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Low velocity impact properties of 3D woven basalt/aramid hybrid composites

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Abstract

In order to determine the effect of fiber arrangement in 3D woven hybrid composites on their low velocity impact properties, aramid (Kevlar®129), basalt fibers, and epoxy resin were used to fabricate interply hybrid composite in which different yarn types were placed in different layers and intraply hybrid composite in which each layer was composed of two types of alternately arranged yarns. These composites were impact tested at 2 m/s and 3 m/s impact velocities along warp and weft directions. The interply hybrid composite showed higher ductile indices (8–220%), lower peak load (5–45%), and higher specific energy absorption (9–67%) in both warp and weft directions than that of the intraply hybrid composite due to a layer-by-layer fracture mode for the interply hybrid composite.

Keywords: A. Textile composites; A. Hybrid Composites; A. Aramid fiber; B. Impact behavior

1. Introduction

It has been shown that 3D woven composites have unique mechanical and physical properties compared with their 2D counterparts [1,2]. They have a reasonable cost due to their relatively simple resin impregnation process [3] and high performance because of their resistance to delamination [4,5]. In addition, 3D composites have high ballistic impact damage resistance and low velocity impact tolerance [6–8]. Low velocity impact properties of 3D woven composites are important for their various applications. This type of loading can occur when tools are dropped on the surface of a composite or when the material is impacted by debris, fragments, or projectiles.

Hybrid composites contain two or more different types of reinforcement fibers which have different mechanical and/or other properties, allowing researchers to design a composite with tailored properties in specific applications [9–11]. In general, the purpose of hybridization is to achieve a composite architecture which synergizes the properties of both materials and/or lowers the cost since one of the fibers could be too expensive. Structures of hybrid composites may be classified as interply hybrids, intraply hybrids, intimately mixed (intermingled) hybrids, selective placement and super hybrid composites [12]. Brittle inorganic fibers and ductile organic fibers are often combined to make hybrid composites such as palm/glass, tong glass/mineral fiber, aramid/glass, etc. [13–15]. The so-called hybrid effect is often in the form of a positive deviation of a certain property from the 'rule of mixtures' [16].

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Low velocity impact properties of a hybrid composite have not been studied extensively. Among limited publications in this subject area, Pegoretti and co-workers [12] studied low velocity impact behavior of E-glass/PVA hybrid laminated woven composites in two structures, namely interply and intraply hybrids. In that research, the intraply composites were composed of fabric layers, in which the warp yarns and the weft yarns were different types. It was found that the intraply hybrid composites had better tensile and impact performance than their interply counterparts. Impact properties of 3D woven composites have been studied [3,17–20]. However, little has been reported in the impact behavior of hybrid 3D woven composites.

As an inorganic fiber, basalt fibers have similar strength and modulus but much better thermal properties than glass fiber though the quality of the fiber is very sensitive to the change of the processing parameters [21,22]. Aramid fibers, on the other hand, have good tensile strength and modulus as well as superior impact resistance, though they are much more expensive than basalt fibers. Therefore a 3D woven hybrid composite of these two fibers will be reasonably priced with reasonable tensile, compression and impact properties. However, it is not clear how the impact properties of the hybrid composites will be changed as the construction of the 3D woven changes. In this study, 3D woven basalt/aramid/epoxy hybrid composites were fabricated in either interply or intraply hybrid structures. Unlike the two types of hybrid structure used by Pegoretti and coworkers [12], single basalt and aramid yarns were placed alternately in each layer and thus a much better mixing of the two yarns was achieved. The low velocity impact properties of these hybrid composites were characterized and a post mortem analysis was carried out.

2. Experimental

2.1. Materials

Basalt fibers of 6144 dtex and aramid fibers (Kevlar®129) were used to weave the 3D hybrid composites. The woven preforms were consolidated with Epoxy618 and hardener Iminazole5510 ($\rho = 1.19$ g/cm^3) from Shanghai Resin Company, whose chemical and mechanical properties were similar to Epon 828.

Basalt fiber, type 3000 from Shenzhen Research Institute, Harbin Institute of Technology in China contains approximately 58.7% SiO_2 and 17.2% Al_2O_3, whose physical and mechanical properties are presented in Table 1.

