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Ballistic impact behavior of the aramid and ultra-high molecular weight polyethylene composites

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Abstract

This paper presents the experimental study of fiber type, fabric structure, orientation of fabric plies and thickness on the ballistic impact behavior of aramid and ultra-high molecular weight polyethylene (UHMWPE) composite laminates. Aramid composite laminates are reinforced by three kinds of fabric structures and UHMWPE composite laminates are reinforced by two kinds of fabric structures. The laminates are fabricated via autoclave curing process. The ballistic behavior of composite laminates is evaluated by ballistic limit velocity, and energy absorbed at ballistic limit. Through a series of ballistic tests, it is demonstrated that unidirectional composite laminates exhibit higher ballistic limit velocity and energy absorption on unit weight basis compared to other laminates. Interesting results are shown by UD-UHMWPE-H62® and UD-UHMWPE-Endumax® fabric-reinforced laminates. Orientation of fabric plies is found to have insignificant effect on ballistic behavior irrespective of material type. A bi-linear relationship is found between the ballistic limit velocity, energy absorption and specimen thickness.

Keywords

Composite laminates, ballistic limit velocity, ballistic behavior, autoclave process, aramids and ultrahigh molecular weight polyethylene

Introduction

Fiber reinforced polymer composites have progressive applications in different engineering fields owing to their inherently superior mechanical properties such as strength, stiffness and light weight than conventional metals.[1] Apart that, their properties and form can also be designed to meet the needs of a specific application. One of the main application areas of these composites is the ballistic protection. The ballistic performance of a composite panel is defined as ‘‘the energy absorption capability of a composite structure during a ballistic impact’’.[2] Composite laminate resists the penetration of projectile by absorbing its kinetic energy during a ballistic impact event. The ballistic performance of a target material is often determined by the ballistic limit velocity V_{50}, of projectile. It is defined as ‘‘the velocity at which 50% of projectiles perforate the target’’.[3] Ballistic limit is an important parameter for designing a composite structure and understanding its dynamic damage behavior in order to effectively utilize it as a protective structure. It is a widely recognized criterion for assessing the efficiency of armors.

Apart from the testing parameters, the contents and the characteristics of reinforcing fiber, geometry of the reinforcement, thickness of composite panel, stacking sequence of layers, hybridization of different reinforcing materials and properties of the matrix are among the major parameters which affect the ballistic impact behavior and ballistic limit velocity of composites.[4]

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The failure modes of Spectra® woven and angle-plied unidirectional fabric reinforced composite laminates were examined under ballistic impact loading by Lee et al.[5] At low areal density, both laminates showed similar ballistic limits. However, the differences in ballistic limits became more apparent as the areal densities of laminates increased. Ballistic impact behavior of plain weave E-glass/epoxy and twill weave T300 carbon/epoxy composites has been studied.[6] It has been observed that, for identical ballistic impact conditions, ballistic limit is higher for E-glass/epoxy than for T300 carbon/epoxy. The ballistic limit of Spectra®/vinyl ester composite has been reported higher than Spectra®/polyurethane composite at a given striking velocity in another study.[5]

Prosser[7] measured V_{50} of fabric laminates by varying the number of layers and revealed that a linear relationship exists between the square of V_{50} and the number of layers, as long as the energy absorption mechanisms remain the same. Cunniff[8] studied the fabric targets with varying number of layers and discovered that, at velocities well above the V_{50}, the layers nearest the strike face have a very small effect on energy absorption as they fail almost immediately under the high initial strain. Larsson and Svenson[9] conducted a comprehensive research in which the effect of hybridization on the ballistic performance of hybridized compliant armor systems using various combinations of carbon, Dyneema® and PBO fibers, was investigated. The performance of laminates composed entirely of either Dyneema® or PBO was first obtained and then compared against the performance of laminates where different percentages of Dyneema® or PBO fibers were replaced with corresponding amounts of carbon fibers. It was found that by using approximately 50% carbon fibers on the impact face of the laminates (i.e. replacing 50% of the Dyneema® or PBO), the ballistic limits were essentially the same as the corresponding laminates containing 100% Dyneema® or PBO. Ballistic limits were improved when 25% carbon fiber was used on the impact surface. Pandya et al.[10] studied the ballistic impact behavior of hybrid composites made using plain weave E-glass fabric, 8H satin weave T-300 carbon fabric and epoxy resin. It was observed that ballistic limit velocity, V_{50}, can be increased for the composites by adding E-glass layers to T300 carbon layers compared with only carbon composites for the same laminate thickness. Placing E-glass layers in the exterior and carbon layers in the interior provides higher ballistic limit velocity than placing carbon layers in the exterior and E-glass layers in the interior.

Different models can be found in literature to predict the ballistic limit velocity of fabrics[11] and composite laminates.[12–14] Mamivand and Liaghat[15] developed an analytical model to study the effect of layer spacing on target performance of multi-layer two-dimensional woven fabrics. It has been concluded that the ballistic limit for constant number of layers, when increasing layer spacing would decrease upto a specific distance between layers (named as layers decoupling threshold) and further increase in gap between layers did not have any effect on the performance of target. Mohan and Velu[16] developed a modified analytical model for unidirectional composites subjected to ballistic impact. They concluded that damage area of composite panel is smaller at velocities lower than the ballistic limit velocity and impact response become more localized resulting in less damage area at velocities higher than the ballistic limit velocity. Morye et al.[17] studied the energy absorption behavior of polymer composites upon ballistic impact and developed a model by combining the parameters; tensile failure of primary yarns, elastic deformation of secondary yarns and kinetic energy of moving target cone to determine the ballistic limit of composites. The model was found in good agreement with the experimentally determined ballistic limit values. The primary yarns are those in contact with the impactor (projectile) whereas secondary yarns are those displaced by the deformation of the primary yarns.[18]

The ballistic impact behavior of multi-layer Kevlar® aramid fabric/polypropylene composite laminate (CL) and plain layered aramid fabric (AF) specimens was investigated.[19] It was found that the thermoplastic PP matrix increases the ballistic performance of CL targets when compared to AF targets with similar areal density, resulting in less aramid fabric needed to obtain the same level of protection when the PP matrix is incorporated, thus resulting in weight saving and lower costs. Othman and Hassan[20] investigated the effects of different textile designs of aramid fabrics on their ballistic performance and found that the cross-ply laminated aramid construction exhibited better ballistic performance in terms of higher energy dissipation and minimum layer of projectile arrest upon impact.

