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Effects of hybridization and hybrid fibre dispersion on the mechanical properties of woven flax-carbon epoxy at low carbon fibre volume fractions

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ABSTRACT

Natural and synthetic fibers are increasingly being used as reinforcements in various applications. While the latter is popular for its generally superior mechanical properties, natural fibers are eco-friendly, cheap and have good vibro-acoustic properties. As more businesses are investing in green and sustainable technologies, natural fibers have been gaining attention in recent years and are already being used in various applications such as car interior, sporting equipment, etc. To date, their applications have been limited to those not requiring very demanding mechanical performance. In this paper, mechanical performance enhancement of natural fiber composites through hybridization with carbon fibers was benchmarked against one of the strongest and stiffest natural fibres, flax, through various interlayer flax-carbon hybrids at low carbon fibre volume fractions. Besides strength and stiffness characterization of hybrid laminates, this work investigates the effects of interlaminar hybrid fiber dispersion on tensile performance. The results suggested that morphology of mating hybrid plies might affect stiffness in woven fabrics. Hybrid laminates with single carbon plies interspersed with flax plies displayed lower tensile stiffness due to absence of nesting of the stiffer woven carbon plies and architectural crimp mismatch between flax and carbon woven fabrics. Comparisons with rule of hybrid mixture predictions showed reasonably good agreement in hybrid laminates exhibiting linear behavior, but significant over-predictions in highly dispersed laminates due to large deviations from linearity.

1. Introduction

Fibre reinforced composites are among the most advanced engineering materials in various industrial applications. Unlike traditional isotropic materials such as metals, the load bearing capability of fibre reinforced composites can be optimized for an intended application through embedding fibres in appropriate matrices and aligning them judiciously. With two or more types of fibre within the same matrix, an even wider range of optimized blended properties are possible. Although this idea, otherwise known as fibre hybridization, has been around for quite some time [1], recent emergence of new materials creates new and exciting possibilities for obtaining superior hybrid composites tailored for particular applications. The need for such material systems are becoming more important as modern composite structures are increasingly required to meet multiple and possibly even competing performance criteria. In many applications, for instance in transport vehicles [2,3], the requirements of stiffness, strength and impact resistance are critical and fundamental. However, lightweightness, lower cost, noise attenuation, and sustainability are also becoming important factors and composites products that can deliver optimal combination of desirable characteristics will be more attractive and competitive. In order to achieve this, some trade-off in properties and performance is usually necessary.

Driven essentially by the need for sustainable eco-friendly materials [4], natural fibres [5,6] have increasingly been used as composites reinforcements due to their low cost and their potential in meeting strength and stiffness [7–9] requirements for non-structural and semi-structural applications. Moreover, they have good vibro-acoustic damping properties [10–12] which make them suitable for various applications such as car interior, door panels, dashboards, etc. [13–15] and sporting equipment [16]. In spite of

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these favorable properties, their hygroscopic behavior and relatively low mechanical properties [17–21] compared to synthetic counterparts, are some of the major impediments to their penetration into higher-end applications. Numerous studies have attempted to address these issues [22–26] in an effort to enhance the performance of natural fibre reinforced composites (NFCs) through improving (1) fiber-matrix adhesion [27,28], (2) processing technique [29], and through (3) hybridization of fibres derived from various plants [30–34]. Although many of these approaches have successfully improved properties of NFCs, performance is still not good enough [35] for most structural applications.

Due to the need for higher mechanical performance, lower cost and sustainability, hybridization of natural fibres with synthetic fibers such as glass [17,31,36–38] and carbon [39–43] have been of increasing interest recently. The objectives of these studies vary from assessing improvements in thermal stability, water absorption behavior, stiffness, strength and impact properties, to acoustic and vibration damping properties.

Dhakal et al. [40] investigated the water absorption behavior, thermal and mechanical properties of unidirectional and cross-ply hybrid laminates, and results showed significant improvements in each of these aspects compared to non-hybrid flax composites. Assarar et al. [44] studied the effects of hybridization and stacking sequences on the damping properties of flax–carbon epoxy composites, manufactured through platen press process. Results highlighted the major role that position of flax layers within the hybrid play on overall laminate bending stiffness and damping properties. Flynn et al. [39] characterized the mechanical properties and mechanical variability of a fixed layup of flax-carbon hybrids at various flax fiber volume fractions. In the biomedical field, flax sandwiched with thin sheets of carbon on either side has been proposed by Bagheri et al. [42,45] for use as an orthopedic long bone fracture plate since mechanical properties of the hybrid are closer to human cortical bone than clinically-used orthopedic metal plates, making the material a potential candidate for use in long bone fracture fixation.

These studies, although limited, collectively indicate a broadening potential for natural fibres as superior substitutes to existing materials through hybridization with synthetic fibres. As interests in hybrid composites involving natural fibers are expected to grow [46], proper understanding of the interactions between the various phases in the hybrids is necessary to derive maximum benefit from these advanced material systems which can potentially stand as superior candidates for design-specific solutions requiring a wider spectrum of properties such as high stiffness, strength, and impact resistance, in addition to good vibro-acoustic damping performance, and eco-friendliness.

In this paper, flax is hybridized with carbon fibres at low carbon fibre volume fractions. Dominance of flax by weight is maintained in order to retain a substantial component of the beneficial attributes of flax fibre – such as the low cost and eco-friendliness of the resulting hybrid, while concurrently gaining significant enhancements in stiffness, strength and impact resistance by virtue of the carbon fibres [47]. Tensile characteristics of various inter-layer hybrids are determined experimentally and compared against plain flax epoxy to quantify the achievable performance enhancement. The reliability of using simple volumetric rule-of-mixture approach in predicting hybrid strength and stiffness is assessed. Several hybrid configurations with dissimilar flax and carbon ply stacking sequences, at the same relative weight fractions, are also developed to study the effects of hybrid fiber dispersion.

2. Materials and method

Hybrid and non-hybrid composite laminates were fabricated from plain woven 4x4 hopsack flax fabric [48] with areal density of 500 g/m^2 (Composite Evolution, UK), and 197 g/m^2 plain woven carbon fabric (Hexcel-282 3K, US). The matrix used for the composites is low viscosity epoxy resin system, Epolam 5051 (Axson, France).

The hybrid laminates developed for this study are shown in Fig. 1, labeled as FC1 to FC5. Although the scope of this work is limited to the performance of flax-carbon hybrids under tension, these layups are developed for studying a wider range of mechanical and vibro-acoustic damping properties of flax-carbon hybrids.

