinforced polymer (FRP) composites generally show brittle breakdown, which restricts their structural reliability. This study aims to develop hybrid sisal–carbon/epoxy composites with pseudo-ductile behavior using the concepts of fiber hybridization and orientation. Stacking sequences in hybrid laminates [±30°s/0c]₁, [±45°s/0c]₁, and [±60°s/0c]₁ were fabricated, where sisal fibres acted as higher elongation reinforcement and carbon fibres provide superior strength and strength. Tensile testing were carried out in accordance with ASTM D3039 to evaluate the mechanical performance and failure characteristics. The results showed positive hybridization effects for all laminate configurations, indicating improved load sharing between fibers. However, the [±45°s/0c]₁ laminate exhibited reduced failure strain due to shear failure of sisal plies. The study demonstrates that pseudo-ductile behavior in hybrid laminates depends on carbon ply thickness, laminate thickness ratio, and mode-II interlaminar energy release rate. Keywords: Pseudo-ductility, Fiber hybridization, Fiber orientation**

I. INTRODUCTION

High-performance polymer composites offer outstanding specific strength, specific stiffness, and good corrosion resistance. Due to these exceptional properties, sectors like aerospace, marine, automobile, and sports are replacing conventional materials to polymer composites. But sudden catastrophic failure [1] as depicted in Figure 1, is the biggest lag to extend the usage of these materials in higher volume in all the sectors. The unfavorable failure of polymer composite is compensated with greater safety margins. The given factor of safety is much greater than the conventional brittle materials, this leads to an increase in the end-product cost. Fiber hybridization is the low-cost stacking technique that causes a shift in the failure mode and failure 1 strain [2]. However, a significant drop in stress was observed following the failure of the LE fiber; this is because the LE fiber broke suddenly, as Figure 2 illustrates. It was discovered that the yarn arrangement, stacking order, and volume percentage all contribute to the hybrid effect [3-6].

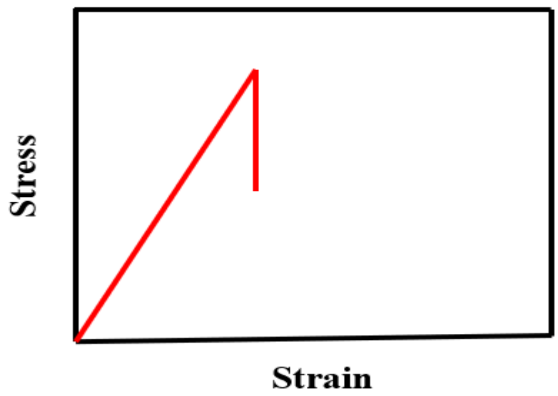


Fig. 1. Catastrophic Failure of traditional Composite

The HiPerDuCT (Highly Pseudo-Ductile Composite Technology) research program, jointly conducted by the University of Bristol and Imperial College London, focuses on developing advanced composite materials that exhibit a more controlled and progressive failure behavior. Conventional fiber-reinforced polymer composites possess high specific strength and stiffness; however, they typically fail suddenly without significant warning. To circumvent this issue, researchers are developing thin-ply composite architectures, which allow gradual damage accumulation and improved structural reliability. These thin layers modify the failure mechanisms of the laminate and promote a more stable response during loading.

Lately, a lot of focus has been placed on pseudo-ductile composite systems, which aim to mimic the gradual deformation behavior of ductile metals while maintaining the high stiffness of fiber composites. The pseudo-ductile strain (εPd) represents the additional strain achieved due to progressive damage mechanisms and is calculated as the difference between the ultimate strain of the laminate and the elastic strain corresponding to the same stress level obtained from the initial modulus. This concept provides a quantitative measure of how much extra deformation a composite can undergo before final failure.

From a structural design perspective, a ductile-like failure response is highly desirable because it prevents abrupt catastrophic collapse and offers warning prior to failure. Researchers have identified several mechanisms that can induce pseudo-ductility in composite laminates. These include fiber hybridization, variation in fiber orientation, and controlled interfacial slip mechanisms in discontinuous fiber systems. Among these approaches, hybrid laminates containing fibers with different stiffness and elongation characteristics have shown promising results in promoting progressive failure behavior.

