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EXPERIMENTAL ANALYSIS OF THE EFFECT OF THE WOVEN ARAMID FABRIC ON THE STRAIN TO FAILURE BEHAVIOR OF PLAIN WEAVED CARBON/ARAMID HYBRID LAMINATES

Sojan Andrews Zachariah, Satish Shenoy, Dayananda Pai

Department of Aeronautical and Automobile Engineering,
Manipal Institute of Technology, Manipal Academy of Higher Education, India

ORCID iDs: Sojan Andrews Zachariah https://orcid.org/0000-0002-1337-3100
Satish Shenoy https://orcid.org/0000-0003-2374-3854
Dayananda Pai https://orcid.org/0000-0003-0334-8718

Abstract. *Remarkable advances in the research and development of micro/mini Unmanned Aerial Vehicles (UAVs) seek thin, lightweight and strong materials for their structural applications. As these structures involve various loading conditions in both the in-plane and through-the-thickness directions during their life cycle, the assurance of the structural stability in each direction is deemed mandatory. The woven Aramid fibers as high strain materials (HSM) are known to improve the through-the-thickness impact strength. However, the addition of the HSM can affect the overall tensile behavior of composite laminates. This study investigates the effect of the woven Aramid fiber on the in-plane tensile behavior of Carbon/ epoxy laminates. Laminates are fabricated using an easy and cost-effective Vacuum Assisted Resin Infusion Molding (VARIM) setup. A uniaxial tensile test was conducted to analyze the tensile behavior of Carbon/Aramid hybrid composites. The effect of adding the woven Aramid layer and the Carbon fabric sequence on the tensile modulus, strain to failure and modulus of toughness are investigated in this study. The results revealed that the presence of Aramid has a positive hybrid effect on the failure strain, exhibiting pseudo-ductile behavior with a compromise in the tensile modulus of the virgin Carbon/epoxy laminate.*

Key Words: *Hybrid composites, Pseudo – ductility, Woven Fabric polymer composites, Ultimate strain to failure*

1. INTRODUCTION

Composite laminates are widely employed for various structural applications in the Engineering Sector. They replace conventional metal structures mainly due to their exceptional strength to weight ratio. Laminated composites hold a significant share of their

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Corresponding author: Dr. Dayananda Pai K.
Professor, Department of Aeronautical and Automobile Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal 576104, India
E-mail: dayanand.pai@manipal.edu

application in aerospace and automotive sectors since they can serve lightweight components better than any other natural materials. However, the strict safety regulations sometimes make these materials suspicious of their ability in ultimate loading conditions as they have a usual tendency to fail catastrophically. This necessitates the designers to maintain higher values of safety factors in their design. Advanced composites are the materials where high strength, high modulus reinforcements are used. They are recognized as a promising lightweight solution [1–3]. Currently, advanced composites based on Carbon fibers are vastly used in high-end structural applications in aviation, UAVs, automotive and energy sectors where the cost of a sudden failure is non-comparable [4].

Bidirectional (BD) woven fabrics are considered as two-dimensional reinforcement elements in the composite industry, especially for aerospace structures. They have better impact stability than conventional unidirectional (UD) laminates due to fiber yarns in the warp and weft directions. However, the in-plane mechanical properties like the elastic modulus, strength and toughness modulus of the composite laminates are closely related to the fiber architecture [5]. The connections between the yarns and the yarn crimp lead to a complex structure in the woven fabric, which affects the mechanical properties. Nevertheless, the enhanced impact response exhibited by fabric reinforced composites and a decline in the tensile properties happen due to the stress concentrations created by weaving undulations [6]. This trade-off among the through-the-thickness and in-plane properties needs to be thoroughly investigated as a part of ensuring safer structural design. Therefore, a comprehensive study of the effects of the construction of fabrics on mechanical properties is deemed vital.

