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Effect of Weaving Structure and Hybridization on the Low-Velocity Impact Behavior of Woven Carbon-Epoxy Composites

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Abstract
In the current study, the low-velocity impact behaviour of composite materials obtained from carbon and carbon-aramid hybrid woven fabrics of different constructions, produced from the same yarn and under the same production conditions, was determined, and the effects of the weaving structure and hybridisation on the low velocity impact properties were investigated. Depending on the weaving structure, the best results were obtained for twill woven composites. The energy absorption capacity was increased by around 9 - 10% with hybridisation. It was observed that peak load values varied with a coefficient between 0.84-0.97 for hybrid composites, whereas the range was 0.49 - 0.87 for 100% carbon composites, depending on the bending stiffness.

Key words: *low-velocity impact, carbon composites, weaving structure, hybridization.*

Introduction

Carbon composites are widely used in the aeronautical industry due to their high specific strength and stiffness properties. Despite their high strength and modulus, the lower impact resistance of carbon composites may restrict their use in primary load carrier applications. However, the lower impact features affect the load carrying capacities of these materials negatively. A carbon composite exposed to an impact load can easily be deformed, resulting in a significant decrease in their load-carrying capacity.

The performance of a material against impact loading depends on its fracture toughness, modulus, and puncture resistance [1]. While carbon composites have low impact resistance, aramid composites have high energy absorption [1 - 3] and fracture toughness properties against both low- and high-speed impacts [4].

Damage behaviors and quasi-static mechanical properties of carbon composites have been investigated comprehensively in many studies [5 - 7]. Weaving structure was found to influence the mechanical properties of carbon composites [8].

Owing to their advantages such as easy andling and processing, woven fabric composites are widely used in the composite industry; hence, it is important to determine their impact behavior [9 - 11]. Woven fabric composites are more advantageous than unidirectional (UD) composites in terms of impact resistance and damage tolerance. Woven composites reduce the extent of impact damage by suppressing inter-laminar delamination, thereby improving the fracture toughness [12, 13].

Research works on the effect of weaving structure on low-velocity impact resistance have generally been conducted by comparing two- and three-dimensional woven composites [14, 15]. The number of such studies is very few, most of which investigated the effect of the weaving structure on low-velocity impact behaviour in two dimensional weaving composites.

The hybridisation of carbon fibres with aramid and glass fibres improves the fracture toughness of the material significantly and also provides high stiffness [16].

The mechanical features, impact behaviour and energy absorption of composites depend on both the hybridisation type and placement of fibres in the composite structure [17, 18]. Many studies have been conducted on the impact behaviour of inter-ply composites that are manufactured by varying the stacking sequences of different fabric layers [19 - 21]. The results show that the impact resistance of composites increases as the amount of aramid increases, but there is a decrease in their mechanical properties and in the modulus.

Impact resistance was measured for inter-ply hybrid weaving composites that consist of different fabric layers. Naik *et al* [22, 23] studied the impact behaviour of glass-carbon/epoxy inter-ply woven hybrid composites with different stacking sequences of different glass/carbon ratios. Energy absorbed in the impact was found to decrease with decreasing carbon content.

A previous study showed that changes in the weaving structure affect the tensile properties of composites significantly [8]. In this study low-velocity impact properties were investigated using the same samples. Studies on the impact resistance of carbon hybrids, as discussed above, generally involved inter-ply hybrids composites. Only a few comprehensive studies have been conducted on intra-ply composites with different fibres in their weaving structure. The present study aims to investigate the effect of the weaving structure and hybridisation on low-velocity impact behaviour and to determine the energy absorption capacities of carbon composites.

Materials and experiments

Materials

The properties and production parameters of carbon woven fabrics and carbon fibres used in this study are presented in ***Tables 1*** and ***2***, respectively. The 12 K carbon yarn was supplied by Dow-Aksa (Turkey), and the Twaron 1000 yarn by Teijin (Netherlands). An 80 tex thermoplastic (TP)-coated glass fibre yarn was used in the weft direction in the quasi-UD woven sample (Sample C). The TP coating on the outer section of the glass

Table 1. Parameters of the carbon woven fabrics used in the study.

Type	A	B	C	D	E
Weave	Plain	Twill 2/2	Quasi-UD	Plain	Twill 2/2
Warp/fill yarns	12K/12K		12K/80 tex TP Glass	12K/Twaron 1000	
Linear density warp/fill, tex	800/800		800/80	800/336	
Ends/picks counts, yarns/cm	3.75/3.75		3.75/1.5	3.75/3.75	
Crimp Warp/Fill, %	0.8/0.8	0.4/0.4	0.1/0.7	0.3/0.5	0.2/0.3
Areal density, g/m^2	615		320	425	
Fabric Thickness, mm	0.6	0.65	0.3	0.4	

Table 2. Parameters of the carbon and aramid fibres used in the study.