FC1 consists of three plies of flax fiber reinforced with two plies of carbon fiber, stacked alternately. The carbon fiber volume fraction is increased in FC2 without altering the degree of hybrid fiber dispersion through insertion of an additional carbon ply on the laminate's upper and lower surfaces. The outer carbon plies are shifted towards the mid-plane of the laminate in FC3, while keeping the number of carbon fiber laminae unchanged. The location of carbon fiber reinforcement in FC3 and FC1 are similar, with the latter having a lower carbon fiber loading and higher hybrid fiber dispersion. Carbon plies in FC3 are shifted to the outer plies in FC4, resulting in a sandwich structure with three plies of flax fibers blocked at the center. All hybrid laminates studied are symmetric with the exception of FC5, where flax and carbon fibers interact at a single interface. Laminates FC2-FC5 have the same flax to carbon fiber ratio and thickness, with varying degrees of hybrid fiber dispersion; FC1 and FC2 are the most dispersed, followed by FC3, FC4 and FC5, respectively. In this paper, fiber dispersion refers to dispersion of the two fiber types (flax and carbon) throughout the laminate.

2.1. Composite fabrication

Flax fabrics were dried in a vacuum oven at 90 °C for 3 h prior to resin infusion, as natural fibers tend to have high moisture content, unlike carbon fibers, due to their hydrophilic nature. Preforms with stacking sequences specified in Table 1 were prepared and vacuum bagged for 2 h at room temperature to evacuate air trapped in the dry fabrics. The low viscosity resin system was used to facilitate fiber wetting. Resin-hardener mixture was allowed to degas for 30 min in a vacuum chamber, prior to preform impregnation through vacuum assisted resin infusion (VARI). Following the manufacturer's recommendations, curing was done at 25 °C over 24 h and post-cured at 80 °C for 16 h. Laminates thicknesses were measured and recorded in Table 1.

2.2. Fiber volume fractions

Samples of dry flax fibers, dry carbon fibers, pure cured matrix, and the hybrid composite laminates were taken for measurements of volume using a standard gas pycnometer, and weight, from which the densities were calculated. According to rule of hybrid mixtures, the density of the hybrid laminate can be expressed as

$$\rho_H = V_F\rho_F + V_C\rho_C + (1 - V_F - V_C)\rho_M \tag{1}$$

where ρ is density, V is fiber volume fraction, and subscripts F, C, M and H stands for flax, carbon, matrix and hybrid composite, respectively. For a particular hybrid laminate with n_F flax plies and n_C carbon plies,

$$\frac{V_C}{V_F} = \frac{n_C \cdot W_C \cdot \rho_F}{n_F \cdot W_F \cdot \rho_C} \tag{2}$$

where W is areal density (densities of flax and carbon fabrics are

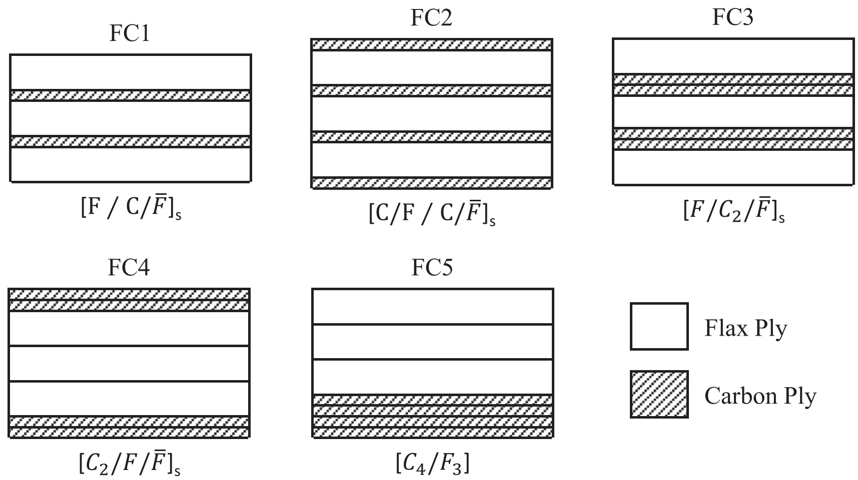


Fig. 1. Schematics indicating the stacking sequences of hybrid flax-carbon epoxy laminates.

Table 1
Thickness and fiber volume fractions of hybrid and non-hybrid laminate layups (specimen type designation: F- flax and C- carbon with subscripts corresponding to the number of plies).

	Layup		Average Thickness /mm	Fiber Volume Fraction (%) Flax V_F	Carbon V_C	$V_F + V_C$	Weight ratio F:C
Flax	$[F_4]$	F1	4.23	29	0	29	1:0
F-C Hybrids	$[[F/C/\bar{F}]_s]_s$	FC1	3.48	31	8	39	1:0.26
	$[[C/F/C/\bar{F}]_s]_s$	FC2	3.80	29	14	43	1:0.52
	$[F/C_2/\bar{F}]_s$	FC3	3.86	29	14	43	
	$[C_2/F/\bar{F}]_s$	FC4	3.73	31	15	46	
	$[C_4/F_3]$	FC5	3.71	28	13	41	
Carbon	$[C_{13}]$	C2	2.85	0	66	66	0:1

500 and 197 g/m^2, respectively). The fiber volume fractions of flax and carbon are determined by solving (1) and (2) simultaneously.

The fiber volume fractions (V_f) of plain flax epoxy and carbon epoxy composites were 29 and 66%, respectively. Total fiber loading in hybrid laminate FC1 was 39%; 31% flax and 8% carbon fibers. With two additional carbon plies added to FC1, carbon fiber volume fraction in FC2-FC5 is increased to an average of 14%, and flax is reduced to 29%. The total fiber loading in these laminates lie between that of plain (non-hybrid) flax and plain carbon epoxy composites at 43% (Table 1). Although hybrid fiber volume fractions vary slightly across FC2 to FC5, amount of fiber used in these laminates are essentially the same, as number of flax and carbon plies laid up is constant. The variations in fiber volume fractions are due to fluctuations in amount of epoxy transferred during impregnation, which is intrinsic to the lab-scale VARTM manufacturing technique used in fabricating these panels.

Dispersion of flax and carbon fibres in the intra-layer hybrids with similar ratio of flax to carbon (FC2-FC5) is approximated by the number of flax-carbon interfaces. There are six such interfaces in FC2; a value of 6 is assigned. Similarly, FC3, FC4 and FC5 are assigned 4, 2, and 1, respectively. These values are normalized and plotted along with the relative distribution of flax and carbon fibers by weight throughout laminate thickness in Fig. 2.

2.3. Tensile test

Specimens of 250 × 25 mm were cut out from the post-cured composite laminates using water-jet. To remove any moisture that might have been introduced during cutting, specimens containing flax fibers were heated at 60 °C for 24 h in an oven. Carbon fiber reinforced epoxy tabs were bonded to test specimens to avoid premature failure in the gripped regions.