Carbon woven fabrics are essential materials for aerospace industry. Many micro/mini UAVs employ Carbon fiber-based composites for the fuselage and belly constructions. Carbon fiber being more brittle proves to be low in impact strength. Hybridization is a practical approach to enhance the impact strength and the in-plane strain and toughness properties. High strain materials (HSM) like Glass and Aramid fibers are the hybrid choices in imparting better toughness and strain properties [7].

The addition of HSM comprises the high strength and modulus properties of carbon composites [8]. The hybrid approach in laminated composites is mainly divided into two methods. The first method is an inter-ply method in which two types of fibers are stacked layer by layer concerning different number, angle and architecture. The other hybrid approach is an intra-ply method in which a mix of different fibers either in single yarn or one type in the warp and other in the weft are weaved in a single layer [9–11]. Erklig and Bulut experimentally investigated the tensile and impact behavior of Kevlar/Glass hybrid laminates. The addition of Kevlar from Aramid class fibers showed an improvement in tensile strength and impact resistance [12]. Thus, Aramid can be a potential HSM for hybridization with LSM reinforced laminates.

Khatri and Koczak [13] investigated the tensile responses of E-Glass and AS4 graphite fibers with a PPS (polyphenylene sulfide) matrix. Experimental studies showed that the strain values of hybrid composites increased by 2–8%. Jesthi et al. [14] studied the Effect of Carbon/Glass with inter-ply sequence and reported that the stacking sequence and the position of hybrid layers have an effect on the flexural and impact properties. Saka and Harding [15] investigated the tensile behavior of Carbon-Glass/epoxy hybrid composites. Sun et al. [16] studied the mechanical properties of Carbon/Basalt fibers and reported evident influence of stacking sequence and hybrid ratio on in-plane and through – the thickness properties.

However, there are limited comprehensive studies of the effect of the woven Aramid fabric on the in-plane mechanical properties of Carbon laminates. It seems that for inter-ply woven hybrid composites, in which hybridization is achieved by layer by layer arrangement of woven fabric, the effect of the woven structure on the trade-off in mechanical properties of low strain materials (LSM) laminates has not been satisfactorily addressed in the literature. Furthermore, a great majority of the studies of hybrid composites are focused on Glass/Carbon fiber hybrid fabric composites, but there are only a few studies on the effects of Carbon/Aramid hybridization on the mechanical properties. Several researchers have investigated the impact performance of unidirectional woven Carbon/Aramid composites [17]. There is a need for additional data on the tensile performances of the woven composites fabricated in effortless and cost-effective methods for the small-scale applications for both academic and industrial applications.

The studies based on the thin woven Carbon/Aramid hybrid laminates for UAV applications are not reported widely. Hence in this work, plain woven Carbon/Aramid hybrid composites have been investigated in order to understand the effect of the woven Aramid layers in CFRP on its tensile properties. In this study, the Carbon and Aramid fibers are reinforced in the epoxy matrix using VARIM. Out of the four types of samples investigated, there is a virgin 3-layer Aramid sample as well as Carbon samples, respectively. Two different hybrid samples are studied with the HSM at the outer sides covering both the faces of the laminates. The effect of the Aramid layer, when added to the Carbon laminate, on the tensile behavior is investigated using a uniaxial tensile test. Photographic images are used to visualize the fracture mechanism in attaining a clear understanding of the effect of the hybrid fiber under tensile load. This study anticipates gaining some useful and novel insights into the Carbon/Aramid hybrid composites to find broad applications in the micro/mini UAVs.

2. Experimental Procedure

2.1. Materials and specimen design

The details of the raw material and the fabrication process employed in this study in order to investigate the hybrid Effect of Carbon/Aramid epoxy laminate composite are explained in this section. A low viscosity CT/E 1564 epoxy, which is suitable for resin infusion, is used. The procured resin system is cured using two hardeners CT/PH-3486 and CT/PH-3487. The physical properties of the resin system are shown in Table 1.