Experimental investigations conducted by Gergely Czél and co-workers demonstrated pseudo-ductility in thin-ply hybrid composite laminates. Their work highlighted that a reduced volume fraction of carbon fibers can significantly enhance pseudo-ductile behavior. Hybrid combinations such as high-modulus carbon fiber paired with E-glass, basalt, or standard carbon fibers were examined. When the proportion of lower-elongation carbon fibers was reduced, the laminates exhibited a more stable and gradual failure process. This behavior occurs because the carbon fibers begin to fragment while the surrounding fibers continue to sustain the applied load, preventing an immediate loss of load-carrying capacity.

Further research by Gergely Czél and collaborators involved the design of thin-ply interlayer hybrid laminates composed of S-glass and carbon prepregs. Their objective was to understand how laminate architecture influences pseudo-ductile response. Among the tested configurations, the SG/XN80S2/SG stacking sequence demonstrated a relatively high initial stiffness along with approximately 2.64% pseudo-ductile strain. During tensile loading, the central carbon layer experienced controlled fragmentation and multiple matrix cracks. At the same time, fiber pull-out mechanisms occurred, which prevented sudden stress drops and allowed the laminate to deform progressively before ultimate failure.

Apart from hybridization, fiber orientation and stacking sequence design also play an important role in inducing pseudo-ductility. Research conducted by J. D. Fuller examined the effect of fiber orientation in carbon/epoxy prepreg laminates. Laminates were fabricated using a stacking configuration represented as [±Q5]s, where the orientation angle varied between 15°, 20°, 25°, 30°, and 45°. Among these configurations, the laminate with 25° fiber orientation provided the most balanced mechanical performance. It achieved a maximum tensile strength of approximately 927 MPa and exhibited a pseudo-ductile strain of about 1.23%, indicating that appropriate fiber orientation can significantly influence the progressive failure behavior of composites.

Another effective strategy for generating pseudo-ductility involves the fragmentation of thin carbon plies combined with off-axis fiber orientations. Laminates with configurations such as [±Qm/Q0]s have been investigated to understand this mechanism. Both analytical modeling and experimental testing were conducted for stacking sequences of [±26°n/0]s, where n equals 4 and 5. The results indicated that the configuration [±26°5/01]s produced a more pronounced pseudo-ductile response compared to [±26°4/01]s, achieving a pseudo-ductile strain close to 2.2%. The additional off-axis plies encouraged controlled damage mechanisms such as fiber fragmentation and matrix cracking, which delayed catastrophic failure.

Overall, these studies demonstrate that thin-ply technology, hybrid fiber systems, and optimized laminate stacking sequences are effective strategies for developing composite materials with pseudo-ductile behavior. Such materials are particularly attractive for high-performance structural applications where high strength, stiffness, and improved damage tolerance are required.