Parameters	12K A-42 carbon (800 tex)	Twaron 1000 aramid (336 tex)
Fibre diameter, μm	7	10
Fibre Young modulus, GPa	240	67
Fibre strength, MPa	4200	688
Fibre ultimate elongation, %	1.8	3.7
Fibre density, g/cm^3	1.78	1.44

Table 3. Properties of the composite plates.

Type	A	B	C	D	E
Fabric ply number	4	4	6	4	4
Stacking direction	Warp	Warp	Warp/Fill	Warp	Warp
Plate thicknesses, mm	2.82±0.08	2.99±0.10	2.02±0.3	1.93±0.07	1.79±0.05
Fibre volume fraction, % Total/(warp/fill)	51.8/ (26.2/25.6)	54.6/ (27.6/27)	51.2/ (25.6/25.6)	51.6/ (33.1/18.5)	49.7/ (32.4/17.3)

yarn consisted of polyamide. All woven fabrics were produced under the same production conditions using the same weaving machine. The fabrics used in the study were woven on a Dornier P1 model rapier weaving machine modified to carbon weaving. The woven hybrid fabrics had the same structure and density as those of 100% carbon fabrics. In hybrid fabrics, warp yarns were made of carbon and fill yarns of aramid. Surface images of the fabrics are presented in ***Figure 1***. Araldit LY 564-type epoxy resin (Huntsman - International company) and XB 3486 hardener were used after mixing at a ratio of 100:34.

Composite production

The fabrics used in the production of composite materials were cut into 50 × 50 cm pieces. ***Table 3*** shows the main production parameters of composite samples such as ply arrangements, number of fabric plies, and thickness of composite plates. The stacking sequence was the same for all samples, except for sample C, whose stacking was performed from the warp to fill directions to obtain balanced composite properties therein. The thicknesses of the finished samples were measured using a caliper. The vacuum-assisted resin infusion method was used to produce the composite plates. All samples were produced on a glass plate. After resin infusion, the samples were in a vacuum for a minimum of 12 hours for hardening and post-cured at 80 °C for 4 hours in an oven.

Experimental methods

Impact tests were carried out using Instron Dynatup 8250 (International company) model low-velocity drop-weight testing equipment. This device consists of weight dropping and data acquisition system. Tests were realised by dropping a steel impactor from a 1 m fixed height. The tip of the projectile has a 12 mm diameter, is hemispherical in shape, and has a 15.6 kN load-cell capacity. The impact energy was adjusted by changing the weight of the impactor head. The samples were fixed on all edges using a clamping device with a circular opening of 75 mm. During the impact, it can record speed, deflection, load and energy data as a function of time.

Impact tests were conducted to study the effect of different weaving constructions and hybridisation on the samples. Samples were cut into 100 × 100 mm dimensions and tested at 18 and 24 J energy levels, selected based on some preliminary tests. The samples just started to be punctured or severely damaged at the 18 J energy level, whereas they were punctured completely at 24 J. At least four tests were conducted for each sample, and data for load, energy, speed and deflection were recorded as a function of time. Damage caused by the impact were reported.

The amount of energy absorbed (E_{abs}) by the samples in the impact tests was calculated with the help of the following formula:

$$E_{abs} = \frac{m}{2}\left(v_0^2 - v_{end}^2\right) \tag{1}$$

where, m is the total mass of the impacting assembly. The initial impact velocity v_0 is obtained from the slope of the displacement-time curves measured, just before the impact. Here v_{end} is the end velocity at the moment of loss of contact between the test specimen and impact head, calculated from the displacement-time curve.

Results and discussion

Low-velocity impact response and damage evaluation of samples

The present work aimed at improving understanding of the behaviour of 100% woven carbon and carbon/aramid

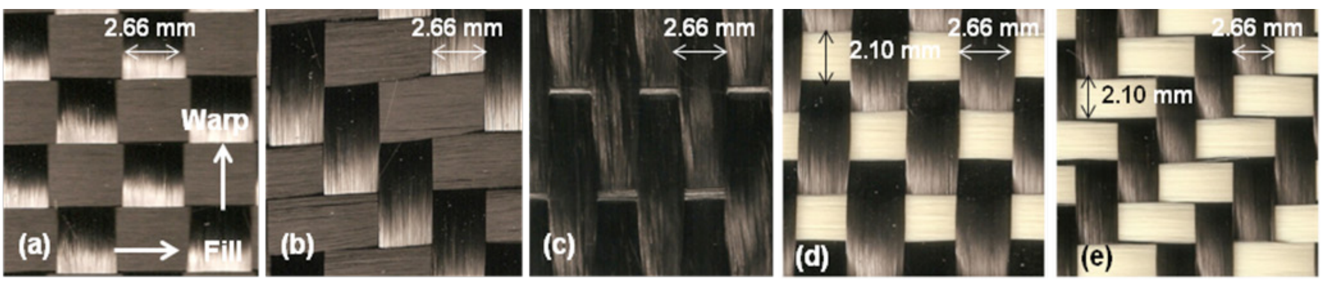

Figure 1. *View of the fabrics used in this study: (a) sample A, (b) sample B, (c) sample C, (d) sample D, and (e) sample E.*

Table 4. Impact test results of samples at the 18 and 24 J energy levels.