Table 1
Physical and mechanical properties of the fibers [24]

Properties	Basalt	Kevlar 129
Linear density (dTex)	6144	3140
Tensile strength (GPa)	4.84	3.45
Modulus (GPa)	89.0	97.0
Elongation at break (%)	3.1	3.3

2.2. Fabrication and consolidation

Two reinforcement geometries with six warp and seven weft layers were adopted in making the composites, namely interply hybrid and intraply hybrid composites. In the interply hybrids, aramid yarns or basalt yarns were placed in different layers while in the intraply hybrids, the two types of yarns were placed next to each other in each layer of warp or weft as shown in Fig. 1. The fabric counts in warp and weft directions were 5 ends/cm and 5 picks/cm while that of the Z yarn was also 5 ends/cm. The aramid (Kevlar®129) yarn was used as the Z yarn for all the samples.

All the composite preforms were fabricated by 3D weaving machine in Donghua University. Consolidation procedure was achieved by vacuum-assisted resin infusion method, with a 2 h curing at 80 °C, followed by half an hour post-curing process at 100 °C. Cross-sectional views of the composites are shown in Fig. 2.

2.3. Impact tests

Low velocity impact properties of the interply hybrid and intraply hybrid composites were tested at two different incident rates, 2.0 m/s and 3.0 m/s corresponding to two impact energy levels of 10.22 J and 22.99 J, using Instron® Dynatup 9210 Impact Tester. The setup of the test was similar to three point bending test in which a rectangular specimen was impacted in the middle while supported at the two ends. The composites were tested in both warp and weft directions because samples had different structures in different directions. At least six 10×70 mm specimens for each sample of the woven composites were tested to perforation. All samples were tested at 20 °C and 65% relative humidity.

In the test, regardless of the yarn structure, the impact energy absorption might be overestimated because a certain amount of elastic energy was stored in the specimen prior to failure and could be dissipated acoustically, thermally, or in the form of kinetic energy of the failed parts [23]. Thus in our experiment, we only consider the total energy loss recorded without separating the energy loss in the above forms.

2.4. Statistical analysis

One-way analysis of variance (ANOVA) and Fisher's pair-wise multiple comparisons were used to compare the peak load and total energy between the two hybrid structures. A P-value <0.05 was considered significant.

3. Results and discussion

3.1. Physical characterization of the composites

The specific densities of the composites were achieved by water displacement method and the thickness of each