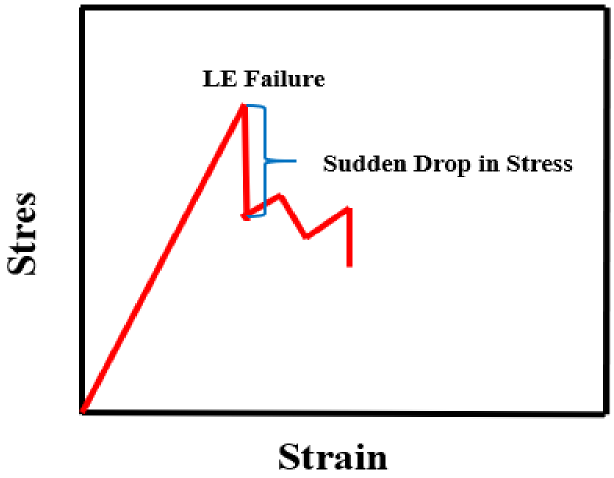


Fig. 2. Sudden Drop of stress in hybrid Composites

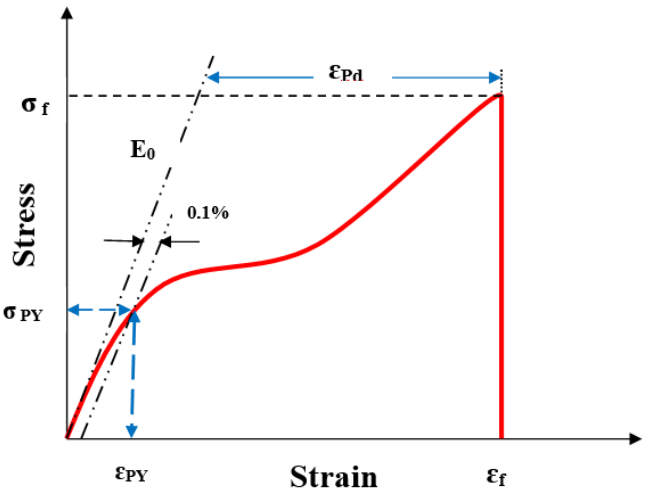


Fig. 3. Schematic of a pseudo ductile stress-strain curve

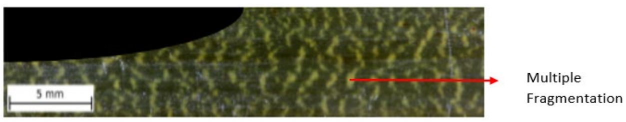


Fig. 4. Multiple fragmentation in "1 ply carbon" hybrid composite [8]

In this work, the experiment was carried to estimate the pseudo ductility using fiber hybridization and orientation technique. The increasing sensitivity to the environment protection and the recent laws against the environmental pollution given by the production of synthetic materials have led to wide attention toward bio composites. Considering these circumstances, an attempt made to induce the pseudo ductility by selecting the sisal fiber as the HE fiber.

II. Materials and Methodology

The Uni-Directional (UD) sisal fiber was procured from the Go Green Products Chennai (India). The UD carbon fabric was supplied by CBS chemicals, Bangalore (India). Epoxy resin was blended with the hardener in the ratio of 10:1 by weight. The matrix consists of epoxy resin with intermediate viscosity (LAPOXY L-12) and hardener (K-6), supplied by atual industries LTD, Gujarat (India). Table 1 reflects the Mechanical properties of the UD sisal fiber, UD carbon fabric and the matrix.

A. Fabrication of Composite

The fabrication of the composite laminates was carried by hand layup technique. Initially, base ply was cut from the sisal and carbon rolls considering the cutting tolerance. The mold was cleaned using the acetone and dried before applying the releasing agent. The releasing agent was applied to the mold plate to overcome the surface damages. Plies laid and epoxy was applied as per the stacking sequence followed in Table 2. Laminates were cured at room temperature for 24 hours. Fabricated laminates were cut in fiber running direction i.e longitudinal direction of carbon fiber as indicated in Figure 5 by referring to ASTM D-3039[13]. Nominal specimen dimensions were the overall length (L):250mm, gage length (GL):150mm, width (W):25mm, and variable thickness: h. The schematic Figure 6 shows the geometrical constraints on the front and side view of the tensile specimens.

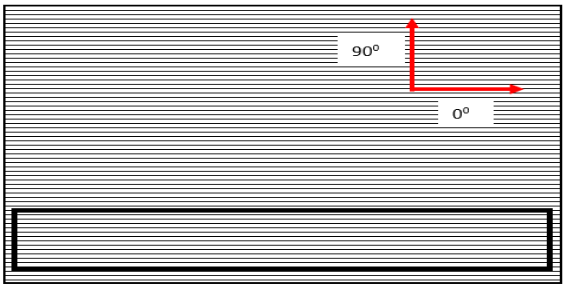


Fig. 5. Schematic of specimen cutting from laminate

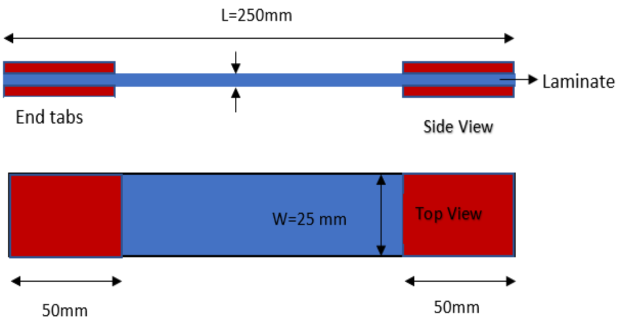


Fig. 6. Schematic of geometrical constraints of tensile sample

TABLE I. MATERIAL PROPERTIES

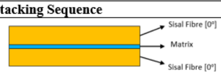
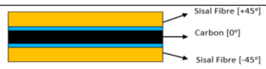
Designation	Orientation	Thickness(mm)	Stacking Sequence
PS	$[0_S]_2$	4.2	
30 Deg-S	$[\pm30^0_s/0_c]_1$	4.5	
45 Deg-S	$[\pm45^0_s/0_c]_1$	4.5	
60 Deg-S	$[\pm60^0_s/0_c]_1$	4.5	