Samples	Impact energy, J	Peak load, N	Maximum displacement, mm	Bending stiffness, N/mm	Absorbed energy, J	Elastic recovery, J	Absorbed energy, %	Material constant
A	18	3302 ± 127	7.70 ± 1.30	659 ± 35	9.76 ± 0.70	8.24	54.25 ± 7.20	0.57
	24	3596 ± 146	10.24 ± 0.60	677 ± 58	14.89 ± 0.60	9.11	62.08 ± 5.40	0.79
B	18	3740 ± 167	6.48 ± 0.40	815 ± 60	7.20 ± 0.24	10.80	39.97 ± 7.10	0.68
	24	3997 ± 154	10.70 ± 0.20	771 ± 86	13.87 ± 0.56	10.13	57.79 ± 6.60	0.87
C	18	3245 ± 115	6.97 ± 0.50	580 ± 38	6.06 ± 0.70	11.94	33.68 ± 8.30	0.49
	24	3226 ± 171	10.97 ± 0.70	585 ± 25	11.68 ± 0.48	12.32	48.67 ± 9.60	0.54
D	18	3312 ± 98	9.74 ± 0.60	569 ± 45	10.74 ± 0.57	7.26	59.65 ± 5.80	0.84
	24	3398 ± 136	14.40 ± 0.90	589 ± 20	16.50 ± 0.66	7.50	68.74 ± 3.90	0.89
E	18	3502 ± 143	8.30 ± 0.30	740 ± 30	9.86 ± 0.47	8.14	54.79 ± 7.40	0.92
	24	3765 ± 182	13.20 ± 0.70	729 ± 42	16.05 ± 0.70	7.95	66.87 ± 4.30	0.97

intra-ply woven hybrid composites, their modes of damage, and failure behaviour under different energy levels which are vital to select an appropriate material for a specific application.

Table 4 shows the results of the impact test for carbon composite samples. ***Figure 2*** shows load-time curves at 18 and 24 J energy levels for 100% carbon composites, and ***Figure 3*** shows those for hybrid composites. The 18 J energy level can be termed as the puncture initiation level for carbon composites. According to the results of preliminary tests conducted, the surfaces of the samples were damaged severely but not perforated completely at energy levels below 18 J. At the 24 J energy level, the samples were perforated completely. Characteristics of the curves obtained from the results of tests conducted at the 18 J energy level were fairly similar. The load decreased suddenly after reaching a peak. However, unlike other samples, the load did not show a dramatic decrease after the peak load for quasi-UD composites. Damage characteristics of these samples were very different from those of the others. After the puncture, it was observed that fibre bundles and threads were split off and delaminated along the fibre direction (***Figure 4.c***). This event changed the characteristic of load-time curves significantly. Of note was a sudden increase observed in the initial portions of the load-time curves for all samples at the 18 J energy level. However, this feature was not seen in the load-time curves obtained for the 24 J energy level. The load level of this sudden increase was around 1250 – 1300 N for hybrid composite samples and around 800 – 1000 N for 100% carbon composite samples. This phenomenon can be explained by the elastic behaviour of composite materials against impacts. The load of the sample increased suddenly at the first