Table 1 Parameters of the Resin System

Type	Unit	Resin (CT/E-1564)	Hardener-1 (CT/PH-3486)	Hardener-2 (CT/PH-3487)
Viscosity at 25°C	mPas	700 – 1,100	< 50	< 70
Epoxy Content	g/eq	166 – 185	–	–
Density at 25°C	g/cc	1.10 – 1.20	0.94 – 0.95	0.98 – 1.00
Flash Point	°C	> 185	>120	>120

The reinforcements used in this study are 12K plain-woven BD carbon fabric manufactured by Hyosung Corporation and ALKEX 3000D Aramid fabric from Hyosung

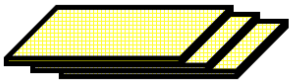
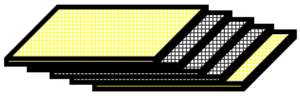
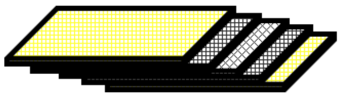
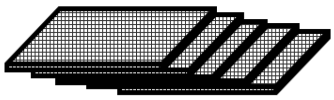
Corporation supplied by Composite Tomorrow Pvt Ltd, India. Table 2 shows the physical parameters and the mechanical properties of the carbon and aramid fabrics, respectively.

Table 2 Physical parameters and properties of the fabrics

Type	Carbon	Aramid
Weave	Plain	Plain
Linear density warp/fill (Tex)	12K	3000D
Ends/picks counts, yarns/10 cm	2.5/2.5	6.7/6.7
Areal density, g/m2	400	450
Fabric thickness, mm	0.42	0.55
Fiber diameter, µm	7	10
Fiber Young modulus, GPa	230	74
Fiber strength, Mpa	3450	2923
Fiber ultimate elongation, %	1.5	3.6
Fiber density, g/cc	1.8	1.44

Parameters of stacking sequences for neat and hybrid specimen types investigated in this study are illustrated in Table 3. Virgin Carbon was made of 5 layers, and the virgin Aramid layer comprised 3 layers. Aramid laminates were named as 3A. In the case of Carbon samples, 5C have been denoted for five-layer Virgin Carbon laminates, respectively.

Table 3 Sequential details of the specimens

Laminate	layers	Stacking sequence	Sample type
	3	$[(0/90)_A]_3$	3A
	5	$[(0/90)_A/(0/90)_C/\overline{(0/90)_C}]_S$	H90
	5	$[(0/90)_A/(0/90)_C/\overline{(\pm 45)_C}]_S$	H45
	5	$[(0/90)_C]_5$	5C

Of the two different hybrid samples of 5 layers each was prepared using Carbon and Aramid fabric. In the hybrid sample, aramid layer was kept at the outside. Studies suggest that HSM materials at the outer layers improve the impact performance [18] and also the strain to failure rate [8,19,20]. The symmetric layup sequence has been made for all the samples. Out of the two varieties of stacking sequence used in experiment, one was with $[(0/90)_A/(0/90)_C/(\pm45)_C]_S$ with a (±45) at the centre named H45 and the other with all the three layers at $[(0/90)_A/(0/90)_C/(0/90)_C]_S$ denoted as H90.

2.2. Specimen manufacturing

The laminates were fabricated using VARIM, as shown in Fig. 1. All the specimens were made with a dimension of (300 x 300) mm. The resin – hardener mixing ratio was 100:34, wherein two hardeners were mixed at a ratio of 25.5: 8.5.