The high-performance fibers such as para-aramids and ultra-high molecular weight polyethylene (UHMWPE) are known for their high resistance-to-impact damage.[21–24] Twaron® (a registered trademark of Teijin), Kevlar® (a registered trademark of DuPont), Dyneema® (a registered trademark of DSM) and Spectra® (a registered trademark of Honeywell) are among the well-known high-performance fibers. These fibers have many desired engineering properties such as high strength, high modulus, light weight and good chemical resistance.[25–27] The high toughness and damage tolerance of these fibers also help in better ballistic performance of composites reinforced with them.

The aim of this study is to compare the ballistic limit velocity and energy absorbed by the composite laminates reinforced with aramid and UHMWPE fabrics. Three fabric structures of aramid (woven, biaxial and unidirectional) and two (unidirectional and unidirectional tape) of UHMWPE are used as reinforcement.

Materials and methods

Materials

Five different ballistic fabrics, whose properties are given in Table 1, were used as reinforcement and nolax A21.2007 low-density polyethylene (LDPE) adhesive film (density $0.94\,g/cm^3$, melting temperature 80–90°C and melt flow rate of 6–9 g/10 min) was used as a matrix system. The properties of fibers, which were used in the preparation of reinforcement structures, are given in Table 2.

Composite manufacturing

The ballistic fabrics were cut to size of 50 cm × 50 cm and composite laminates were prepared, with same number of fabric layers and different panel thickness, different fabric layers and same panel thickness, different orientation of fabric layers and same panel thickness and different number of fabric layers and different panel thickness, using the autoclave process. The temperature of the process was kept to 110°C and the pressure of the vacuum to 14.8 bar. Figure 1 shows the different stages of manufacturing process. The fiber volume fraction (V_f) of all composite panels was calculated using the following formula

$$v_{f=}\frac{n.m}{\rho.h} \tag{1}$$

where n is the number of fabric plies, m is the fabric areal weight, ρ is the fiber density and h is the panel thickness. V_f values of hybrid samples were calculated for each reinforcement separately.

Ballistic testing

The ballistic performance of composites was assessed by measuring their ballistic limit velocity i.e. V_{50} according to MIL-STD-662 F test method, V_{50} per composite areal density AD, energy absorbed (Ea) at ballistic limit and Ea per composite areal density. The energy absorption was calculated by using the following equation

$$Ea = 0.5\,m\,(V_{50})^2 \tag{2}$$

Table 1. Properties of reinforcements used in the study.

Reinforcement type	Reinforcement code	Reinforcement producer	Weave type	Linear density of Warp/Fill yarns, Tex	Warp/Fill (or 0°–90°) yarns	Thread density, threads/10 cm	Areal density,g/m^2	Crimp Warp/Fill, %	Reinforcement thickness, mm
Aramid woven fabric-CT736	R_1	Teijin	2 × 2 Basket weave	336/336	Twaron 2000/Twaron 2000	127/127	410	0.8/0.8	0.6
Aramid Bi-Axial non-crimp fabric-XA450	R_2	Seartex	Bi-axial non-crimp	336/336	Twaron 2000/Twaron 2000	127/127	465	Non-crimp	0.40
Aramid UD sheet-GS3000	R_3	FMS	UD	126/126	Kevlar 49/Kevlar 49	–	510	Non-crimp	0.50
UHMWPE UD sheet-Dyneema H62	R_4	FMS	UD	176/176	Dyneema SK62 / Dyneema SK62	–	240	Non-crimp	0.25
UHMWPE-Endumax	R_5	Teijin	UD	Tape yarn/Tape yarn	Endumax TA 23/Endumax TA 23	–	199	Non-crimp	0.18

Table 2. Parameters of the aramid and ultra-high molecular weight polyethylene (UHMWPE) fibers used in the study.

Parameters	Twaron 2000® (Aramid)	Kevlar 49® (Aramid)	Dyneema SK62® (UHMWPE)	Endumax® TA 23 (UHMWPE)
Young modulus, GPa	85	112	113	125
Strength, cN/Tex	235	208	338	280
Ultimate elongation, %	3.5	2.4	3.6	1.5–2
Density, g/cm^3	1.44	1.44	0.97	0.97
U^*[28]	2194.177	1528.656	6769.722	2949.157