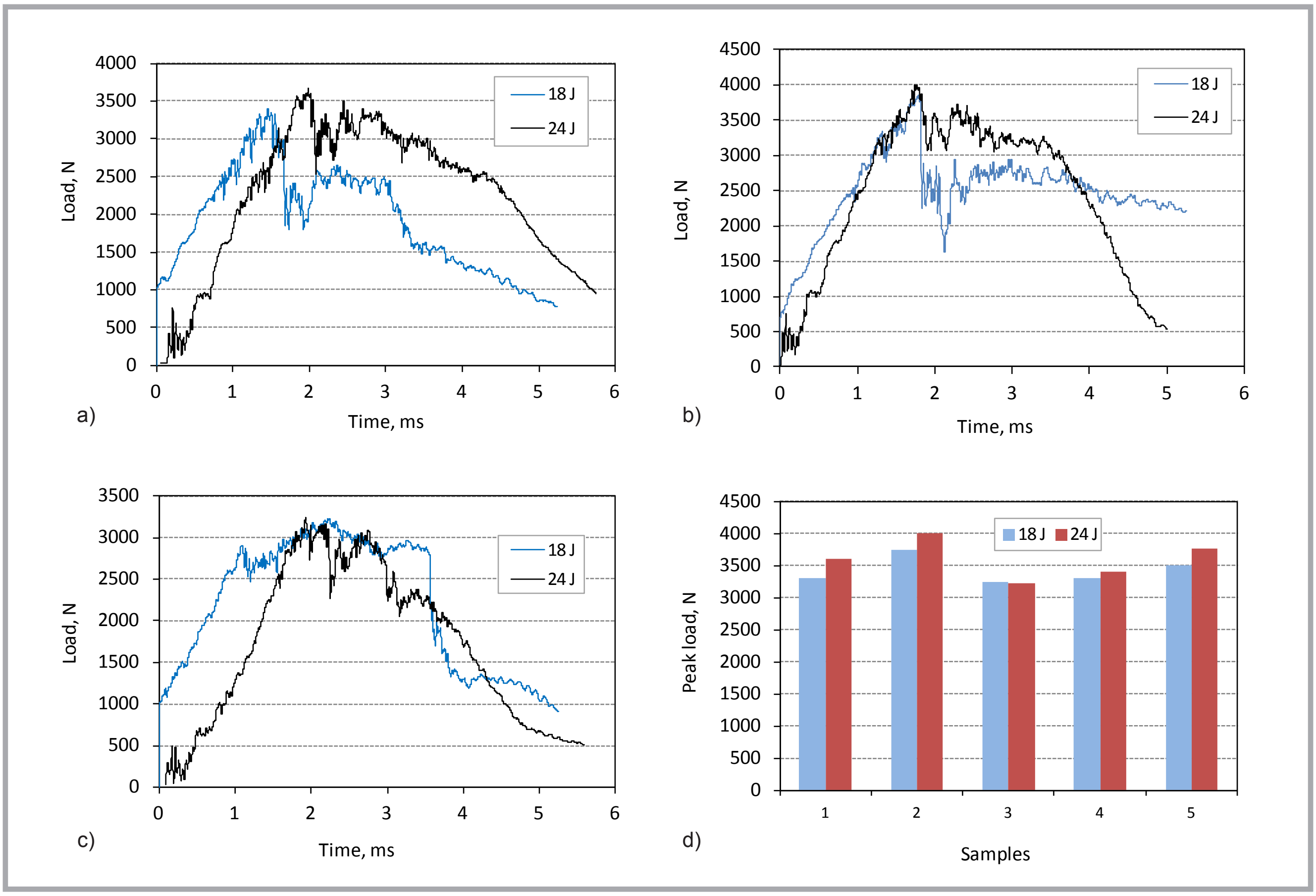

Figure 2. *Typical impact load–time curves of different carbon composites for 18 and 24 J impact energies: (a) sample A; (b) sample B; (c) sample C; and (d) peak load of samples for different impact energy levels.*

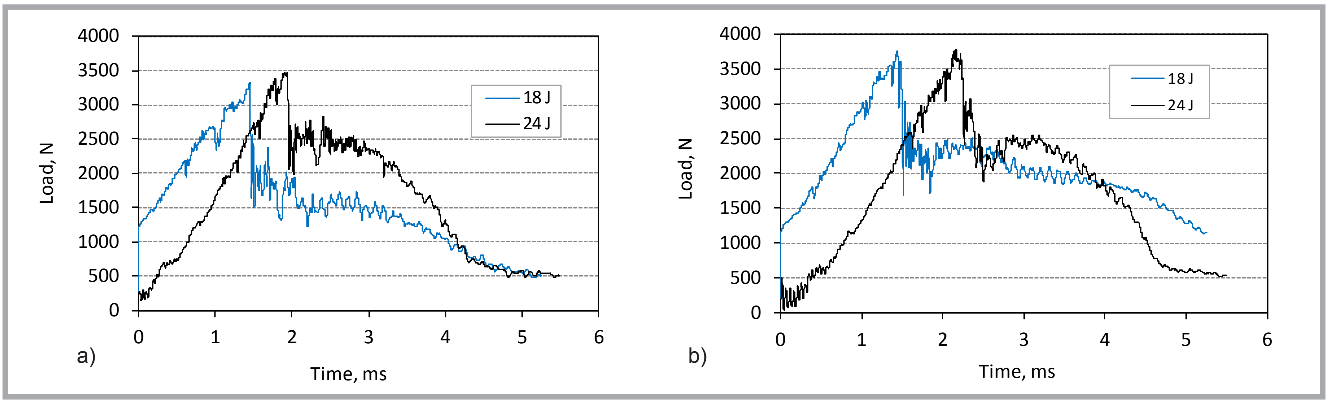

Figure 3. *Typical impact load–time curves of hybrid composites for 18 and 24 J impact energies: a) sample D and b) sample E.*

touch of projectile, without any deformation. The elastic load level increased significantly with aramid fibre reinforcement. Around the peak load, significant oscillation was observed in the curve, indicating matrix and fibre fractures. A sudden decrease in the peak load indicates that the samples were punctured and a significant amount of fibre – matrix delamination occurred around the impact point.