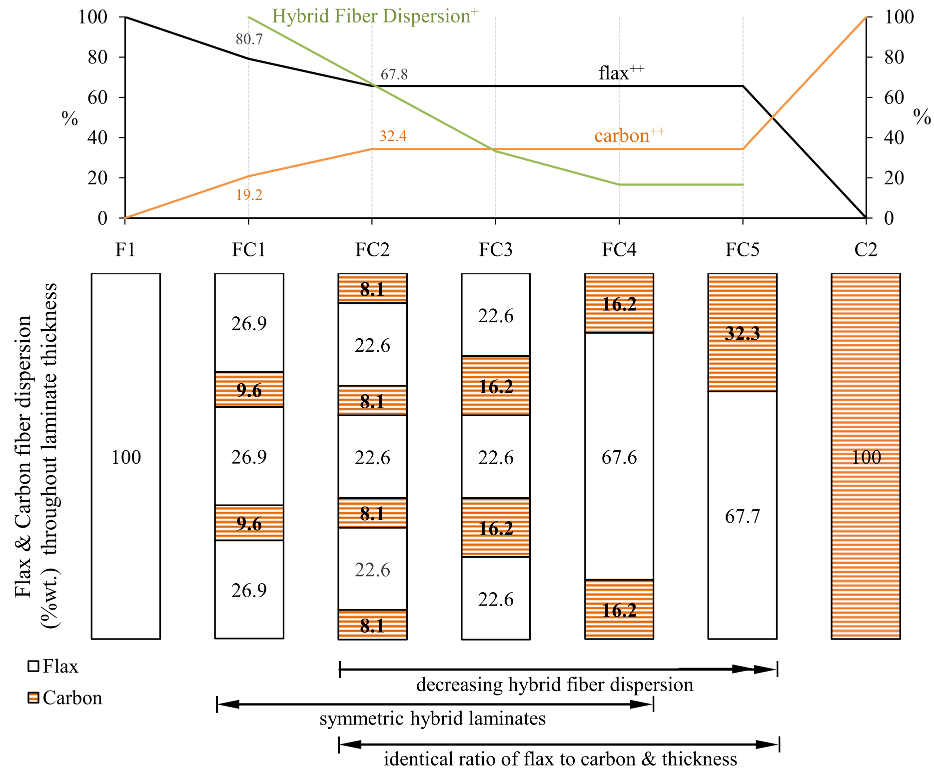
Tensile tests were performed on laminates F1, FC1-FC5 and C2. Strain along the loading direction was measured using strain gages. For each test case, five specimens were loaded to failure using a Shimadzu universal testing machine, with a 50 kN load cell, at 2 mm/min cross-head displacement rate as recommended by ASTM D3039 [49] standard. All tests were conducted at 23 °C, 65% relative humidity. Failure was defined when maximum load was reached.

3. Results and discussion

3.1. Strength and stiffness improvement

Experimental results from tensile tests conducted on plain flax epoxy, carbon epoxy and flax-carbon epoxy hybrid laminates are shown in Table 2 and plotted against carbon fiber volume fraction in Fig. 3. Failure in the tabs was successfully avoided in most samples. Ratio of hybrid laminate's tensile strength σ, and modulus E, with respect to non-hybrid flax epoxy strength, σ_F and modulus, E_F, respectively, are also shown.

The average tensile strength of plain flax epoxy (F1) laminates was 95.15 MPa. Upon introduction of 8% carbon fibers by volume in FC1, strength is increased by 72% to 163.96 MPa. With 14% carbon fibers in FC2–FC5, strength of the overall hybrid composite is 232.50 MPa (144% increase compared to non-hybrid flax epoxy). In other words, replacing one of the four flax plies in F1 with 2 carbon plies resulted in a tensile strength increase of 1.72 fold, and further



+normalized number of flax-carbon interfaces.
++with respect to overall fiber volume fraction

Fig. 2. Dispersion of flax and carbon fibers throughout laminate thickness in interlayer hybrids.

Table 2
Tensile properties of hybrid and non-hybrid composite laminates.

	C:F[a] weight ratio	Strength				Modulus			
		Average	CV	Increase[b]	Prediction[c]	Average	CV	Increase[b]	Prediction[c]
		/MPa	/%	σ/σ_F	/MPa	/GPa	/%	E/E_F	/GPa
F1	0:1	95.15	17	1.00	–	7.07	13	1.00	–
FC1	0.26:1	163.96	6	1.72	174.1 (+6.2%)	10.94	3	1.55	13.1 (+19.9%)
FC2	0.52:1	224.63	6	2.36	237.5 (+5.7%)	14.59	4	2.06	17.8 (+28.5%)
FC3		238.75	3	2.51	236.2 (−1.1%)	16.48	6	2.33	17.6 (+7.0%)
FC4		229.43	3	2.41	250.1 (+9.0%)	17.28	4	2.45	18.8 (+8.9%)
FC5		237.21	2	2.49	232.7 (−1.9%)	17.05	3	2.41	17.3 (+1.7%)
C2	1:0	763.17	2	–	–	55.81	4	–	–

[a] Carbon to flax ratio.
[b] With respect to non-hybrid plain flax epoxy.
[c] Predictions based on equations (5) and (6). Deviations from experimental values are displayed in between brackets "( )".

strengthening of the composite by addition of two more carbon plies gave rise to a 2.4 fold increase. A similar trend is observed in the laminates' tensile modulus, where 55 and 130% increase is achieved at 8 and 14% carbon fiber volume fractions, respectively.

Except for the modulus of FC2, variations in strength and modulus values noted across FC2 to FC5 are minor since they essentially have the same flax-carbon fiber weight fractions and vary only in the hybrid ply stacking sequence. The variations noted cannot be ascribed to differences in fiber volume fractions recorded in Table 1 as they have mutually inconsistent trends: FC4 with the highest fiber volume fraction is the second least strong hybrid laminate among FC2–FC5. A discussion on how failure mechanisms in the interlayer hybrid composite with fibers having dissimilar failure strains could affect hybrid composite strength is presented in section 3.5.

3.2. Constitutive behavior

The addition of carbon fibers to the composite affect overall constitutive relationships. Unlike carbon epoxy, flax epoxy exhibits considerable non-linear stress-strain characteristics (Fig. 4a). This non-linearity is a consequence of the nonlinear tensile behavior of the natural fiber constituents arising from the presence of defects or dislocations in the fibers [50,51]. Hybridization with carbon fibers decreases overall non-linearity of the resulting composites (Fig. 4b); the extent of which is mainly dependent on the carbon fiber volume fraction.