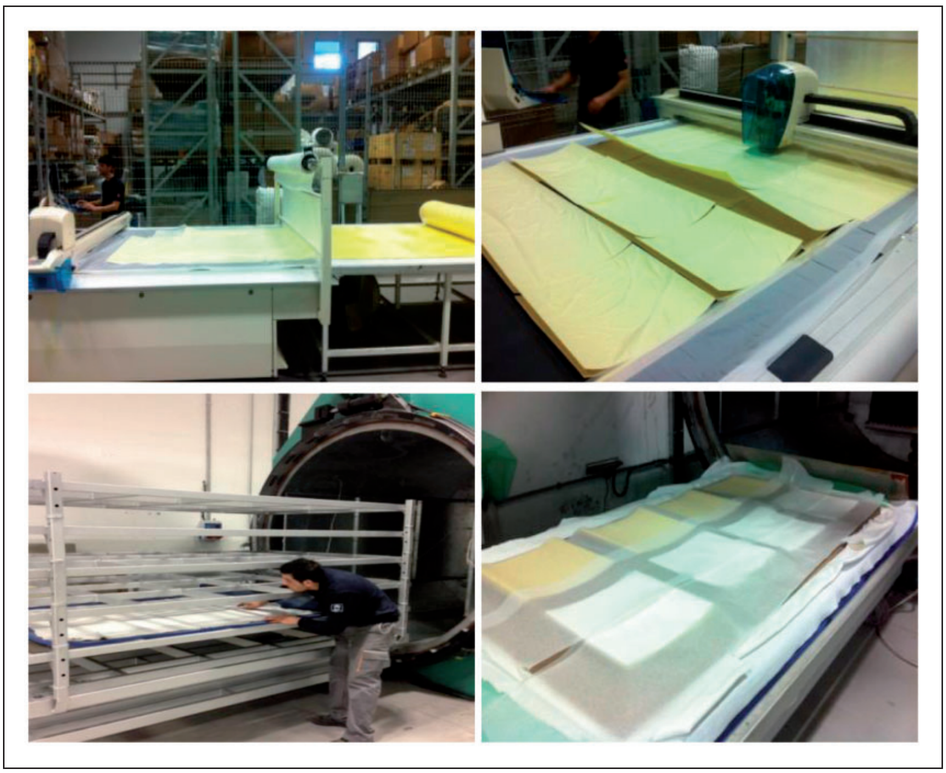

Figure 1. Different stages of composite manufacturing process.

where V_{50} is the ballistic limit and m is the mass of projectile. The ballistic testing apparatus is shown in Figure 2(a). The ballistic test was performed using 7.5-mm diameter, 9-mm long, 2.93 g special type of projectile (shown in Figure 2(b)). A projectile, which passes through the panel or causes material to be thrown off the back of the panel, is considered to be a complete penetration. All other impacts are defined as being partial penetrations. The V_{50} for a panel is defined as that velocity for which the probability of penetration of the projectile is exactly 0.5. After obtaining a partial and a complete penetration, the propellant increment or decrement of 15 m/s was practised.

After a number of projectiles have been fired, the V_{50} was calculated as the mean of equal number of (generally three shoots) highest partial penetration velocities and lowest complete penatration velocities.

V_{50} ballistic limit is a statistical test originally developed by the US military to evaluate hard armor. Fundamental to the concept of ballistic limit is a relationship between the probability of penetration of the armor and the striking velocity of the projectile. The projectile-armor relationship satisfies the mathematical conditions of probability distribution i.e. for low velocities probability approaches zero; for high velocities the probability approaches one and between those extremes of velocity, the probability increases with the increase of velocity. When the general model describes physical behavior, the probability of penetration can be treated as a probability distribution and is usually described as a Gaussian or normal distribution. The normal distribution curve has been found to give a reasonably good representation of the probability of penetration in many cases. One-way analysis of variance (ANOVA) was done using the SPSS statistical software package.

Results and discussion

Effect of material type

Table 3 shows the details of composite laminates produced from different reinforcements. Same numbers of fabric layers (24 layers) were used in each composite panel. Since all reinforcing fabrics have different areal density and thickness, the areal density and thickness of all laminates is different based on same number of fabric layers. The composite laminates with greater areal density and thickness have higher V_{50} and absorbed greater energy of projectile as shown in Figure 3. The LP_3 composite panel reinforced with UD aramid-GS3000 shows the highest V_{50} and Ea values because of its greater thickness and areal density. LP_3 panel has 18.10% higher V_{50} and 32.93% higher Ea than the panel reinforced with aramid CT736 and 25.03% higher V_{50} and 43.80% higher Ea than the panel reinforced with UHMWPE-Endumax® sheet. In order to see the effect of different material types on ballistic performance, it is better to compare the V_{50}/areal density and Ea/areal density of composites. It is clear that V_{50}/areal density and Ea/areal density of composites reinforced with UD-UHMWPE fabrics is higher than those reinforced with UD and woven aramid fabrics. The hierarchy of V_{50}/areal density and Ea/areal density of composites is as follows

$$V_{50}/\mathrm{AD} \quad LP_5 > LP_4 > LP_2 > LP_1 > LP_3 \tag{3}$$

$$Ea/\mathrm{AD} \quad LP_5 > LP_4 > LP_3 > LP_2 > LP_1 \tag{4}$$

It is interesting to note that the hierarchies as given in equations (3) and (4) are different. The best results in terms of V_{50}/AD and Ea/AD are shown by the LP_5 composite panel reinforced with UD-UHMWPE-Endumax® sheet which shows 22.88% higher V_{50}/AD and 21.45% higher Ea/AD than UD-UHMWPE-H62 reinforced composite. Furthermore, LP_5 composite shows 47.93% higher V_{50}/AD than LP_3 (UD aramid-GS3000 reinforced) composite and 42.07% higher Ea/AD than LP_1 (aramid CT736 reinforced) composite as shown in Table 3 and Figure 3. It is known that the materials possessing high modulus and low density disperse the strain wave rapidly away from the impact point,[29] and thus distributes energy over a wider area and prevents large strains from developing at the impact point. The high specific toughness of materials along with high modulus and low density also contributes to their better energy absorption and ballistic performance.[28] Both Dyneema® SK62 and Endumax® TA23 have high specific toughness and modulus and

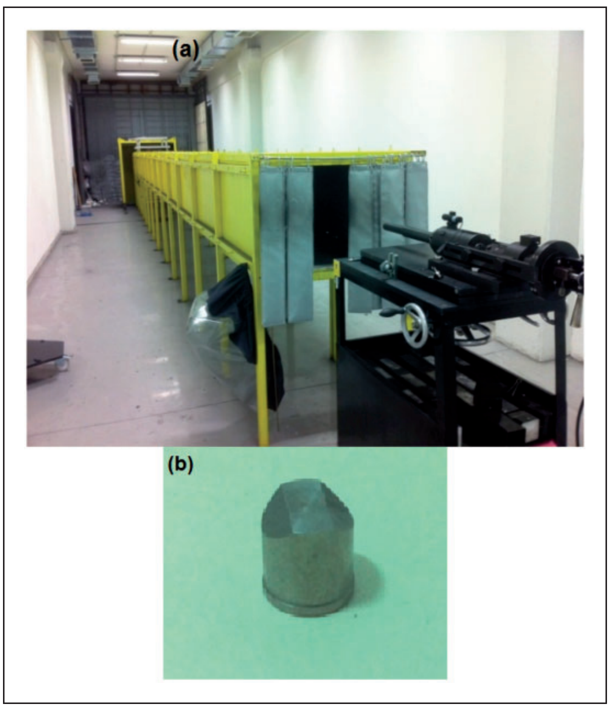

Figure 2. (a) Apparatus for ballisitc testing; (b) projectile used for ballistic testing.