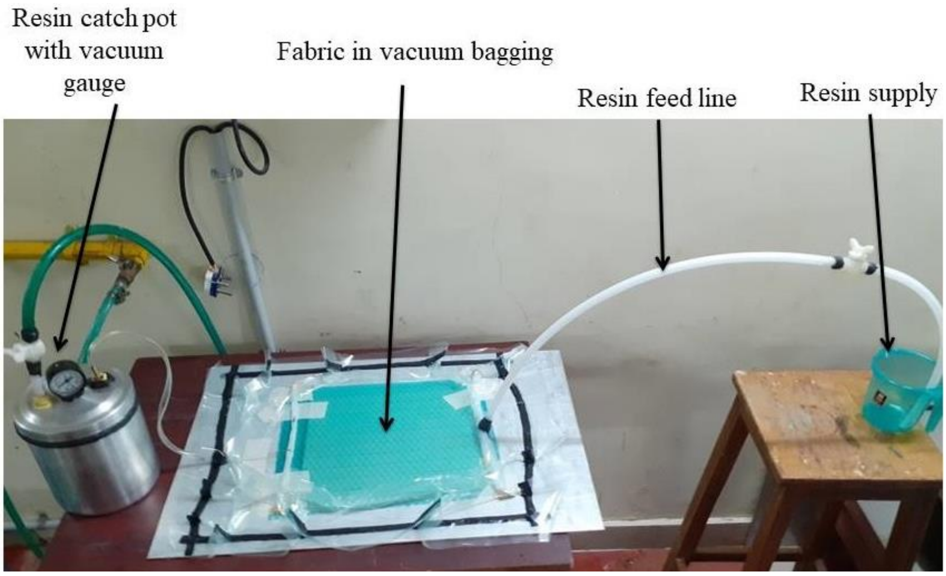


Fig. 1 Vacuum-Assisted Resin Infusion Moulding (VARIM) set up

The woven fabric reinforcements have been placed on aluminium plate mould. Vacuum bagging and required tubing for resin inflow, outflow, and vacuum have been made appropriately. During the pre-filing stage [21,22], vacuum has been maintained for 1hr at -710 mm Hg for compacting the dry fabric. During that time, it was confirmed that there is no leak. The filling pressure was maintained at – 650 mm Hg. After the infusion of resin into the stacked fabric, the tubes have been sealed for holding the vacuum at -720 mmHg to avoid any bending or expansion of the ply during curing. Resin impregnated fabric has been cured in an oven at 80°C for eight hours as recommended in the supplier datasheet. Density and void fraction of the laminates were calculated using Eqs. (1), (2) and (3) and are tabulated in Table 6.

Experimental density ρ_{exp} is calculated using Eq. (1) where *M* and *V* are mass and volume of the laminate, respectively. Theoretical ρ_{th} is found out using Eq. (2). Theoretical density ρ_{th} is calculated using Eq. (2) with weight fractions W_{FC}, W_{FA} and W_M of Carbon fiber, Aramid fiber and matrix, respectively; their values are as shown in Table 4. Notations $\boldsymbol{\rho}_{FC}$, $\boldsymbol{\rho}_{FA}$ and $\boldsymbol{\rho}_{M}$, are the densities of Carbon fiber, Aramid fiber and matrix, respectively, as given in the manufacturer datasheet listed in Table 5.

$$\rho_{exp} = \frac{M}{V} \tag{1}$$

$$\rho_{th} = \frac{1}{\frac{W_{FC}}{\rho_{FC}} + \frac{W_{FA}}{\rho_{FA}} + \frac{W_M}{\rho_M}} \tag{2}$$

$$Void\% = \frac{\rho_{th} - \rho_{\exp}}{\rho_{th}} * 100 \ , \tag{3}$$

Table 4 Micro mechanical properties of the fabricated laminates

Sample	ρ_{FC} (g/cm^3)	ρ_{FA} (g/cm^3)	ρ_M (g/cm^3)	W_{FC}	W_{FA}	W_M
3A	-	1.44	1.15	-	0.58	0.42
H90	1.8	1.44	1.15	0.283	0.233	0.484
H45	1.8	1.44	1.15	0.304	0.246	0.449
5C	1.8	-	1.15	0.53	-	0.47

Notation W_C is the weight of the composite laminate. The percentage of void denoted by *Void %* is calculated using Eq. (3). The calculated values are shown in Table 5.