Load-time curves corresponding to the 24 J energy level are slightly different from those obtained for 18 J. Firstly no sudden increase was observed at the beginning of the load-time curve at this energy level. The curve was found to have oscillation even at the beginning. This condition indicates that the impactor initiated the damage as soon as it hit the sample surface. Oscillations in the curve increased significantly around the peak load, indicating the occurrence of severe damage. A sudden decrease in the peak load indicates a complete puncture at this point.

Damage patterns of the samples at 18 J are shown in ***Figure 4***. According to ***Figure 4***, plain weave sample A was perforated completely; however, damage was limited to the impactor diameter, indicating that impact energy did not propagate to the surface of the sample. Characteristics of brittle damage, fibre fractures, and delamination among fibres were observed around the impact point. Twill weaving sample B was not perforated completely, although it had serious damage at the 18 J energy level. However, fibre and matrix fractures and delamination were observed on both the upper and lower surface. In sample B, the damage was limited to the impact point and the energy did not propagate to a wider surface. The damage characteristic of quasi-UD weaving sample C were very different from that of the others. While there is a quite fragile puncture on the front surface of the sample, the splitting through of fibres was observed in the last layer of the lower surface of the sample. Layer stacking in the production of the sample was carried out at 0 - 90º since the fibre in the fabric for sample C was only one directional. This stacking sequence prevented the complete splitting of the samples. If the layers had been ranged in only one direction (like 0º), it would be irreversible for the sample to be separated through the fibre. The separation of fibres in the last layer resulted in the formation of a longer plateau region in the load-time curve of sample C when compared to other samples. However, despite its higher mechanical properties, the peak load value of sample C was lower than that of other samples because of its brittleness.

Damage patterns of the hybrid composites were very similar to those of the 100% carbon samples. The damage on the back surface of sample D indicates that perforation just started at 18 J. No matrix delamination was observed around the impact point, indicating that impact energy did not propagate to the sample surface. Similar features were also observed for sample E. Fibre and matrix fractures were observed together with perforation that started to occur around the impact point.

The damage features, discussed above, that occurred at the 24 J energy level were similar to those occurring at 18 J (***Figure 5***). At the 24 J energy level, perforation just started in twill weave sample B, whereas other samples were perforated completely, with the tip of the impactor reaching the reverse side of the samples. Severe fibre bundle delamination was observed on the back surface of the UD sample.

Peak load values belonging to different samples are given in ***Table 4***. As is evident from the table, no significant differences were observed in the peak load values achieved at 18 J and 24 J energy levels. However, complete perforation of samples by the impactor occurred at the higher energy level. According to the peak load values listed in ***Table 4***, the highest value was achieved for sample B. The peak load results of samples A and C were quite similar. Among the hybrid samples, twill weave sample E showed the best result with respect to peak load values. Peak values were found to decrease slightly for hybrid samples compared to 100% carbon samples. No significant difference was observed between samples A and D at the 18 J energy level in terms of peak loads, but sample D showed a decline of around 5.5% compared to sample A at the 24 J energy level. In the same way, sample E showed declines of around 6.4 and 5.8% at the 18 and 24 J energy levels, respectively, compared to sample B. A comparison of peak values for all samples is given in ***Figure 2.d***.

An examination of the displacement values given in ***Table 4*** revealed no meaningful variation in 100% carbon composites with respect to the weaving structure. However, as a result of hybridisation, a significant variation was observed in displacement values. According to the results obtained, displacement values of samples D and E showed an increase of around 18 – 29% when compared to samples A and B, depending on the energy level; especially for the 24 J energy level, displacement values increased significantly. This indicates that aramid fibre reinforcement increased the tough-