Table 3. Composite laminates produced with same number of fabric layers (24 layers).

Label	Reinforcement	Fabric orientation	Panel thickness, mm	Areal density, kg/m^2	V_f, %	V_{50}, m/s	Ea, J	V_{50}/AD, m^3/kg s	Ea/AD, Jm^2/kg
LP_1	R_1	0°/90°	12.4	9.840	55.1	579.00	491.13	58.80	49.91
LP_2	R_2	45°/−45°	9.20	11.040	53.3	650.00	618.96	58.90	56.07
LP_3	R_3	0°/90°	12.1	12.240	64.2	707.00	732.28	57.80	59.83
LP_4	R_4	0°/90°	6.20	6.312	68.7	540.00	427.19	85.60	67.68
LP_5	R_5	0°/90°	4.25	4.776	70.1	530.00	411.52	111.00	86.16

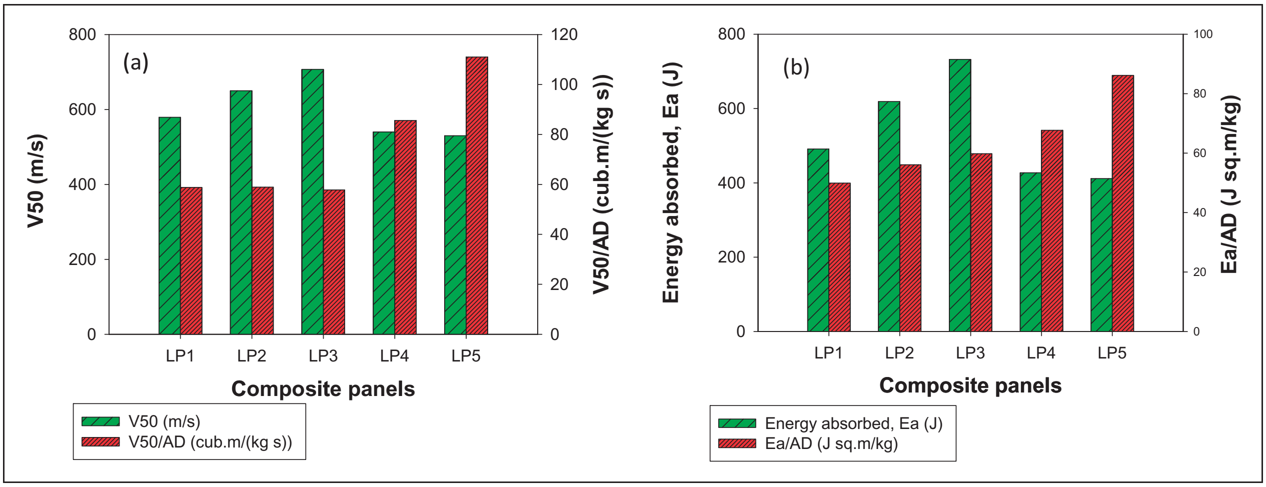

Figure 3. Ballistic behavior of composites reinforced with same number of fabric layers: (a) V50 and V50/AD, and (b) Ea and Ea/AD.

Table 4. Composite laminates produced with same thickness (9.5 ± 0.6 mm) and different ply number.

Label	Reinforcement	Fabric orientation	Fabric ply number	Areal density (kg/m^2)	V_f, %	V_{50}, m/s	Ea, J	V_{50}/AD, m^3/kg s	Ea/AD, Jm^2/kg
LT_1	R_1	0°/90°	25	10.150	54.6	611.00	546.92	60.20	53.88
LT_2	R_2	45°/−45°	24	9.660	54.0	605.00	536.23	62.60	55.51
LT_3	R_3	0°/90°	21	10.710	65.0	707.00	732.28	57.80	59.83
LT_4	R_4	0°/90°	31	8.153	66.4	623.00	568.61	76.40	69.74
LT_5	R_5	0°/90°	44	8.756	68.5	637.00	594.45	72.70	67.89

low density than aramids used in this study. It is also known that UD fabric laminates absorb more energy than woven fabric laminates for unit areal density.[30] These parameters might be contributing factors in the better V_{50}/AD and Ea/AD of UHMWPE reinforced composites laminates. The analysis of variance also revealed a statistically significant effect of material type on V_{50}/AD and Ea/AD with 95% confidence interval ($\alpha \leq 0.05$).

Effect of fabric plies number

Table 4 presents the particulars of composite laminates of similar thickness, reinforced with different number of fabric plies. It is obvious from Table 4 and Figure 4 that LT_3 composite panel reinforced with UD aramid-GS3000 has 13.58% higher V_{50} and 25.31% higher energy absorbed compared to aramid CT736 reinforced panel with the values of other laminates in between. This may be attributed to higher areal density of the fabric as well as the composite panel reinforced with it and UD architecture of fabric. The hierarchy of V_{50}/AD and Ea/AD of composites is as follows

$$V_{50}/\mathrm{AD} \quad LT_4 > LT_5 > LT_2 > LT_1 > LT_3 \qquad (5)$$

$$Ea/\mathrm{AD} \quad LT_4 > LT_5 > LT_3 > LT_2 > LT_1 \qquad (6)$$

It is again interesting to note that the hierarchies as given in equations (5) and (6) are different. V_{50}/AD and Ea/AD of both UHMWPE fabrics reinforced composites is improved than laminates reinforced with aramid fabrics as shown in Figure 5. The best results are shown by LT_4 composite panel which is reinforced with UD-UHMWPE-Dyneema® H62 whose V_{50}/AD is 21.05% and Ea/AD is 22.74% higher than aramid CT736 reinforced panel and 25% and 14.21% higher, respectively, than the panel reinforced with UD aramid-GS3000. The possible reasons for this have already been explained above. The analysis of variance also revealed a statistically significant effect of fabric ply number on V_{50}/AD and Ea/AD with 95% confidence interval ($\alpha \leq 0.05$).