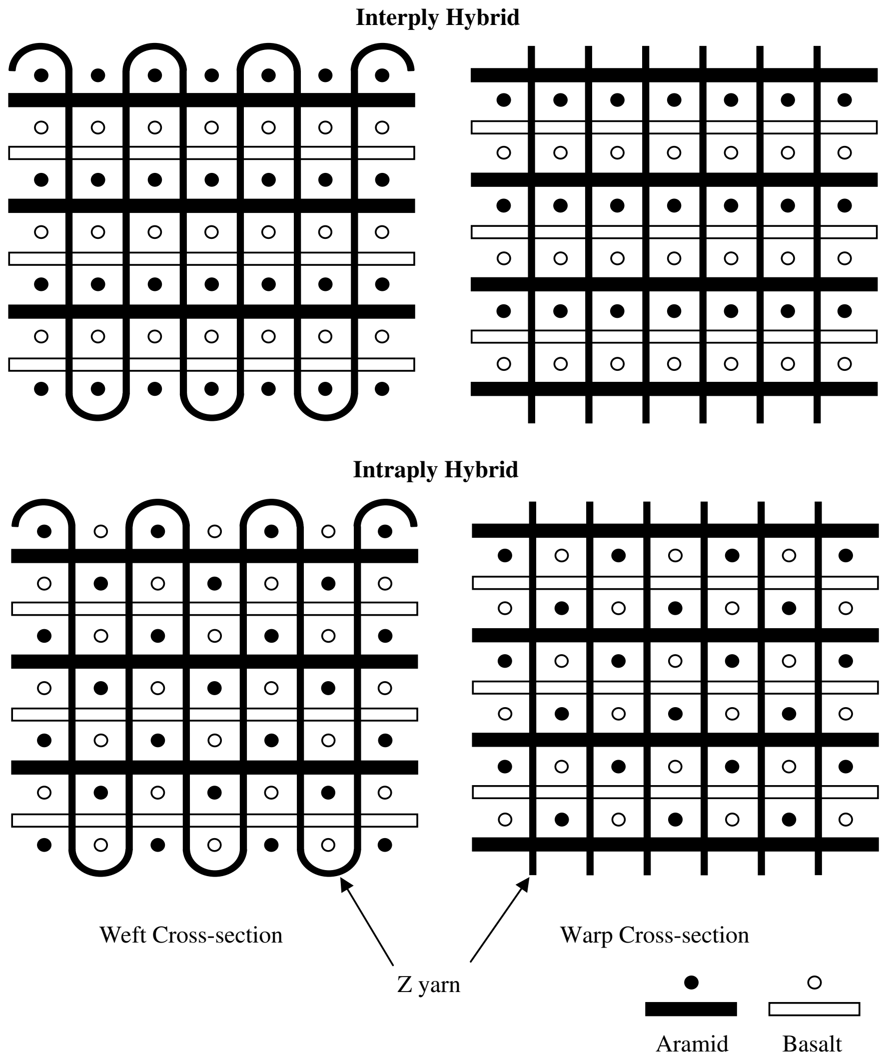

Fig. 1. Schematic of the two hybrid composite performs.

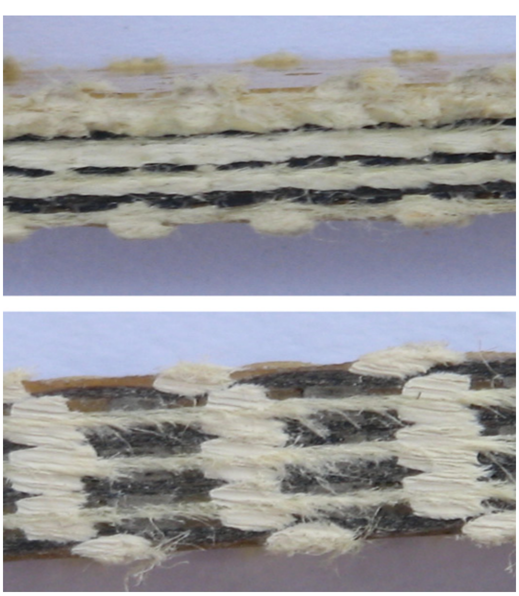

Fig. 2. Cross-sectional views of the interply (top) and intraply (bottom) specimens.

specimen was measured in six different points (Table 2). The volume fractions of the fibers in each direction and the matrix were estimated based on the yarn sizes, fiber specific densities, preform constructions, and composite specific densities (Table 3).

3.2. Impact performance

Typical load–time curves at different impact velocities are given in Figs. 3 and 4 to compare the strength and energy dissipation of the two geometries in both warp and weft directions. Impact responses of the composite specimens were characterized in terms of maximum impact force, energy to peak load, and total energy absorption. For all the samples, the load-time curves showed slight vibration during the initial stage, which was probably due to the vibration of the un-clamped ends of the specimen. In the initial stage, the impact response of the specimens was similar to part of a sinusoidal wave (Fig. 2). Damage was initiated within the composite

Table 2
Density of the four geometries

Composites	Layer of warp yarns	Layer of weft yarns	Density (g/cm^3)	Thickness (mm)	Fiber type	
					Warp	Weft
Interply	6	7	1.51	5.10 ± 0.05	A + B	A + B
Intraply	6	7	1.44	5.00 ± 0.07	A + B	A + B

A: kevlar fibers; B: basalt fibers.

Table 3
Fiber volume fractions of the Composites

Composites	Warp		Weft		Z-yarns (%)	Overall fibers (%)	Matrix (%)
	Basalt fibers (%)	Kevlar fibers (%)	Basalt fibers (%)	Kevlar fibers (%)			
Interply	6.03	6.89	11.92	18.17	8.19	56.59	43.41
Intraply	6.26	7.15	14.22	16.27	6.82	56.87	43.13