For the same carbon fiber volume fraction, larger deviation from linear behavior is noted when single carbon epoxy plies are interspersed or distributed between flax plies in FC2, compared to hybrid laminates where carbon plies are blocked (FC3-FC5). The

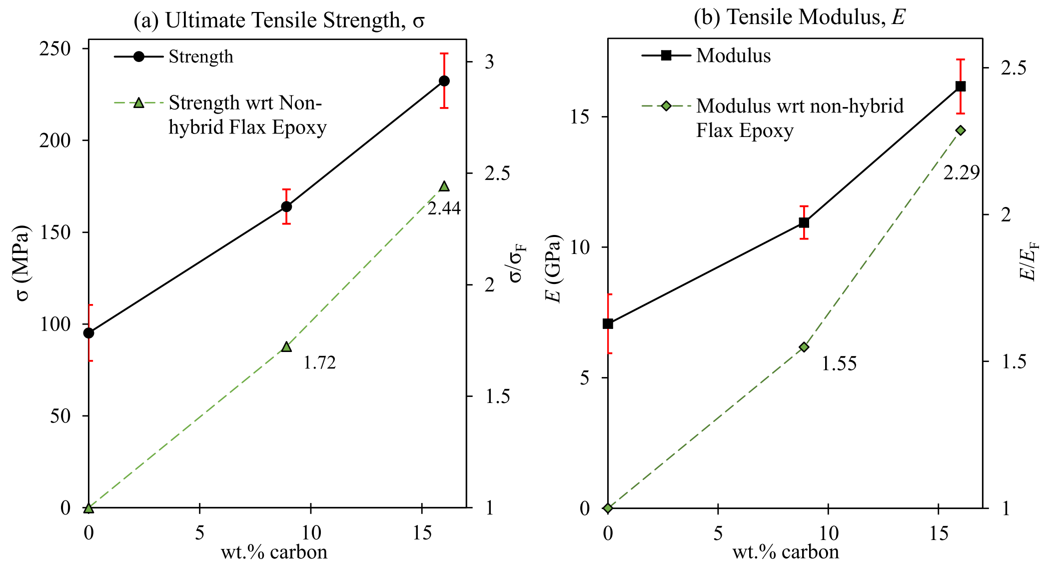


Fig. 3. Effect of carbon fiber volume fraction on tensile strength and modulus of flax-carbon hybrid composite. σ_F and E_F are strength and modulus of non-hybrid flax epoxy.

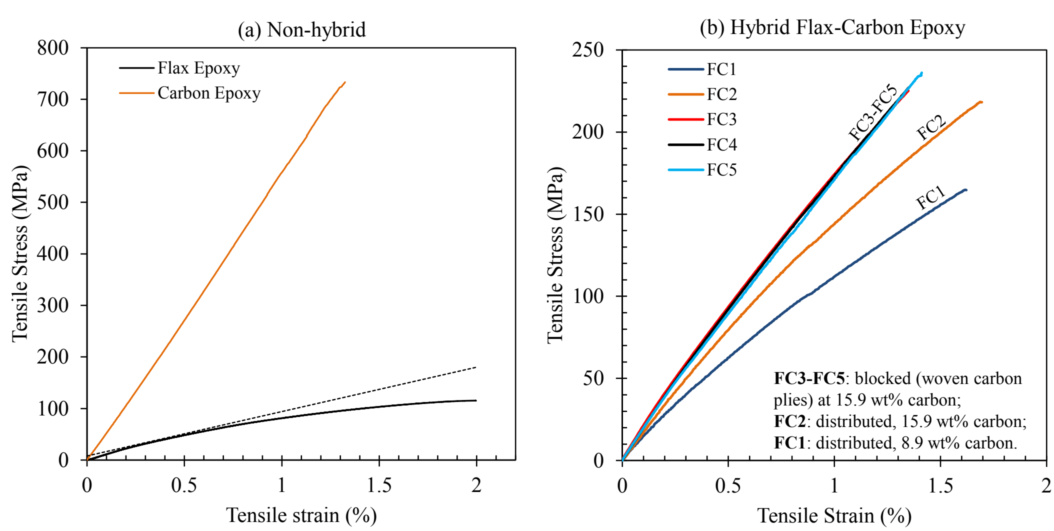


Fig. 4. Stress-strain characteristics of (a) non-hybrid flax and carbon epoxy, (b) hybrid laminates FC1-FC5 under tension.

origin of this behavior is presented in the following section.

3.3. Effect of carbon-ply blocking on hybrid stiffness

Although overall tensile performance of the woven flax-carbon laminated composite is mostly governed by carbon weight fraction, hybrid fiber dispersion of the dominant carbon plies can potentially have some influence as well. When the hybrid plies are stacked alternately in FC2, stiffness reduction (-14%), accompanied by increased failure strain, is exhibited in comparison to hybrid laminates FC3-FC5 of similar carbon content (Fig. 4b). The average failure strain of FC2 is 16, 36 and 27% higher than that of FC3, FC4 and FC5, respectively, while their strengths deviates no more than 2.4%.

This discrepancy has two main origins, largely related to the absence of carbon ply blocking in FC2, as opposed to FC3-FC5. Firstly, out-of-plane normal forces are developed intrinsically in woven fiber-reinforced composites under uniaxial tension (Fig. 5a). If single carbon plies are interspersed with single flax plies, the carbon yarns are able to deform more in response to the out-of-plane normal stresses because the surrounding flax plies are more compliant. However, if the carbon plies are surrounded by adjacent similar carbon plies, they are more constrained to deform, thereby resulting in greater stresses and higher stiffness. The compliance of flax plies are due to presence of relatively larger resin-rich zones, and their lower density – attributable to existence of lumens. The contrast between carbon and flax phases in the hybrid is evident from optical micrographs (e.g. Fig. 7 and Fig. 11) corroborated by the low fiber volume fraction of flax in F1 against that of carbon in C2 (28 versus 66%, Table 1). This dissimilarity allows a small, non-trivial, geometric shift of the weft carbon fibers when carbon plies are interspersed with single flax plies, thereby reducing effective ply stiffness. It is worth noted that blocking of the carbon plies give the possibility for nesting, where fiber yarns from adjacent plies are interlocked giving rise to (i) smaller resin pockets, manifested by higher fiber volume fraction, and (ii) improved interlaminar shear strength and stiffness (Fig. 6).