Effect of fabric plies orientation

The information about composite laminates produced with four types of reinforcements with different fabric plies orientations is given in Table 5. All composites have almost the same panel thickness. Two types of orientations of each reinforcement were studied. It can be observed from Table 5 and Figure 5 that ballistic

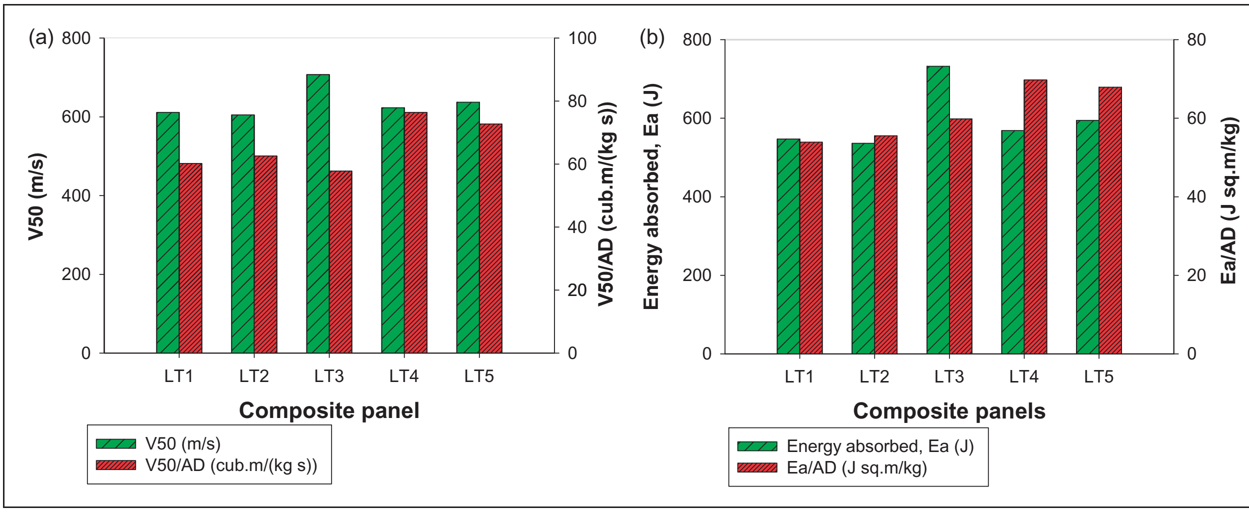

Figure 4. Ballistic behavior of composites reinforced with different number of fabric plies and same thickness: (a) V50 and V50/AD, and (b) Ea and Ea/AD.

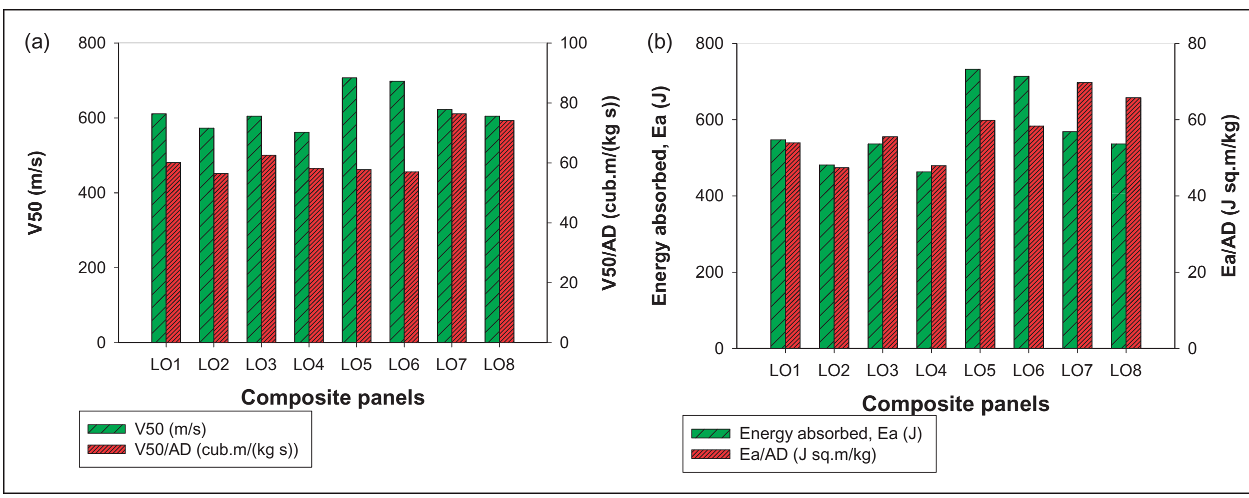

Figure 5. Ballistic behavior of composites reinforced with different orientations of fabric plies: (a) V50 and V50/AD, and (b) Ea and Ea/AD.

Table 5. Composite laminates produced with same thickness (9.5 ± 0.6 mm) and different fiber orientation.

Label	Reinforcement	Orientation of fabric plies	Areal density (kg/m^2)	V_f, %	V_{50}, m/s	Ea, J	V_{50}/AD, m^3/kg s	Ea/AD, Jm^2/kg
LO_1	R_1	0°/90°	10.150	54.6	611.00	546.92	60.20	53.88
LO_2	R_1	0°/90°/45°/−45°	10.150	54.6	573.00	481.00	56.50	47.39
LO_3	R_2	45°/−45°	9.66	54.0	605.00	536.23	62.60	55.51
LO_4	R_2	0°/90°/45°/−45°	9.66	54.0	562.00	462.71	58.20	47.90
LO_5	R_3	0°/90°	12.24	65.0	707.00	732.28	57.80	59.83
LO_6	R_3	0°/90°/45°/−45°	12.24	65.0	698.00	713.75	57.00	58.31
LO_7	R_4	0°/90°	8.153	66.4	623.00	568.61	76.40	69.74
LO_8	R_4	0°/90°/45°/−45°	8.153	66.4	605.00	536.23	74.20	65.77

Table 6. Composite laminates produced with different thickness, different ply number and same fabric orientation.