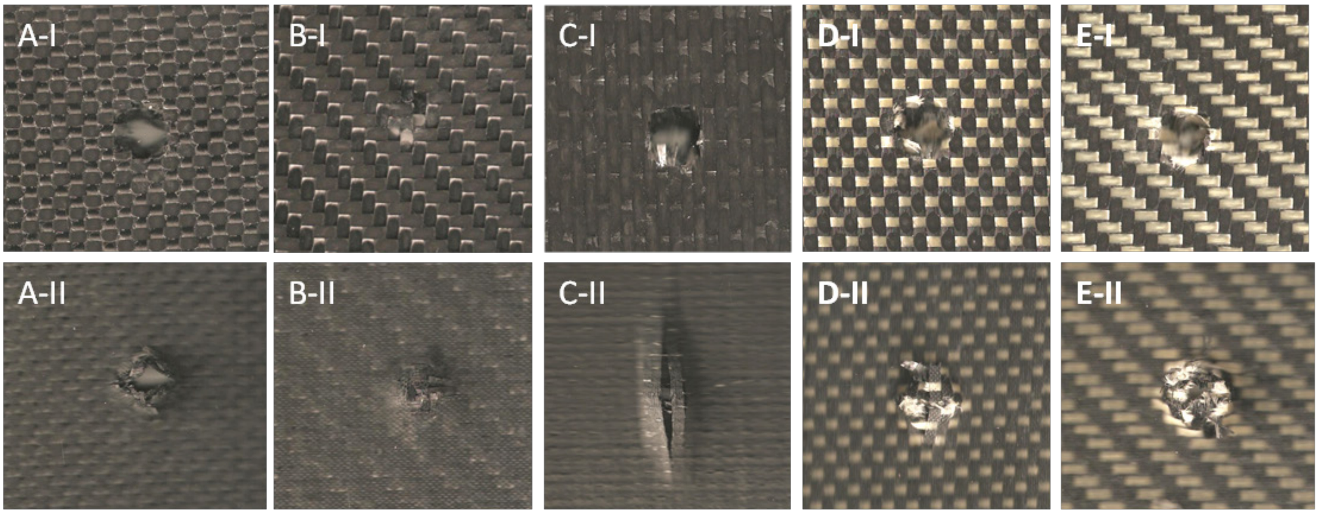

Figure 4. *Pictures of damages occurring at the impact locations on top (I) and bottom (II) surfaces of composite samples for 18 J impact energy (A, B, C, D, and E indicate sample codes).*

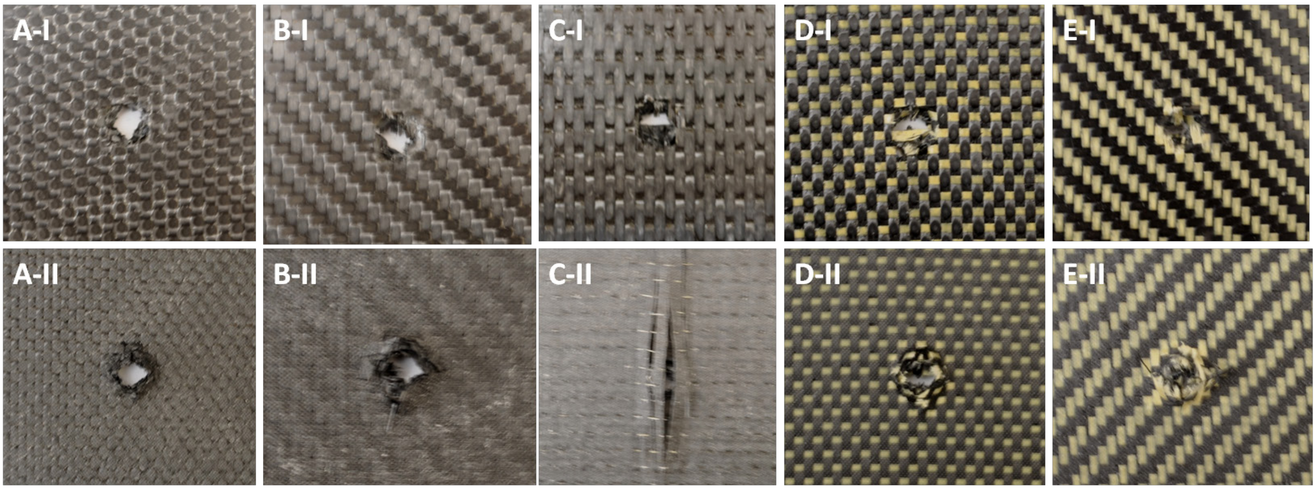

Figure 5. *Pictures of damages occurring at the impact locations on the top (I) and bottom (II) surfaces of composite samples for 24 J impact energy (A, B, C, D, and E indicate sample codes).*

ness of the composite and as well as the energy absorption capacity, which can be explained by the high ultimate elongation of aramid fibres [24, 25].

The mechanical properties under the uniaxial tensile loading of carbon and carbon–aramid hybrid composites were defined in a previous study [8]. According to the results obtained, the highest values were achieved for the quasi-UD composite sample. The samples used in the present study were identical to those used in the previous study [8] in terms of fibre volume fraction and plate thickness. In the present study, the lowest peak load and displacement values under impact loading were obtained for the quasi-UD composite sample. The peak load and displacement values of plain and twill woven fabric reinforced composites were relatively high. However, the quasi-UD composite sample exhibited inferior impact properties, although the mechanical properties were pretty satisfactory. The main reason for this condition is the brittle structure of the quasi-UD sample. Hybridisation was found to improve the impact response of composite samples significantly. In hybrid samples, a significant increase in displacement values was achieved without a significant decline in the peak load, as compared to 100% carbon samples. Therefore the energy absorption capacities of the samples are expected to increase with hybridisation.