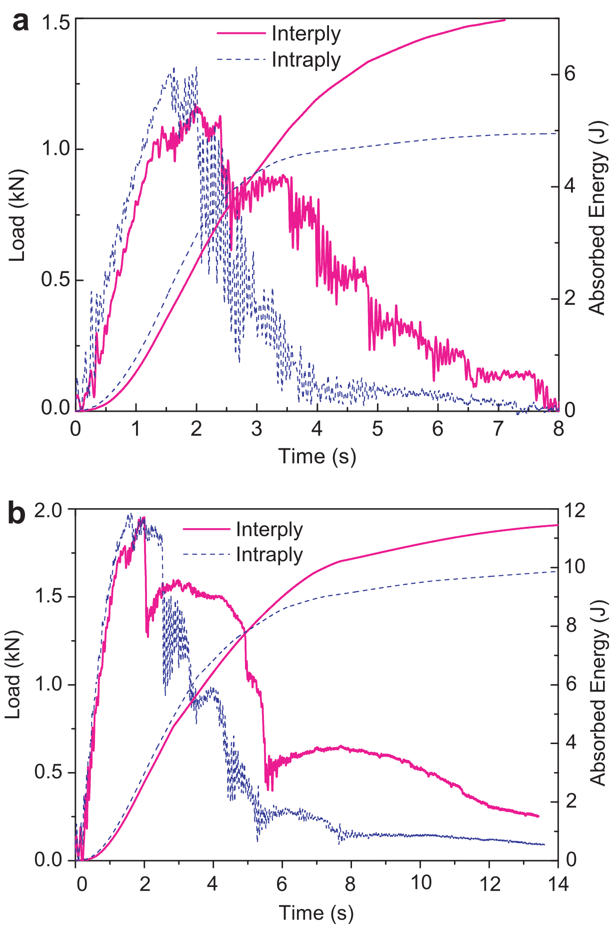

Fig. 3. Impact force and AE versus time curves at 2 m/s impact speed for 3D woven aramid/basalt composites: (a) warp direction, (b) weft direction.

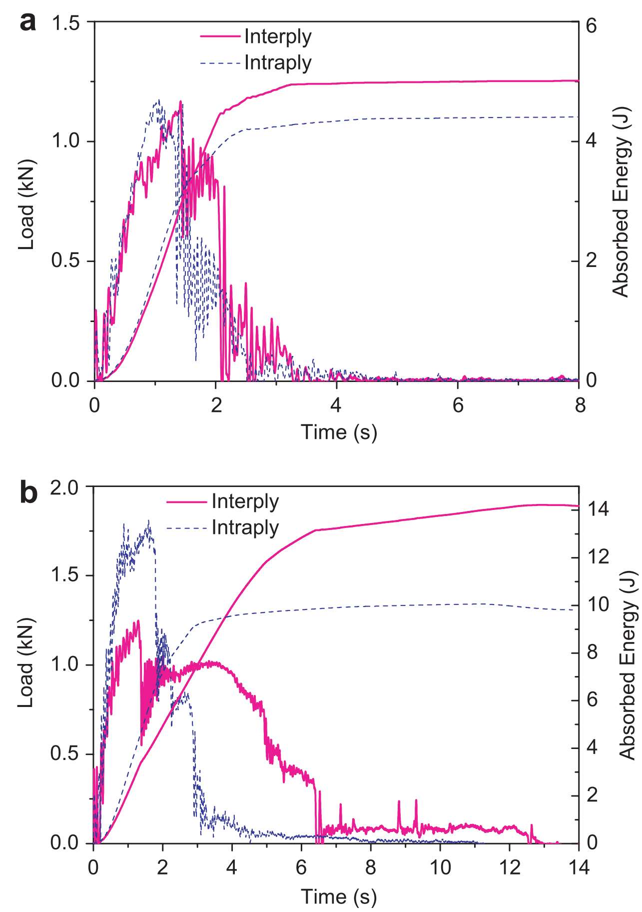

Fig. 4. Impact force and AE versus time curves at 3 m/s impact speed for 3D woven aramid/basalt composites: (a) warp direction, (b) weft direction.

architecture where the load–time curve had an obvious slope change.

For most materials, the ductility index is defined as the energy absorption after the maximum load divided by the energy absorption to the maximum load. However, for a hybrid composite, the composite failure process could be initiated much earlier than the maximum load point as it can be seen in the impact load versus energy curves in the current study. Therefore it may be more meaningful to use the energy to yield point as the initiation energy, E_i, where the impact load versus time curve starts to change slope. Energy dissipated after the yield point is defined as E_p (propagation energy). Therefore the ductility index, $DI = E_p/\ E_i$, reflects the ductility of the material.

The larger the DI value, the more ductile the composite material.

Total impact energy, ductility index, impact strength data for various composites are summarized in Tables 4–6. As shown in Table 4, at $v = 2$ m/s, the peak loads of interply hybrid composite were similar to those of the intraply hybrid composite ($P > 0.05$). The interply hybrid composite had lower energy to yield but higher energy to peak load than the intraply hybrid composite. The ductility indices of the interply composite (9.7/15.3) were much higher than those of the intraply composite (7.4/9.4). At 3 m/s, the peak load for interply hybrid composite in weft direction was substantially lower than that for the intraply hybrid composite (1.009 kN versus 1.854 kN). The total energy absorption for the interply hybrid composite was significantly lower than the intraply hybrid composite in both warp and weft directions. This indicates that the difference in impact behavior of the 3D composites was enhanced at higher impact speed. Therefore it was concluded that the interply hybrid composite had higher impact resistance than the intraply hybrid composite. Meanwhile, the peak load of the interply hybrid composite was either similar or lower than that of the intraply hybrid composite.