Label	Reinforcement	Fabric ply number	Panel thickness, mm	Orientation of fabric plies	Total areal density, kg/m^2	V$_f$, %	V_{50}, m/s	*Ea*, J	V_{50}/AD, m^3/kg s	*Ea*/AD, Jm^2/kg
LD$_1$	R$_1$	10	4	0°/90°	5.21	53.8	318.00	148.15	61.00	28.44
		15	6	0°/90°	6.82	53.5	403.00	237.93	59.10	34.89
		20	8	0°/90°	8.02	53.2	498.00	363.33	62.10	45.30
		25	9.5	0°/90°	10.15	54.6	611.00	546.92	60.20	53.88
LD$_2$	R$_2$	12	4.5	45°/ − 45°	5.5	54.1	306.00	137.18	55.60	24.94
		16	6.2	45°/−45°	6.9	53.0	405.00	240.30	58.70	34.83
		20	8.1	45°/−45°	8.0	54.7	483.00	341.77	60.40	42.72
		24	9.5	45°/−45°	9.66	54.0	605.00	536.23	62.60	55.51
LD$_3$	R$_3$	8	3.9	0°/90°	5.7	66.2	398.00	232.06	69.90	40.71
		12	5.9	0°/90°	8.3	67.1	521.00	397.66	62.80	47.91
		16	8.2	0°/90°	10.40	66.2	613.00	550.50	58.90	52.93
		21	9.5	0°/90°	10.71	65.0	707.00	732.28	57.80	59.83
LD$_4$	R$_4$	15	4.6	0°/90°	4.1	67.4	318.00	148.15	77.60	36.13
		20	6.0	0°/90°	5.2	66.8	420.00	258.43	80.80	49.70
		25	8.1	0°/90°	6.55	66.1	516.00	390.07	78.80	59.55
		31	9.5	0°/90°	8.15	66.4	623.00	568.61	76.40	69.77
LD$_5$	R$_3$+R$_4$	6+10	4.7	0°/90°	5.1	67.0	348.00	177.42	68.20	34.79
		8+12	6.1	0°/90°	6.2	66.4	450.00	296.66	72.60	47.85
		10+12	8.3	0°/90°	7.4	67.2	546.00	436.74	73.80	59.02
		10+16	9.5	0°/90°	9.02	67.5	655.00	628.52	72.60	69.68

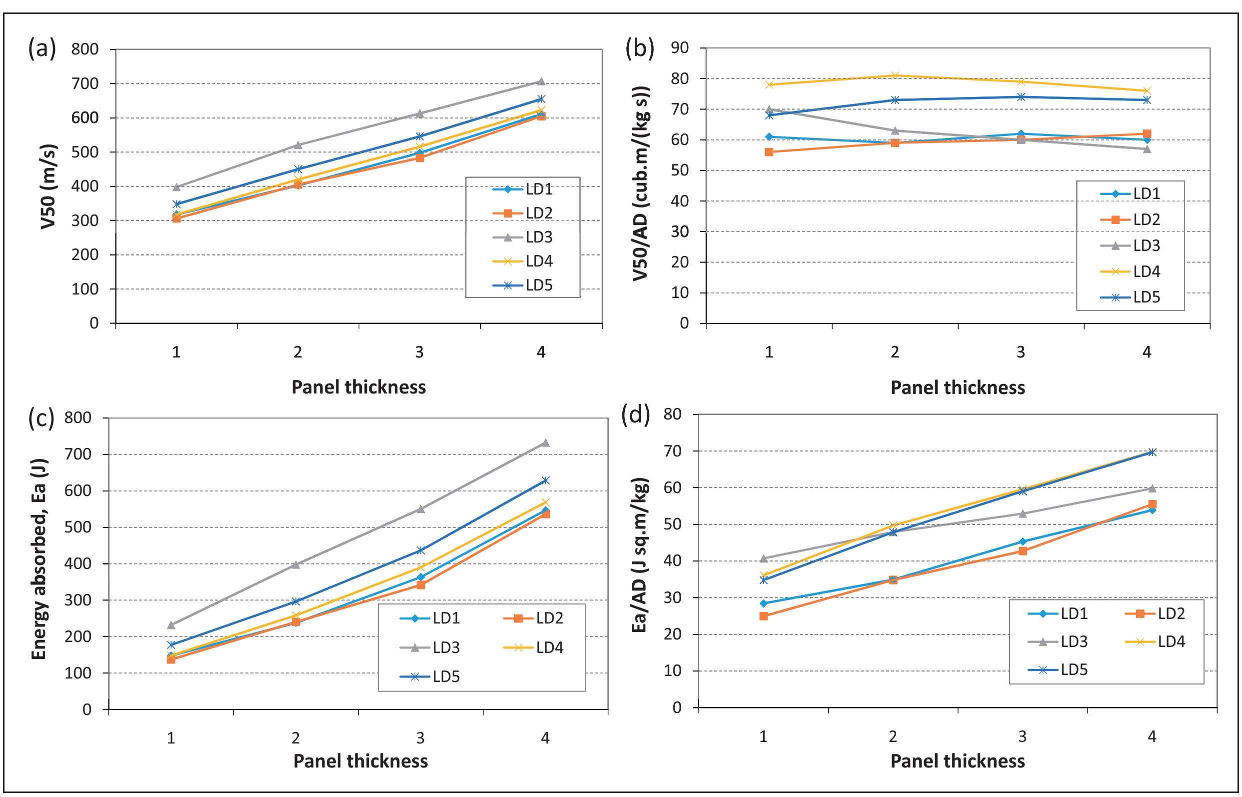

Figure 6. Ballistic behavior of composites with different thickness (a) V_{50} (b) V_{50}/AD (c) *Ea* (d) *Ea*/AD.