The stiffness reduction noted in FC2 (Fig. 4b) is also due to

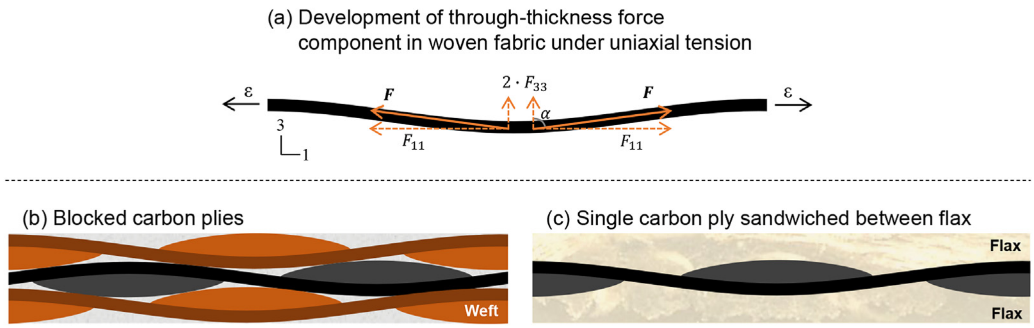


Fig. 5. Development of out-of-plane normal force component in woven fabric under uniaxial tension resulting in dissimilar out-of-plane deformation when carbon plies are (b) blocked and (c) interspersed between flax plies. For the same relative flax-carbon fiber volume fractions, out-of-plane deformation is more pronounced in (c) where single carbon ply is sandwiched by more compliant flax epoxy than the stiff and densely packed carbon fibers in (b).

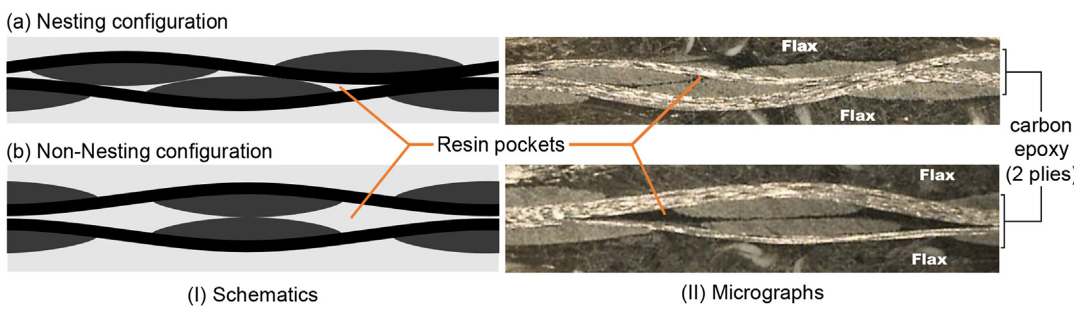


Fig. 6. (I) Schematics illustrating interlayer (a) nesting, and (b) non-nesting configurations in woven carbon epoxy plies. (II) Micrographs of two carbon epoxy plies sandwiched between flax in hybrid laminates.

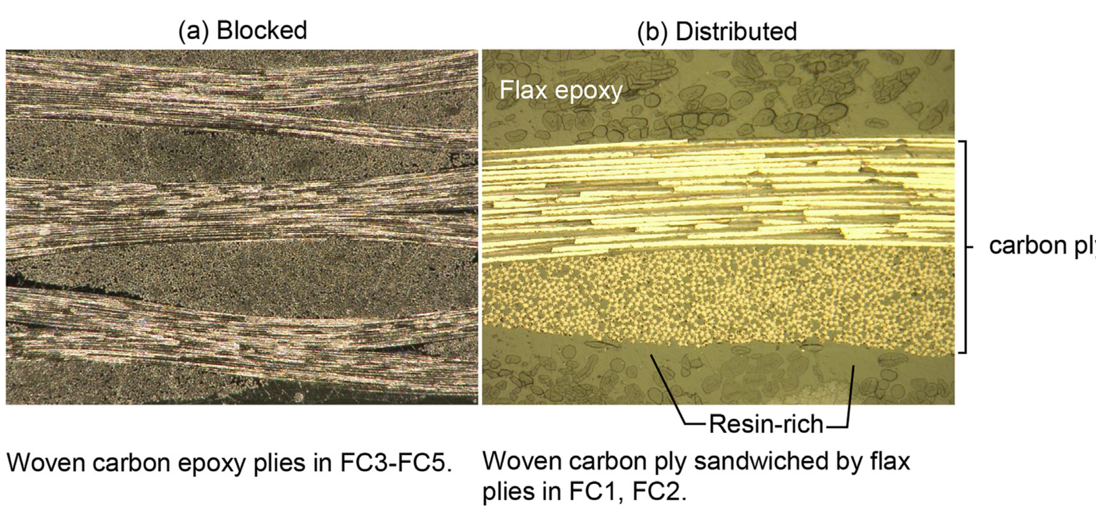


Fig. 7. Micrographs illustrating dissimilar out-of-plane normal boundary conditions for a woven carbon ply when (a) blocked, and when (b) distributed throughout flax-carbon interlayer hybrid laminates. Carbon ply sandwiched by densely packed stiff carbon fibers in (a), and by sporadically distributed flax fibers with relatively high resin-rich zones in (b).

planar distortion of the thinner carbon plies sandwiched between flax plies. During manufacturing, the carbon ply does not remain straight (Fig. 8a) when consolidated together with the flax plies in the hybrid composite (Fig. 8b), but instead conforms to the curvature of adjacent flax plies. The extent of this distortion is dependent on the degree of crimp mismatch between mating fabrics. In the current study, crimp in the flax fabric is approximately two and a half times that of the carbon fabric, which showed noticeable distortion. With more flax-carbon interfaces in FC2, the distortion is amplified, and manifested as an apparent hybrid stiffness reduction.

3.4. Rule of hybrid mixture (RoHM)

Experimental values are compared with predictions based on linear volumetric rule of hybrid mixtures (RoHMs). Equations relating hybrid composite strength and modulus with constituents' properties are derived through application of force equilibrium on the hybrid laminate's cross section:

$$F_H = F_F + F_C + F_M \tag{3}$$

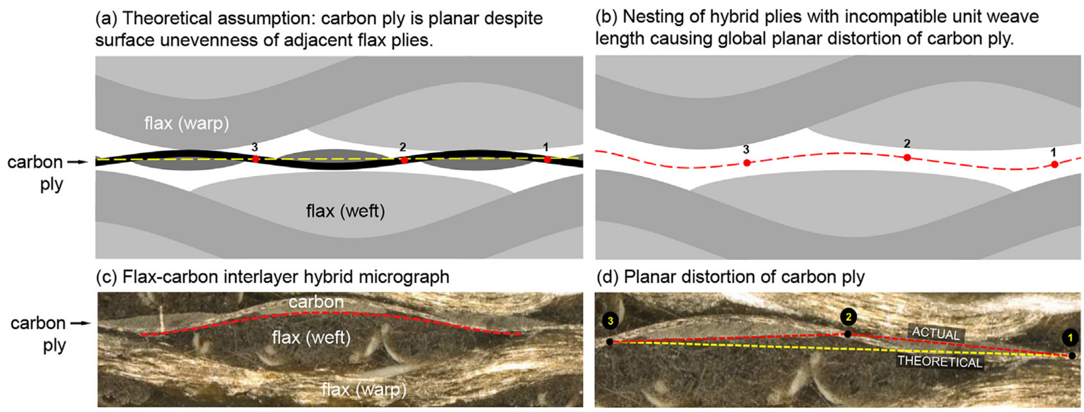


Fig. 8. Planar distortion of thin carbon plies sandwiched by flax plies due to crimp mismatch in the plain woven fabrics. 16.