Difference in all parameters between warp and weft direction was observed for each type of the composite. In general, the properties along weft direction were much better than that of the warp direction because the fiber volume fraction in the weft direction was twice as much as that in the warp direction as shown in Table 3. In addition the weft direction had one more layer than the warp direction, which made the composite more resistant to bending as well as impact since the outmost two layers were weft yarns.

At $v = 3$ m/s, the absorbed energies at different stages of impact were similar to those at $v = 2$ m/s. However, the ductility indices of the materials were reduced at $v = 3$ m/s as shown in Table 6. This is because the strength and modulus of the matrix increased as the strain rate increased, and thus the matrix appeared to be more brittle.

3.3. Failure analysis

Figs. 3 and 4 show the load–time curves of the composites at two velocities. For the intraply sample, the initial stage of the curve where the slope started to change substantially was longer than the interply sample, indicating that for the interply structure, internal damage initiated at a load level was significantly lower than that for the intraply structure. This might be due to the residual stress induced by different thermal expansion coefficients (8.01×10^{-6}/°C for basalt [25] and -5×10^{-6}/°C for aramid axial direction [26]) between the neighboring two layers of different yarns in an interply hybrid composite. This effect did not exist in the intraply hybrid composite since the two types of fibers were evenly distributed in each layer. In addition, the intraply hybrid composite will be stronger than what is predicted by rule of mixtures because of the hybrid effect in each layer. A lower peak load was observed for the interplay hybrid composite which could result from the early delamination or debonding between the layers. After the peak load, the load-time curves showed longer steps or much more gradual decline for the interply structure than the intraply structure because the former failed in a layer-by-layer mode, while the latter failed in a more catastrophic manner. This could be confirmed by the post-mortem analysis of the specimens under microscope. Fig. 5 shows the failure cross-sections of the

Table 4
Peak load and energy absorption of the hybrid composites at $v = 2$ m/s

Loading direction	Hybrid type	V_f (%)	Thickness	Peak load (kN)		Energy to yield (J)		Energy to peak load(J)		Total energy (J)	
				Mean	STDV	Mean	STDV	Mean	STDV	Mean	STDV
Warp	Interply	51.2	5.10 ± 0.05	1.107	0.090	0.520	0.133	2.707	0.118	5.541	1.194
	Intraply	50.7	5.00 ± 0.07	1.173	0.162	0.532	0.147	2.567	0.651	4.457	0.665
Weft	Interply	51.2	5.10 ± 0.05	1.716	0.175	0.658	0.132	4.137	0.792	10.700[a]	1.246
	Intraply	50.7	5.00 ± 0.07	1.847	0.166	0.858	0.236	3.212	0.263	8.888[a]	1.356

[a] The properties are significantly different between interply and intraply hybrid composites ($P < 0.05$).

Table 5
Peak load and energy absorption of the hybrid composites at $v = 3$ m/s

Loading direction	Hybrid type	V_f (%)	Thickness	Peak load (kN)		Energy to yield (J)		Energy to peak load (J)		Total energy (J)	
				Mean	STDV	Mean	STDV	Mean	STDV	Mean	STDV
Warp	Interply	51.20	5.10 ± 0.05	1.091	0.046	0.933	0.630	3.386	0.670	5.281*	0.842
	Intraply	50.72	5.00 ± 0.07	1.213	0.139	1.571	0.429	2.265	0.610	4.591	0.293
Weft	Interply	51.20	5.10 ± 0.05	1.009[a]	0.173	1.199	0.870	2.807	0.794	15.294[a]	2.034
	Intraply	50.72	5.00 ± 0.07	1.854	0.095	0.893	0.258	3.664	1.215	8.723	0.917

[a] The properties are significantly different between interply and intraply hybrid composites ($P < 0.05$).