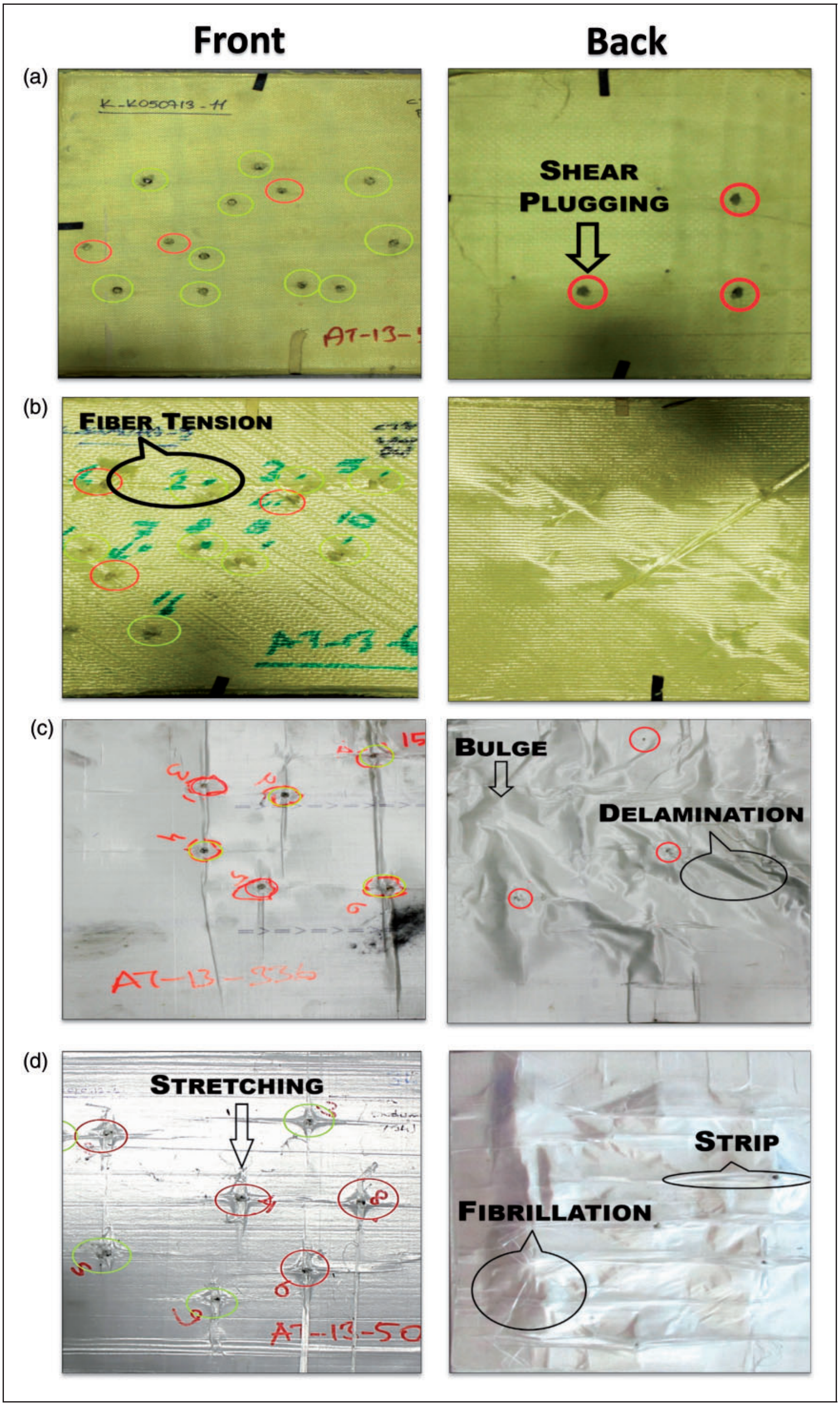

Figure 7. Damage patterns of composite reinforced with (a) aramid CT736 (b) biaxial aramid XA450 (c) UHMWPE-H62 (d) UHMWPE-Endumax®.

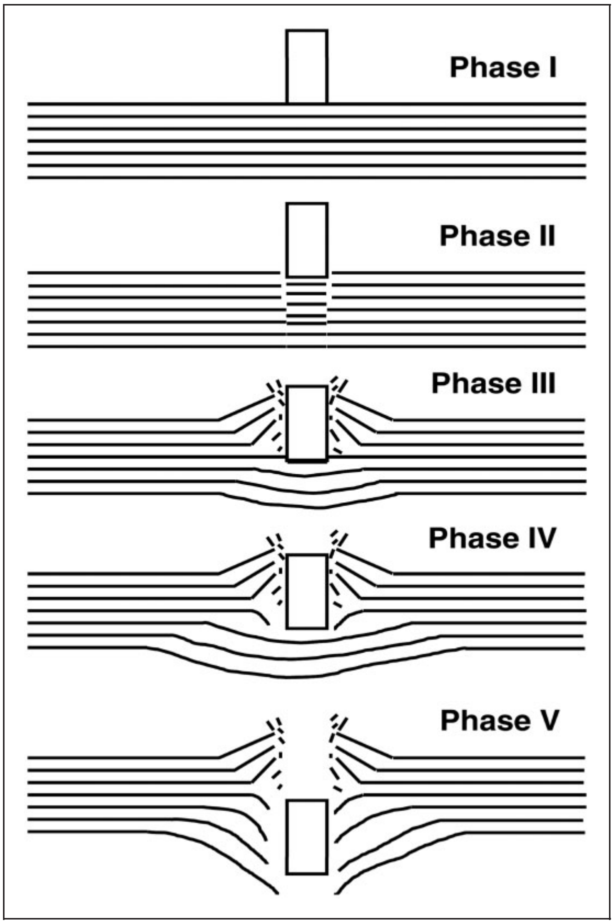

Figure 8. Different phases of projectile penetration in a composite target during ballistic impact.[33]

limit, V_{50}, and energy absorption, Ea, of composites reinforced with UD aramid-GS3000 and V_{50}/AD and Ea/AD of composites reinforced with UD -UHMWPE-Dyneema® H62 sheet are greater than other composite laminates irrespective of their fabric orientations. Moreover, V_{50}, Ea, V_{50}/AD and Ea/AD of composites made with 0°/90° orientation are slightly higher than 0°/90°/45°/−45° orientation for each reinforcement category showing insignificant effect of fabric orientation on ballistic performance. This finding may be explained by the fact that the fabric structural parameters, which are considered dominant in the energy absorption of projectile, are same for each reinforcement category which might result in minor effect of fabric orientation on ballistic limit. The analysis of variance showed statistically no significant effect of fabric orientation on V_{50}/AD and Ea/AD with 95% confidence interval ($\alpha \leq 0.05$). The hierarchies of V_{50}/AD and Ea/AD of composites are also found different.