Energy absorption properties

The amount of impact energy absorbed was calculated using ***Equation 1***. ***Figure 6.a*** shows the relationship between the total impact energy, absorbed energy, and elastic recovery energy. The absorbed energy during impact is given in ***Table 4. Figure 6.b*** shows a comparison of the percentage of absorbed energy for all samples. Among the 100% carbon composite samples, sample A showed the highest amount of energy absorption. The absorption of energy by sample A was more than that by samples B and C by 26 and 38%, respectively, at the 18 J energy level, and by 7 and 61%, respectively, at the 24 J energy level. At the 18 J energy level, less energy was absorbed by sample B as it was not perforated and the impactor rebounded. At the 24 J energy level, both samples were punctured, and hence it is more appropriate to compare the values corresponding to this energy level. For 24 J, no significant difference was observed between the amounts of energy absorbed by samples A and B. However, results show that energy absorption by sample C was significantly low.

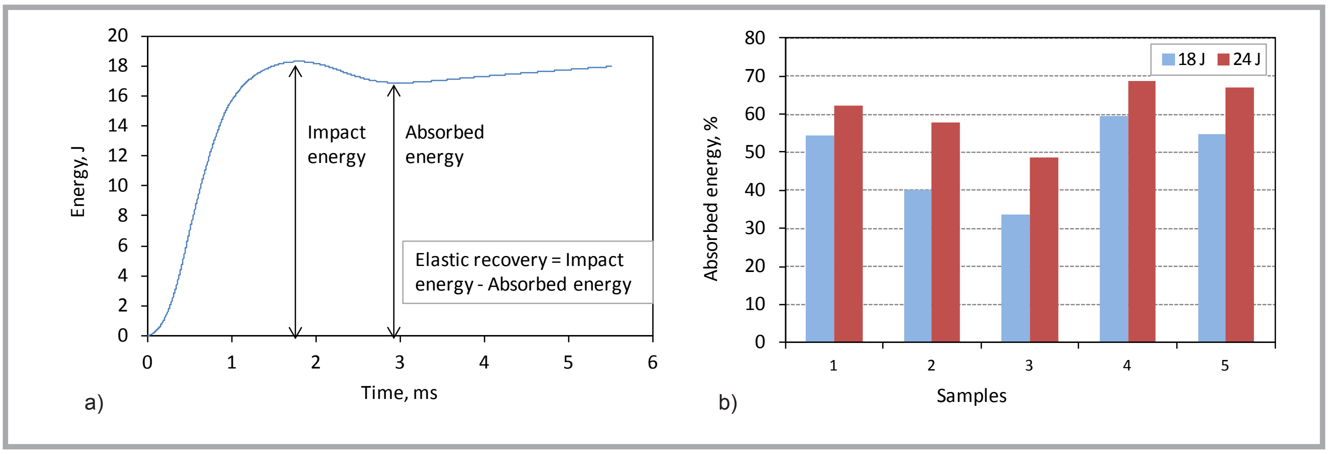

Figure 6. (a) Typical energy–time curve and the relationship between elastic recovery energy, absorbed energy, and total impact energy. (b) Percentage of energy absorbed by different samples at the 18 and 24 J impact energy levels.