Table 5 Properties of test specimens

Sample	W_C (g)	Area (cm)^2	Thickness (cm)	Volume (cm)^3	$\rho_{\exp}$ (g/cc)	ρ_{th} (g/cc)	Void fraction (Vv)	*Void %*
3A	276	1054	0.211	222.39	1.241	1.302	0.046	4.68
H90	423	985	0.325	320.32	1.320	1.351	0.022	2.29
H45	390	980	0.299	293.28	1.329	1.369	0.029	2.91
5C	325	840	0.282	236.88	1.372	1.422	0.035	3.53

2.3. Tensile test

The specimen was cut into test coupons as per ASTM D3039 -17 using waterjet cutting at Stonemax Industries, Cochin. Each test coupon had a dimension of (250 x 25) mm. The final samples were visually inspected to assure appropriate quality. A good integrity of the hybrid laminates was confirmed during the testing procedures, and no phase separation was observed. Tensile testing of the hybrid laminates was performed under uniaxial tensile loading and displacement control using a crosshead speed of 2 mm/min on a computer-controlled ITW BiSS 50KN rated universal test machine with wedge-type grips. The results of the minimum 3 specimens are considered to check the repeatability of the results and the averaged values of each sample type are considered for the result analysis to impart clarity of discussion. The data on tensile strength, elastic modulus, strain to failure modulus of toughness and specific strength have been analyzed for conducting a comprehensive investigation on the in-plane mechanical behavior of Carbon /Aramid hybrid composites. The chord modulus is calculated at a strain range from 0.001 to a value that is 25 % of the total strain as per ASTM D3039 -17.

3. Results and Discussion

3.1. Tensile stress-strain result

The stress-strain curves of the virgin and hybrid composite as shown in Fig.2 exhibited an initial knee after a linear growth in the stress. This is the general bilinear behavior observed in BD fabric laminate caused due to the undulations in the weaving pattern and the pre-failure of 90° fibers [23]. The wavy pattern in weft and wrap gets straightened with the increase in strain [24]. Beyond the knee point, the curve shows a slight linear growth until the ultimate strength of the composite. The tensile behaviors of the virgin Carbon and Aramid laminate are discussed in order to make a clear and comprehensive comparison between the virgin and hybrid samples. The virgin Carbon sample 5C exhibited a steep slope in the stress-strain variation when compared to the virgin Aramid and hybrid samples. However, the virgin Aramid layers took the maximum stress when compared to all the samples. A higher ductility combined with a greater tenacity of the Aramid fiber when compared to the carbon one is the reason for a high-stress rate of the Aramid laminate.

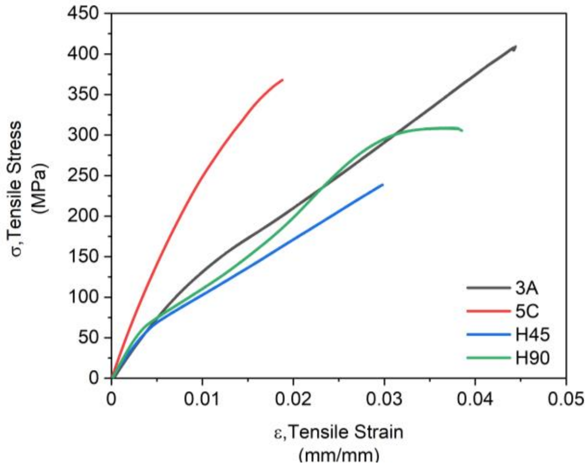


Fig. 2 Overall comparison of the stress-strain variations

The hybrid samples H90 with inter-ply hybrid layers of Carbon and Aramid fibers a stress-strain behavior intermediate to the virgin samples indicates a positive hybrid effect. The high strain Aramid layer helped in the gradual stress drop in H90 sample that exhibited a pseudo- ductile behavior. The pseudo- ductile behavior can be attributed as a warning before a catastrophic failure.

However, the hybrid sample H45 undergoes a sudden drop in the stress-strain slope immediately after the failure of the Carbon layer due to the stress concentrations created by ±45 Carbon layer. Thus, it is the position; the fiber stacking orientation has a significant influence in imparting a positive hybrid effect.