$$\sigma_H A_H = \sigma_F A_F + \sigma_C A_C + \sigma_M A_M \tag{4}$$

$$\therefore \sigma_H = \sigma_F V_F + \sigma_C V_C + \sigma_M (1 - V_F - V_C) \tag{5}$$

where F is tensile force acting through cross section, A, σ is tensile strength, and subscripts F, C, M and H refer to flax, carbon, matrix and hybrid composite, respectively. Under isostrain condition, equation (5) can be expressed in terms of the longitudinal tensile modulus, E:

$$E_H = E_F V_F + E_C V_C + E_M (1 - V_F - V_C) \tag{6}$$

Equations (5) and (6) are used to compute RoHM strength and stiffness of the hybrid laminates. Tensile stress, extracted from the non-linear stress-strain curve of flax epoxy at the failure strain of carbon epoxy in Fig. 4a, is used to compute σ_F based on RoHM. The ratio of warp fiber yarns (aligned along loading direction) to the sum of warp and weft fiber yarns is 1:2 and 7:13 for the carbon and flax fabrics used, respectively. These were multiplied with volume fractions shown in Table 1 before their application in equations (5) and (6) to discount fibers oriented perpendicular to applied load.

Except for stiffness of highly dispersed FC1 and FC2 laminates, RoHM predictions are within 10% of experimental values (Table 2). Unlike discrepancies in strength prediction, modulus prediction shows divergence with increasing fiber dispersion, with the least fiber dispersed FC5 being the most accurately predicted, and FC1 and FC2 the least. This is attributable to the linear elastic assumption underlying equations (5) and (6), contravened by the non-linear stress-strain behaviors exhibited by FC1 and FC2 (Fig. 4b, respectively).

3.5. Failure mechanism

The primary mode of failure noted in all hybrid laminates investigated is brittle failure of carbon and flax plies. As carbon fibers have lower failure strain, they reach failure first. The catastrophic nature of the carbon plies brittle failure causes cracks to develop at the flax-carbon interfaces, and the associated spring effect strains neighboring flax fibers locally, resulting in sequential failure of the flax fibers.

Examinations of failed hybrid specimens reveal no evidence of major interlaminar debonding at cracked zones. We assume isostrain conditions and no debonding occurs prior to the first lower elongation (LE) fiber tensile failure. LE fibers fail first as they have smaller failure strain than higher elongation (HE) fibers, causing out-of-plane normal crack(s) in the hybrid composite; HE fibers continue to carry stress near the cracked zone, giving rise to stress concentration build-up in HE plies around the failed LE fibers. HE fibers bordering LE-HE ply interface fails, and crack progresses deeper. The energy required for crack progression through all HE plies for ultimate failure depends on the stacking sequence of hybrid laminate. For instance, crack in the HE plies initiates at only one location in FC5 (Fig. 9a) as there is a single LE-HE interface, and progresses through length, 3a before laminate's ultimate failure. Conversely, when each HE ply is sandwiched between LE plies (FC2), crack in the HE plies now initiates at multiple locations through the cross-section (Fig. 9b) as there are several LE-HE interfaces, each travels through only $a/2$ to complete failure of the laminate. Assuming these multiple cracks occur on the same horizontal plane across the thickness as depicted in Fig. 9b, a lower energy is sufficient to fail the laminate with higher hybrid fiber dispersion, hence lower strength. This assumption seems reasonable based on macro- and micro-fractographic analysis of ruptured specimens (Fig. 10 and, e.g. Fig. 13b) where tensile fracture is seen to have a tendency of occurring in a horizontal plane. This understanding is supported by the larger discrepancy of 6 against 2% (absolute values) between measured and predicted strengths of highly fibre-dispersed FC2 and least dispersed FC5, respectively.

3.6. Physical examination

Composites used in this study were meticulously prepared to avoid poor wetting of fibers that usually leads to reduced stress transfer across fiber-matrix interface and increased porosity. Even with a low viscosity resin, infusion was done slow enough to allow ample time for resin to settle between elementary fibers in the technical fiber bundles (Fig. 11). This is particularly important for natural fibers whose walls tend to have some permeability, allowing resin to penetrate through and occupy empty lumens. If curing is done rapidly, resulting composites tend to have larger amount of voids. Physical examination of micrographs taken at random locations throughout cured plates used in this study indicate a high consistency of low void content throughout the composites.

Optical microscopy of the cross-sections of flax epoxy and carbon epoxy in Fig. 11 highlights a sharp contrast in the regularity of fiber shape, dimension, and distribution between these two fibers, with the flax being marked by a relatively high degree of randomness and irregularity in the fiber shape, size and distribution, compared to the synthetic fibers. To some extent, this explains the greater variations noted in the experimental results involving flax composites, which tend to reduce with addition of carbon

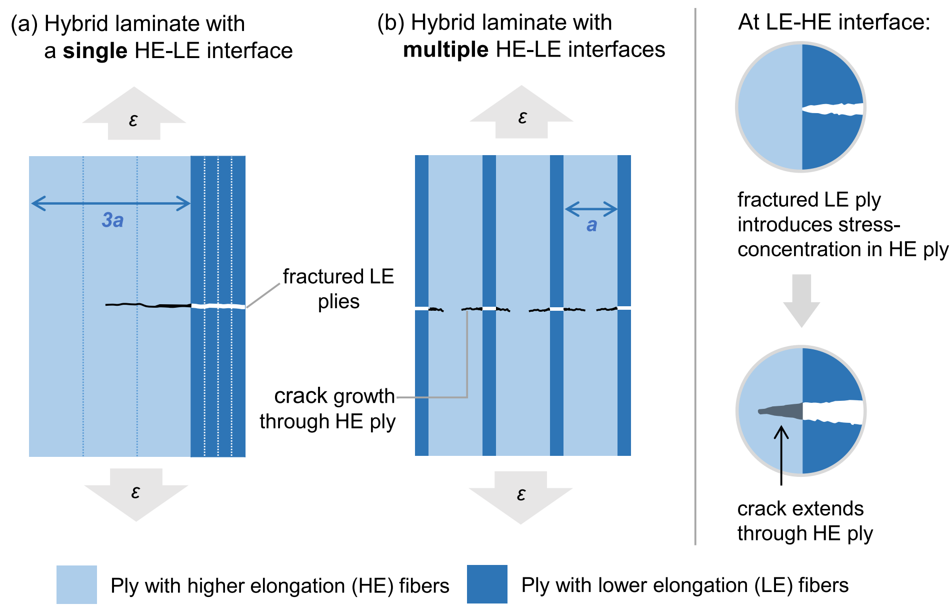


Fig. 9. Progressive failure post LE-ply rupture in hybrid laminates with (a) single, and (b) multiple LE-HE interface(s).