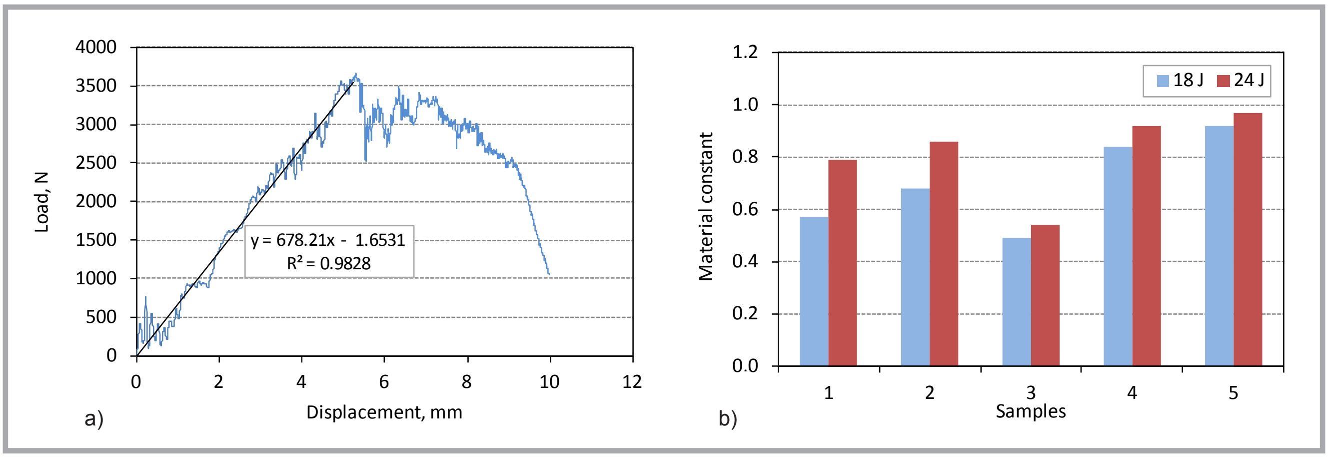

Figure 7. (a) Slope of load-displacement curve and (b) material factor of different samples for 18 and 24 J impact energy.

Energy absorption by composite samples was found to increase significantly with hybridisation. Energy absorption by sample D was 9 and 9.6% more at the 18 and 24 J energy levels, respectively, than that by sample A, despite both samples having the same weaving construction. Energy absorption by sample E was higher than that of sample B by around 54% and 14% at the 18 and 24 J energy levels, respectively. This substantial difference in energy absorption at the 18 J energy level can be attributed to the fact that sample B was not perforated completely at this level, leading to significantly reduced energy absorption or high elastic recovery. Thus the energy absorption capacity can be expected to increase by around 9%–10% with hybridisation, which can be explained by the well-known high energy absorption characteristics of aramid fibres [2, 3].

The above-mentioned results have shown that energy absorption features of laminate composites are considerably low compared to sandwich composites [26], which can be explained by the fact that in laminate composites the propagation of impact energy to the sample surface is low. Damage patterns shown in ***Figures 4*** and ***5*** prove that damage occurred only around the impact point and did not progress to the sample surface.

Material factor

The aforementioned data are not sufficient to explain the effect of the weaving structure and hybridisation on the impact behaviour of samples. Thus evaluation of the bending stiffness of composite samples would be more useful. The following formula can be used to derive the relationship between the peak load and bending stiffness [27]:

$$F_{max} = \sqrt{E \cdot S_b \cdot c} \qquad (2)$$

Here F_{max} is the maximum load, E the total impact energy, S_b the bending stiffness, and c a coefficient that changes depending on the weaving structure and fibre type. F_{max} values can be obtained experimentally and are given in ***Table 4***. S_b values, on the other hand, can be estimated from the slope of the initial part of the load–displacement curve (***Figure 7.a***). According to this correlation, the relation between F_{max} and S_b values depends on factor (c), which changes depending on material properties.

The c values obtained using ***Equation 2*** are given in ***Table 4***. These data are quite useful for comparing the impact behaviours of composites that are obtained from different woven fabrics. The best result among the three different carbon fabrics was obtained for sample B, which was produced from a 2 × 2 twill woven fabric. Sample B had 16 and 28% higher material constant values than samples A and C, respectively, at 18 J, and moreover it had 8.2 and 32% higher material constant values than samples A and B, respectively, at 24 J. In can be concluded that, in this case, the best fabric construction is 2 × 2 twill with respect to impact response, and the UD fabric structure is definitely not an appropriate choice due to its excessive brittleness under impact loads.

The effect of hybridisation on the impact behaviour was examined and more interesting results were obtained when they were evaluated with the material factor. At 18 J, sample D had a 32% higher material constant value than sample A. Again at 18 J, sample E had a 26% higher material constant than sample B. At the 24 J energy level, sample D had a 14% higher constant value than sample A, and sample E had an 11% higher value than sample B. This study shows that through proper fabric construction and hybridisation, the impact resistance of the composite structure can be improved and adjusted to different performance levels.

Conclusions

In this study, the impact behavior of 100% carbon and carbon–aramid hybrid composites was investigated experimentally; the results are as follows:

- With respect to the impact response, 2 × 2 twill weaving was found to represent a better weaving structure than plain fabric.
- 2 × 2 twill woven fabric composites have higher peak loads. The peak load for hybrid composites decreases by 5.5 – 6.5% compared to 100% carbon composites.
- No considerable differences in displacement values were noted among 100% carbon composite samples; however, for hybrid composites these values increased by around 18 – 29% compared to 100% carbon composites.
- It was discovered that 100% carbon composites are quite limited in their energy absorption capacity; however, this was found to improve by about 9 – 10% via hybridisation.
- Whereas peak load coefficients were found to vary from 0.49 to 0.87 for 100% carbon composites depending on bending stiffness, they range from 0.84 to 0.97 for hybrid composites. This results show the effect of hybridisation on the impact response.

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