The virgin Carbon samples 5C showed a highest elastic modulus among the samples under investigation. The virgin Aramid sample produced an elastic modulus almost 36% lower than the virgin Carbon laminate. This is an obvious behavior due to the excellent modulus of the Carbon fiber. However, Aramid samples attained the maximum failure stress due to the inherent higher toughness and tenacity when compared to the Carbon fiber. The overall strength and modulus data from the experiment are shown in Fig.3. Sample H90 had a significant positive hybrid effect with the E value almost 20% lower and 22% higher when compared to the virgin Carbon and Aramid samples, respectively. However, the presence of ±45 ply at the midplane of the H45 sample led to the lower values tensile properties when compared with all the samples under study. Thus, it is inferred that the ply orientation also has a significant role in deciding the hybrid effect of hybrid composites.

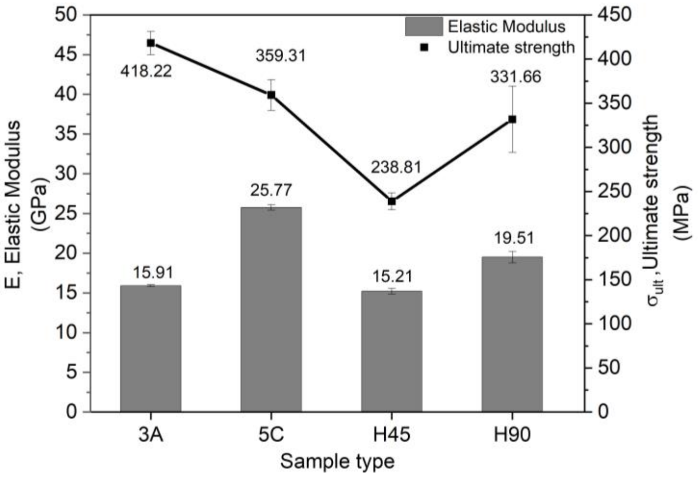


Fig. 3 Elastic modulus and ultimate strength of the tested samples

3.2. Strain to failure and toughness modulus analysis

Strain to failure is a property that is worth studying in composites since the values of strain at failure have a significant dependency HSM fiber used during hybridization. The enhancement of the strain to failure value contributes to the pseudo ductile behavior. Increased strain to failure behavior can also improve the energy absorption capability of a laminate which in fact is the modulus of toughness measured for a material. So, it is worth investigating the ultimate strain and the modulus of toughness together to get an inclusive picture of the effect of hybridization in composite laminates. As shown in Fig.4, the hybrid approach increased the failure strain of the samples up to 55% in H45 samples and 75% in H90 samples as compared to virgin Carbon samples. This increase is due to the presence of the Aramid layer that can be justified with higher values of failure strain and toughness modulus. When the virgin 3A sample is compared to the 3C and 5C samples, the 3A sample showed for about 114% and 170% higher values of strain to failure and toughness modulus, respectively.

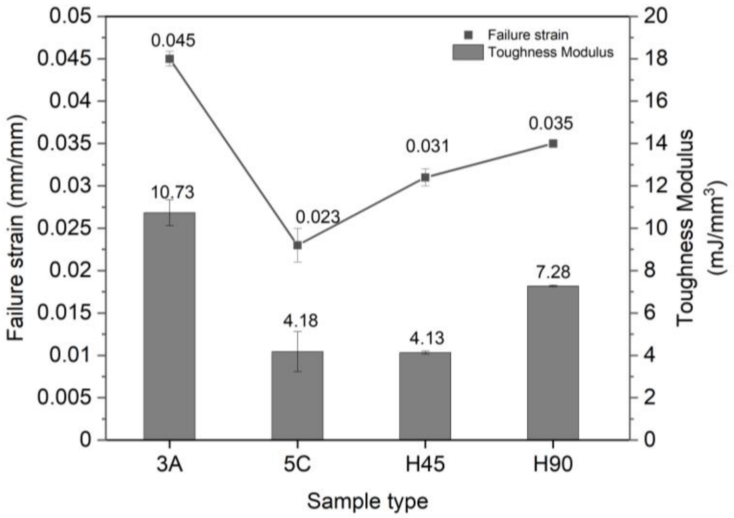


Fig. 4 Failure strain and toughness modulus of the tested samples

The hybrid samples H90 and H45 exhibited enhanced performance in the strain to failure value with an increase of 66% and 47 %, respectively, when compared to the 5C virgin sample. The H90 showed an 83% improvement in the toughness when compared to the virgin Carbon sample. However, the H45 sample did not exhibit an appreciable change in comparison with the Carbon sample. The early failure of ±45 layer creating a drop in the overall stress value during the tensile loading is the reason for unchanged toughness modulus.