TABLE II. DIFFERENT STACKING SEQUENCE (IN ORIENTATION SUBSCRIPT 'S' INDICATES THE SISAL FIBER AND 'C' INDICATES CARBON FIBER)

Sl. No	Materials	Density (g/cm^3)	Youngs Modulus in GPa	Tensile Strength in MPa	Strain to Failure (%)
1	Carbon	1.83 g/cm^3	230	4000	1.7
2	Sisal	1.5 g/cm^3	38	700	2.5
3	Matrix	1.1 g/cm^3	4	70	3.0

III. EXPERIMENTATION

A. Tensile Test

A universal testing apparatus with a capacity of 400kN as per the ASTM D-3039[13] with a 2 mm/min displacement rate. The sample was fixed in movable jaws without damaging it, as shown in the Figure 7. Average results on 5 sample tests were noted as per ASTM recommendation to minimize the experimental and manufacturing error. During the testing change in the gauge length was recorded to the corresponding load applied.

Fig. 7. Sample Fixed in UTM

Fig. 8. Shear failure of sisal fabric under Tensile loading

IV. RESULTS AND DISCUSSIONS

The tensile response of all the test samples were determined using the universal testing machine (UTM). The load concerning the displacement for all configurations is shown in Figure 9. It has been noted that, as the rise in the orientation angle of sisal fiber, the load-carrying capacity is also increases. The improvement in load-carrying capacity was achieved due to the good compatibility between the fibers and matrix. But, for stacking of [±450s/0c]1 reduced strain to failure was noticed as depicted in Figure 12. This behaviour may be due to the shear failure of the sisal plies under the tensile loading as shown in Figure 8. The shear failure of sisal fabric is due to the higher volume dispersion of the weft thread. Stress-Strain curve is plotted to estimate Tensile strength and pseudo ductility of the hybrid composites. It has been observed that as the sisal fiber orientation increases the tensile strength also increases is showed in Figure 10 & 11. In all the orientation pseudo ductility didn't achieved due to the catastrophic failure. The multiple fragmentations in LE fiber are the key to induce the pseudo ductility [8]. But in this study sudden failure of carbon ply was noticed. This disastrous failure resulted in a hybrid effect of less than 1%. In addition to the stacking sequence, pseudo-ductility also depends on the proportion and thickness of higher modulus plies, the mode-II energy release rate, the relative thickness of plies, and the thickness of the laminate. [8-9].