Effect of composite thickness

Table 6 presents the data of composites prepared with different thickness and different ply number of fabric reinforcements. The orientation sequence of fabric plies is similar in all composite laminates. It can be seen from Figure 6(a), (c) that V_{50} and Ea increase almost linearly with the increase in panel thickness irrespective of the reinforcement type. The same results are also witnessed by Nayak et al.[31] and Nair et al.[32] The increase in target thickness offers more resistance to penetration of the projectile due to different energy absorbing mechanisms, especially the shear plugging, thus leading to higher ballistic limit V_{50} and energy absorption.

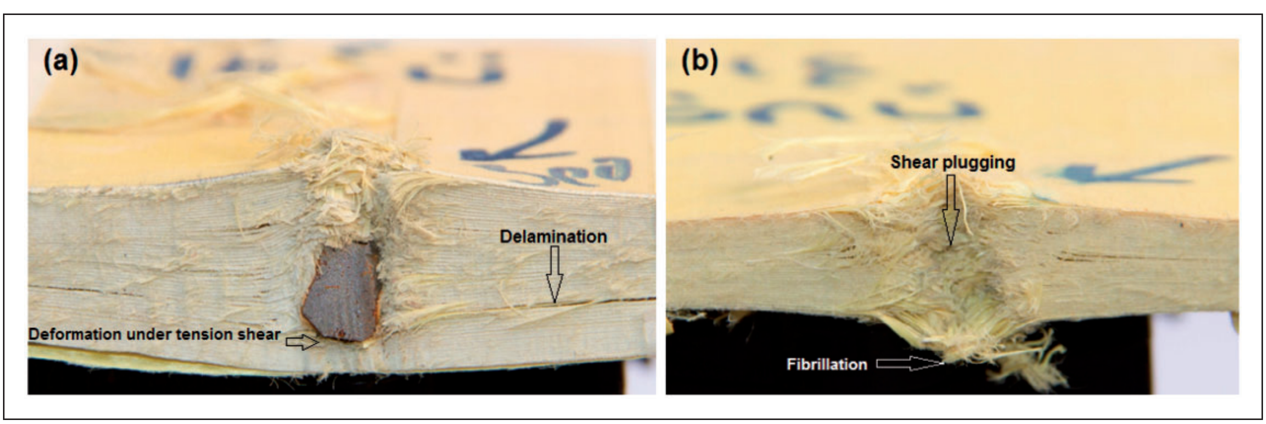

Figure 9. Cross-section view of ballistic perforation of GS3000 UD-aramid reinforced panel (a) partial perforation (b) complete perforation.

The Ea/AD also increases linearly with the increase in panel thickness irrespective of the reinforcement type as shown in Figure 6(d). However, the trend is not similar for V_{50}/AD as shown in Figure 6(b). The analysis of variance exhibited a statistically significant effect of composite thickness on V_{50}/AD and Ea/AD with 95% confidence interval ($\alpha \leq 0.05$).

Damage analysis

Damage patterns due to ballistic impact from the front and bottom sides of the composites reinforced with aramid CT736, biaxial aramid XA450, UHMWPE-H62 and UHMWPE-Endumax® specimens are given in Figure 7. It should be noted that the ballistic impact parameters namely projectile mass and projectile diameter were kept same during the study. It can be observed that the size of damage around the point of impact on front side is larger for laminate reinforced with UHMWPE-Endumax®. The intensity of damage in the inner region is found to be greater than that of the outer region for all the impacted composite laminates. The damage is more localized on the front side of laminates reinforced with aramid CT 736 and biaxial aramid XA450. Different failure modes such as shear plugging, fiber breakage, fiber stretching, bulging, delamination and fibrillation are observed (Figure 7). For a rigid cylindrical projectile, ballistic impact and penetration of a composite laminate can be described in five different phases.[33] These phases are (i) Phase I – Impact–contact and stress wave propagation, (ii) Phase II – Hydrostatic compression and local punch shear, (iii) Phase III – Shear plug formation under compression-shear, (iv) Phase IV – Large deformation under tension-shear and (v) Phase V – End of penetration and structural vibration (Figure 8). The phases III, IV and V can be clearly identified in Figure 9 showing ballistic perforation of composite panel reinforced with GS3000 UD-aramid.

Conclusion

In the current study, experimental investigations were carried out to assess the effects of fiber type, fabric structure, orientation of fabric plies and thickness on the ballistic limit and energy absorption of different composite laminates. Based on our results, following conclusions are made:

- Unidirectional fabrics reinforced composites exhibited higher ballistic limit velocity and energy absorption per unit areal density compared to other laminates.
- Composite laminates with biaxial aramid fabric showed higher ballistic limit and energy absorption per unit areal density than the one with woven aramid fabric.
- Based on same thickness of laminates, UD-aramid GS3000 reinforced composite displayed good ballistic limit and energy absorption than others. However, UD-UHMWPE-H62® and UD-UHMWPE-Endumax® reinforced composite showed good ballistic limit and energy absorption per unit areal density.
- Fabric orientation had insignificant effect on ballistic performance of composites irrespective of reinforcement type.
- A linear relationship was observed between ballistic limit, energy absorption and composite thickness.
- Woven and bi-axial fabric reinforced laminates exhibited localized damages with little delamination. However, unidirectional laminates had large areas of damages, mainly including delamination and bulge.

Conflict of interest

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