3.3. Failure mode analysis

A study of the fracture morphology can give an insight into the reasons for the in-plane tensile behaviors exhibited by the samples. After the tensile tests, the specimens were photographed, and the failure modes were classified in accordance with the three-part failure mode code as per ASTM D3039.

Virgin Carbon sample, as shown in Fig. 9, underwent a perfect brittle failure with the Lateral Gage Middle (LGM), which is as expected due to the lower elongation to failure of the carbon fiber. Tow fracture is the most visible failure observed in the fracture end. As shown in Fig. 10, fibrillation of fiber has been observed in the virgin Aramid samples, and the fibers at the failure section have undergone a ductile elongation with Multimode Gage Middle (MGM) mode of failure. Tow fracture and tow splitting were observed in the virgin Aramid sample. Delamination was observed more in 3A samples because of two reasons, namely, fiber fibrillation and a lower wettability of fabric to the matrix material. The above-mentioned reasons for the ductile failure of Aramid are the factors that bring up pseudo-ductile behavior in laminated polymer composites.

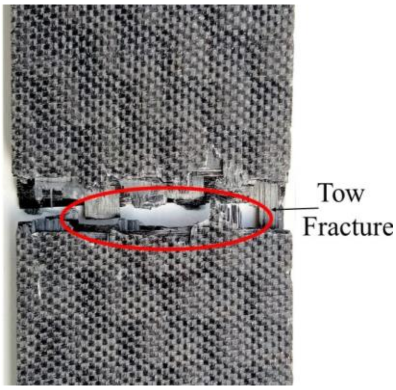


Fig. 9 Tensile fracture of virgin 5C Carbon laminate

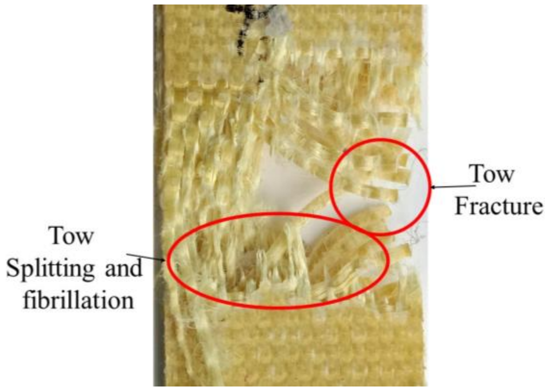


Fig. 10 Tensile fracture of virgin 3-layer 3A Aramid laminate

The fracture images of the hybrid sample exhibited a real combination of the damage morphologies in virgin Carbon and Aramid sample. The delamination and fiber breakage are observed in the hybrid samples. The mixed behavior accounts for the property enhancements achieved through proper hybridization. As shown in Fig. 11-a, A "V" shaped failure intersection is observed with an Angle Gage Middle mode of failure for the H45. It is mainly due to abrupt failure due to stress concentration of the (±45) carbon layer present in the midplane. The nature of the failure is abrupt, with the Aramid fibers failed along with the Carbon layer. In the H45 sample, the failure in Aramide was tow fracture with delamination and tow splitting was found in the Carbon layer.