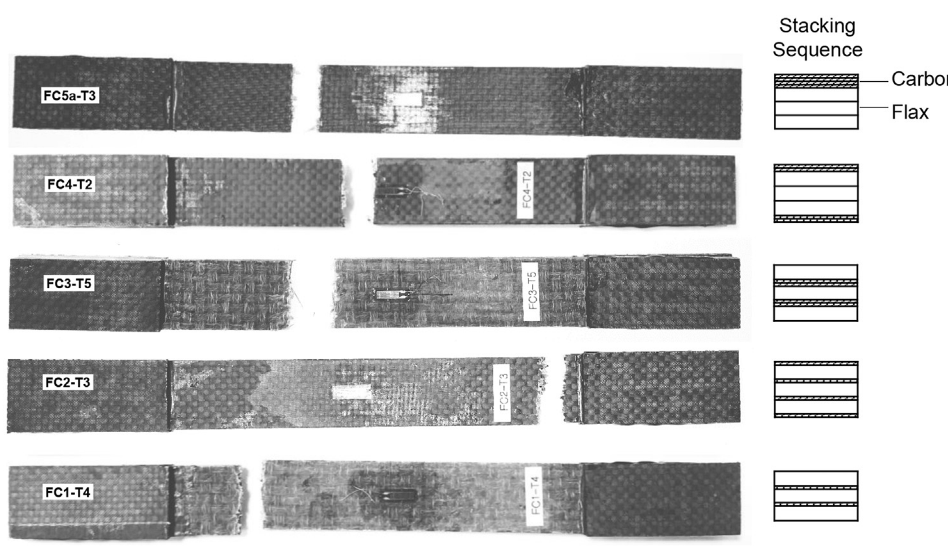


Fig. 10. Failed interlayer hybrid flax-carbon epoxy samples under uniaxial tension.

fibers in the composite. As recorded in Table 2, the strength and stiffness values of plain flax epoxy has coefficient of variation of 17 and 13%, respectively. These values are, however, reduced to an average of 4 and 4%, respectively, in the flax-carbon hybrids.

SEM micrographs indicate good wetting of flax fibers (e.g. Fig. 12d, Fig. 13a) and carbon fibers (e.g. Figs. 12a and 13d) in the hybrid composites. Residual epoxy debris on fiber surfaces (e.g. in Fig. 12b) are indications of good fiber-epoxy adhesion. Due to the porous nature of natural fibers, low-viscosity epoxy resin can infuse through the fiber wall pores. Moreover, surface unevenness of the natural fiber develops a mechanical interlocking mechanism that improves the fiber-matrix interfacial shear strength. However, there are traces of fiber pull-out at the fracture surfaces as well (e.g. Fig. 13), although the pullout lengths were found to be minimal, exhibiting more or less uniform fracture. Micro-fractographic analysis of the fracture surfaces of carbon fibers (e.g. Fig. 12a, d, Fig. 13d) and flax fibers (e.g. Fig. 13a-c) indicate predominance of brittle fiber failures. Indications of ductile failure of matrix is visible from Fig. 13 (a) and (c).

4. Conclusions

In this study, the performance enhancement of natural fiber reinforced composites through hybridization with carbon fibers is benchmarked against flax, one of the strongest and stiffest natural fibers [7], commonly available commercially as continuous unidirectional fibers or woven fabrics. The tensile behavior of various interlayer flax-carbon hybrid configurations at low carbon volume fractions is assessed experimentally and significant improvements in strength and stiffness were noted. With 8% of carbon by volume, more than 50% increase in strength and stiffness is achievable, and specific strength is 30% higher than Aluminum. With an additional 6% increase in carbon volume fraction, the composite is more than 2.3 times stronger and stiffer than flax epoxy. Comparisons with

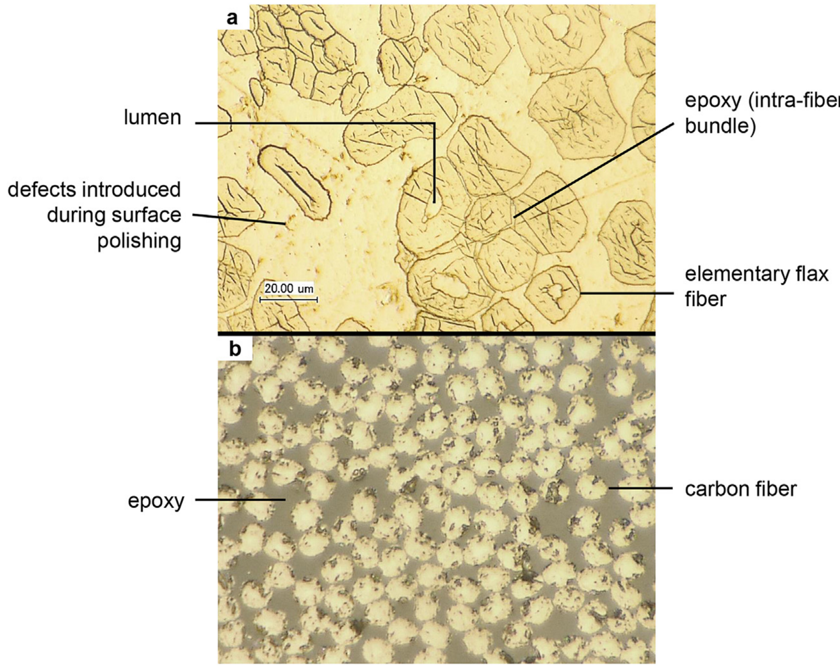


Fig. 11. Optical microscopy of the cross-sections of (a) flax epoxy, (b) carbon epoxy.