Table 6
Ductile index and impact strength comparison

Velocity	Direction	Hybrid type	Ductility index	Impact strength (kJ m^{-2})	Specific total impact energy(J m kg^{-1})
2 m/s	Warp	Interply	9.7	110.8	73.4
		Intraply	7.4	89.1	61.9
	Weft	Interply	15.3	214.0	141.7
		Intraply	9.4	177.8	123.5
3 m/s	Warp	Interply	4.7	105.6	69.9
		Intraply	1.9	91.8	63.8
	Weft	Interply	11.7	305.9	202.6
		Intraply	8.8	174.5	121.2

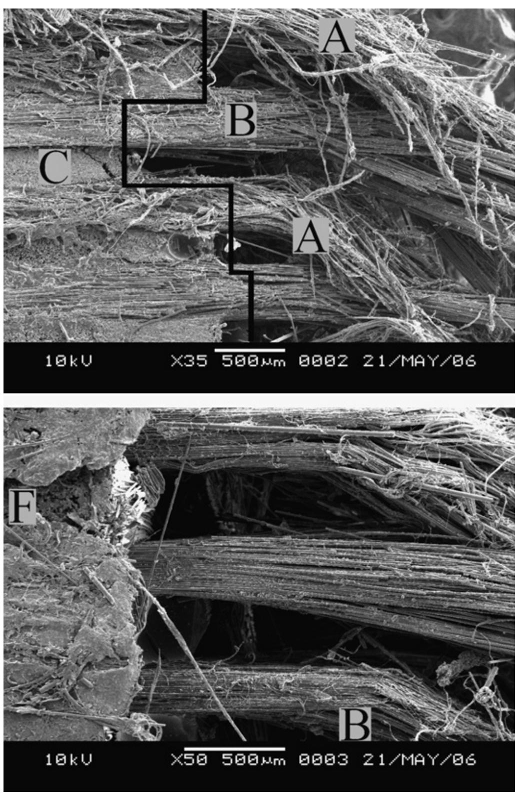

Fig. 5. Comparison of damage mechanisms between interply (top) and intraply (bottom) hybrid composites, tested at 2 m/s.

two types of hybrid composites; the interply hybrid composite had a stepwise failure cross-section while the intraply hybrid composite had a clean cut cross-section. The layer-by-layer type of failure for the interply hybrid composite was also a result of the hybrid structure in which one layer had higher modulus and thus was harder while the next layer had somewhat lower modulus and thus was softer. When the first hard layer (aramid) was perforated by the dropping tup, the second layer (basalt) was not stretched to the limit yet since it had different mechanical properties and therefore could absorb more impact energy before failure. This sequential failure was the basic reason for the long steps of the load-time curves of the interply composite which could be modeled as a step growth crack as shown in Fig. 6. In the intraply hybrid composite, each layer had the same property and thus when the first layer fails, the second layer had also almost reached the limit and thus would fail immediately afterwards. Therefore the total energy absorption and the ductility indices in both directions of the interply hybrid composites were significantly better than those of the intraply hybrid composites.

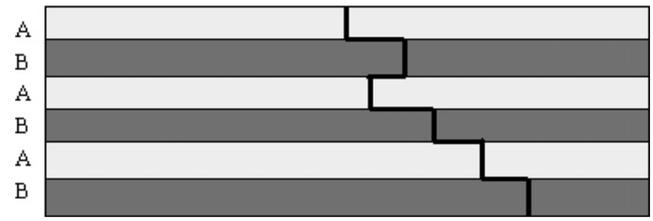

Fig. 6. Crack propagation path of interply composite in low velocity impact.

These results are in contrary to what was found by Pegoretti and co-workers [12] who reported that hybrid intraply composites showed higher ductility indices than those of the interply hybrid composites. However, it is understandable because the intraply composites they used were different from ours. In this study, an intraply structure was used in each layer of the composites while in theirs, within each layer of the fabrics, the yarns in each direction were the same type. Therefore, the composite property should be similar to our interply hybrid composite. The reason for the better performance of their intraply composite is that compared with their interply composites, the intraply composites had a better mixing or thinner single type layers. Since one layer of the woven fabric could be considered as composed of two layers of yarns, each of which had different fiber compositions, resulting in different properties. The thinner layers in that study might make the cracks travel longer distance and thus absorbed more energy.

4. Conclusions

Two types of 3D woven basalt/aramid hybrid composites with similar fiber volume fraction and dimension were designed and fabricated, namely interply and intraply hybrid composites. Their low velocity impact properties were tested. The interply hybrid composite had higher ductile indices, lower peak load, and higher specific energy absorption in both warp and weft directions than those of the intraply hybrid composite. The load time curves of the interply hybrid composite showed a step by step decrease of the load while those of the intraply hybrid composite showed a more sudden drop of the load. Postmortem photographic analysis indicated that interply hybrid failed in a layer-by-layer mode, leading to much larger energy absorption, while intraply composite showed a brittle mode, resulting in significantly lower energy absorption.

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