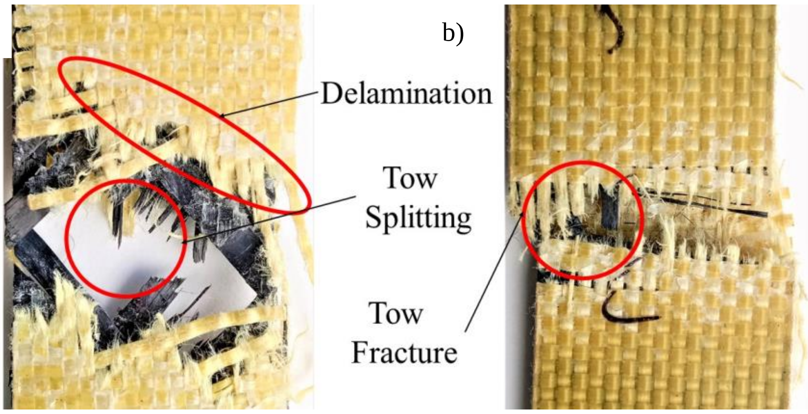


Fig. 11 Tensile fracture of hybrid samples, (a) H 45 and (b) H90

The hybrid sample with only (0/90) layers of Carbon as shown in Fig. 11-b had a gradual failure as is visible that the Aramid layer remained at one side after the separation of the Carbon layers. The failure mode was LGB. This indicates that the sample took the load even after the carbon layers failure whereby resembling a pseudo-ductile tensile failure.

4. CONCLUSION

In this work, the in-plane tensile behavior of bidirectional woven Carbon/Aramid epoxy composite laminates manufactured using VARIM with different Carbon fiber layup sequence of 0/90 and ±45 fiber orientations are conducted. The study analyzed the effect of hybrid layers in the overall tensile characteristics of the woven hybrid laminates during uniaxial tensile loading. The HSM like Aramid fibers are used in the LSM reinforced laminates to enhance the energy absorption capability, strain to failure and impact properties. However, the effort in improving these properties compromises the tensile modulus and strengths. The sample laminates were made with Aramid layers at the outside and Carbon as inside layers with an inter-ply hybrid approach, and the following conclusions were drawn.

1. The investigated hybrid samples exhibited a positive hybrid effect by increasing the strain to failure when compared to the virgin carbon composite.
2. The hybrid approach enhanced the failure strain of the samples up to 50% in H45 samples and 66 % in H90 samples as compared to the virgin Carbon samples. This increase is due to the presence of Aramid an HSM.
3. The toughness modulus of the hybrid samples showed influence on the stacking sequence of the Carbon laminate; nevertheless, the presence of the Aramid layer. The hybrid sample H90 exhibited a significant improvement in toughness modulus as compared to the virgin Carbon laminate. However, the H45 sample with an angle ply at the midplane has not produced any significant improvement from the virgin Carbon sample.
4. The hybrid Samples showed a compromise in the in-plane mechanical properties, namely, the elastic modulus and strength. There has been a decline of 24% and 40% in the elastic modulus by H90 and H45, respectively. Nevertheless, the compromise in the modulus value, H90 maintained the ultimate strength almost the same as the carbon laminate. However, the H45 had a reduction of 31% in the ultimate strength when compared to the virgin carbon sample.
5. VARIM process enabled the fabrication of the hybrid samples with acceptable void percentage. The pre-compaction, post-compaction, and the monitoring of the vacuum pressure throughout the curing time are a factor that decides upon thickness, density, integrity, and fiber-matrix ratio of the final structure. The vacuum pressure maintained during the curing time was -720 mm Hg, and it helped in making the laminate with good strength and uniform thickness. The pressure drop at any stage of the process reduces the inter-laminar strength, increases the overall thickness, produces non-uniform ply thickness at different locations, and adversely affects the stiffness of the composite structure.

A trend of pseudo-ductile behavior was observed in the H90 hybrid sample. The current study expects to have provided valuable insights for making thinner and robust Hybrid CFRP with enhanced properties using cost-effective fabrication with pseudo-ductility in the hybrid Carbon/Aramid laminates that can be used in making thin, stiffer and more rigid structural materials for small and medium UAVs and various aerospace applications. The data from this experimental study can be utilized for numerical validations that are deemed necessary for the future research and developmental activities of engineering composites in order to reduce the time and cost of experimental studies.

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