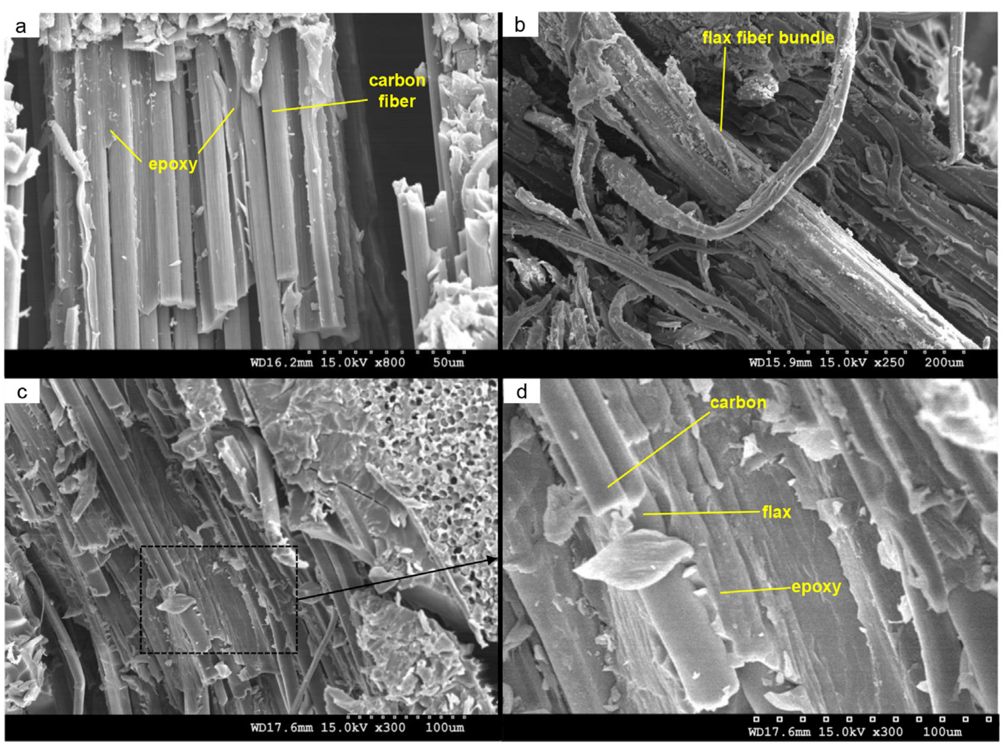


Fig. 12. SEM micrographs of (a) fibers in carbon-rich and in (b) flax-rich zones, (c) flax-carbon interlaminar hybrid zone, magnified in (d) illustrating the physical proximity of dissimilar fiber types.

rule of hybrid mixture predictions show reasonably good agreement in hybrid laminates exhibiting linear behavior, but significant over-predictions in highly dispersed laminates due to non-linearity. Beyond the remarkable increase in mechanical properties, addition of carbon fibers to natural fibers reduces the scatter (standard deviations) in mechanical properties which stems from variability in natural fiber formation. Smaller variations in overall composite properties favors more effective material usage in engineering designs.

Results of this study has also shown that in interlaminar hybrids with woven fabrics, hybrid fiber dispersion may affect tensile modulus if the difference between out-of-plane normal stiffness of mating fabrics is large. This is likely the case when natural and synthetic fibers are both present in the same composite. In such

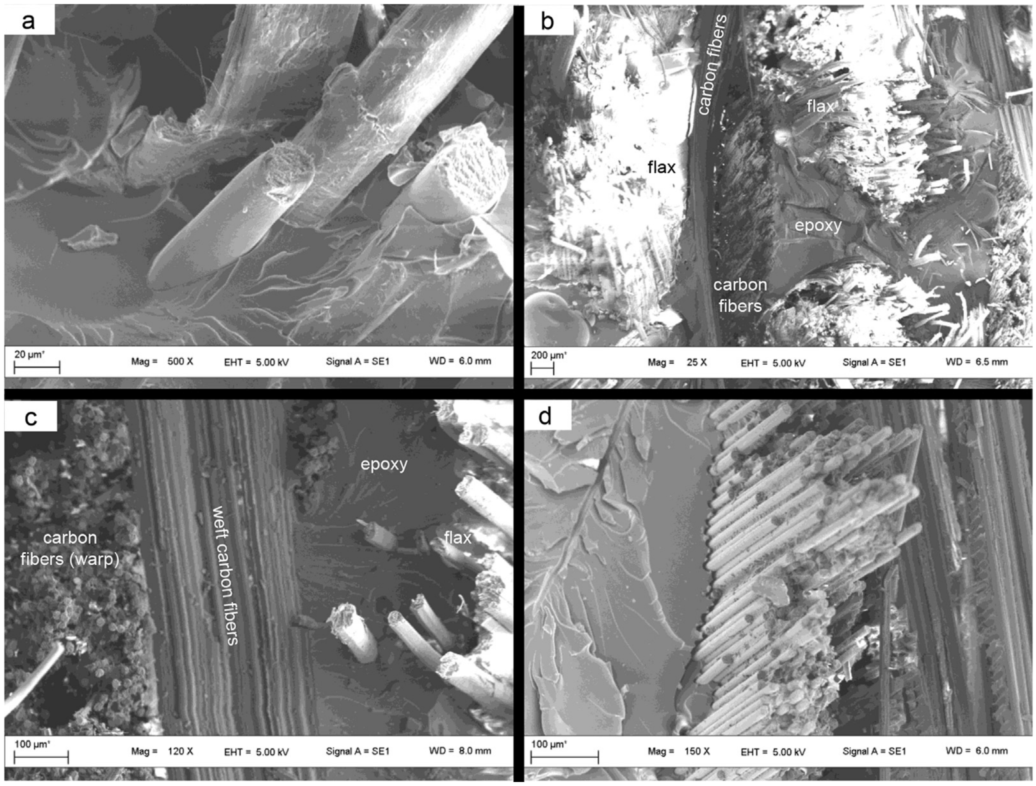


Fig. 13. Fracture surface morphology of composites failed under tension, illustrating (a) flax epoxy, (b) flax-carbon epoxy hybrid, magnified in (c), and (d) carbon fiber-matrix interfacial crack.

cases, blocking the stiffer plies is preferable over distributing them between the compliant ones. Secondly, since fabrics used do not necessarily have similar thickness/crimp, additional planar distortion may be introduced during fabrication when there is a large crimp mismatch between mating fabrics, reducing overall uniaxial tensile stiffness of the hybrid composite. In hybrids where the overall stiffness is predominantly controlled by the stiffer plies, the influence is greater when the stiffer ply is significantly thinner (as thinner plies are more likely to undergo planar distortion). This effect can be minimized by reducing the number of hybrid interfaces through ply-blocking.

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