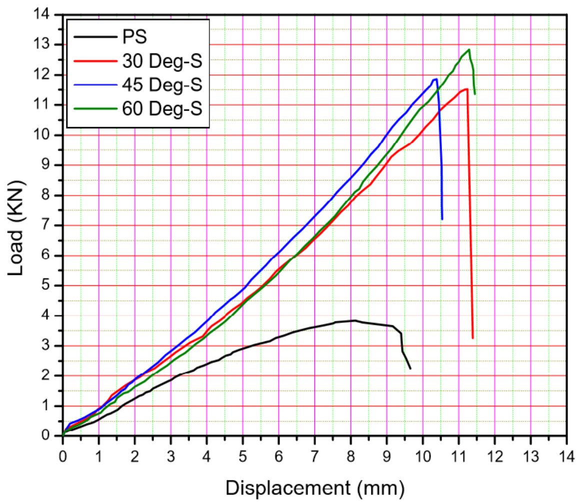


Fig. 9. Plot showing load versus displacement for all configurations

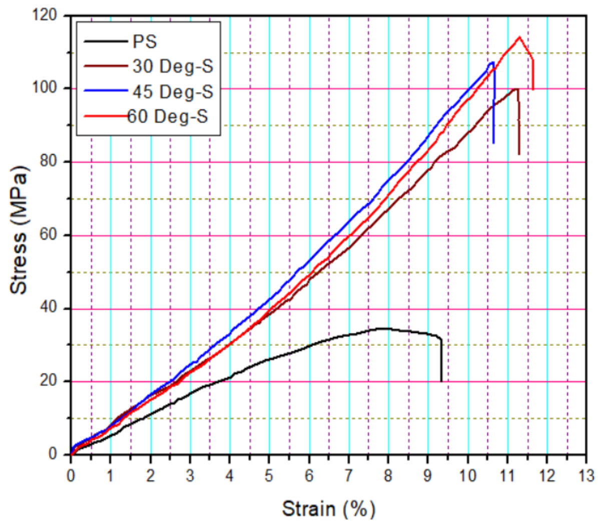


Fig. 10. Plot showing stress versus strain for all configurations

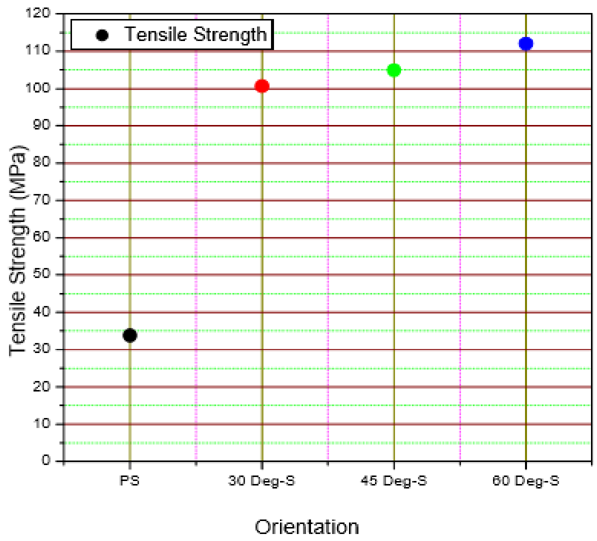


Fig. 11. Plot showing variation in tensile stregth versus orienation

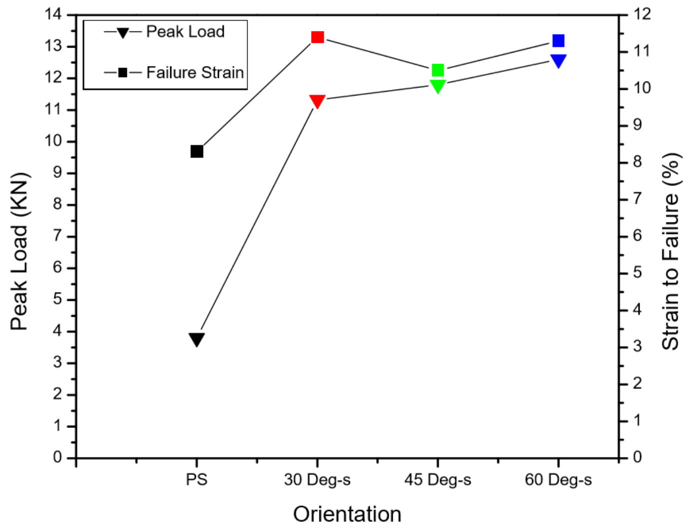


Fig. 12. Effect of orientation on load carrying capacity and strain to failure

V. CONCLUSIONS

The present work examined the tensile performance of sisal–carbon/epoxy hybrid laminates in order to explore the possibility of obtaining ductile-like behavior in composite materials. Hybrid laminates were fabricated using thin unidirectional carbon fiber layers combined with sisal reinforcement through a hand lay-up process, and their mechanical response was evaluated through tensile testing conducted according to ASTM standards. The experimental observations lead to the following conclusions.

- Among the tested laminates, the $[\pm60°s/0c]_1$ configuration exhibited the highest tensile strength of approximately 112 MPa. This improvement can be attributed to the fiber orientation being more closely aligned with the applied load, which enhances the efficiency of load transfer within the laminate.

- The hybrid laminates also demonstrated enhanced deformation capability compared with the pristine UD sisal laminate. The stacking sequences $[\pm30°s/0c]_1$, $[\pm45°s/0c]_1$, and $[\pm60°s/0c]_1$ showed increases in failure strain of 27.19%, 20.90%, and

26.54%, respectively. This improvement is mainly associated with fiber realignment toward the loading direction during tensile loading.

- The results further indicate that the content of weft threads significantly influences the strain capacity of the laminates, contributing to improved ductility-like response.
- Overall, the results suggest that the pseudo-ductile response of hybrid composite laminates is governed by several structural parameters, including the thickness of the lower-elongation carbon plies, the distribution and volume fraction of these plies, and the relative laminate thickness.

The outcomes of this study demonstrate that natural–synthetic hybridization using sisal and carbon fibers can effectively enhance deformation capacity and promote progressive failure in laminated composites, making them promising candidates for sustainable and damage-tolerant structural applications.

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