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# Influence of hybridization on the performance of glass composites under low and high velocity impact

**T. Sreekantha Reddy, P. Rama Subba Reddy*, V. Madhu**

*Defence Metallurgical Research Laboratory, Kanchanbagh, Hyderabad 500058, India*

*Corresponding author. Tel: (+91) 40-24588021; E-mail: rsreddy@dmrl.drdo.in

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## ABSTRACT

Hybrid composites find applications in many advanced fields that include aerospace and armour due to their high specific strength and high energy absorption capacity. The present study has attempted to develop cost effective E and S2 glass based hybrid composites for armour applications in order to get advantages of both fibres i.e superior impact properties at reduced cost. Three hybrid composites based on E glass and S2 glass in the volume ratios of 75:25, 50:50 and 25:75 were fabricated using epoxy matrix. Low velocity impact (60-110 J energy) experiments using instrumented drop tower on 2 mm thickness laminates show that composites perform better when impacted on E glass strike face than on S2 glass strike face. Hybrid composite made of 25% E glass and 75 % S2 glass (ES 25-75) has shown equal performance to that of 100 % S2 glass/epoxy (S 100) laminate. Ballistic evaluation on 6 mm thick laminates against 7.62 mm mild steel projectile also prove that the performance of hybrid composites increases with increase in S2 glass content and ES 25-75 composite performs similar to S 100 laminate in terms of energy absorption as well as damage volume. Copyright © 2016 VBRI Press.

**Keywords:** Hybrid composites; low velocity impact; ballistic impact; energy absorption; S2 glass.

## Introduction

Composites that are made up of two or more different fibres using same matrix or vice versa are generally termed as hybrid composites. Combining two or more fibres in the same composite is expected to provide performance improvement by utilising merits of individual fibres. In most cases, one of the fibres in hybrid composite is high modulus fibre such as carbon or boron and the other one is low modulus fibre such as glass or aramid. The high modulus fibre contributes to stiffness and load bearing capability while the low modulus fibre makes the composite more damage tolerant. This approach provides balance of strength, stiffness, toughness and weight reduction. This resultant synergistic effect is called 'hybrid effect'. The 'positive hybrid effect' is to obtain a composite property whose value is higher than the value predicted from the rule of mixtures [**1**].

Hybrid composites find applications in many advanced fields such as automobile, aerospace and defence due to their high specific strength and high energy absorption capacity. Characterization of impact properties of these composites is very important to realise the intended applications especially in armour technology for armed forces. A great deal of work has been reported in literature on low and high velocity impact studies of various hybrid composites. For example Naik *et al.* [**2**, **3**] carried out low velocity as well as ballistic impact experiments on carbon-E glass/epoxy hybrid composites with different configurations. They observed that the presence of carbon fabric layers on top and bottom of the hybrid composite shows improvement in energy absorption, decrease in displacement and increase in compressive strength after impact for low velocity impact tests. It was also reported that combination of E glass and carbon improves ballistic limit velocity of composites. Later it was confirmed by Galvez *et al.* through simulation studies [**4**]. Zhang *et al.* studied the effect of stacking sequence on mechanical properties of carbon/E glass based hybrid composites and concluded that the studied stacking sequence did not show any noticeable influence on tensile properties but significantly affected flexural and compressive properties [**5**]. Effect of temperature and impactor geometry on performance of carbon - glass hybrid composites under low velocity impact has also been studied. [**6, 7**].

Sarasini *et al.* have carried out low velocity impact studies on hybrid composites made of basalt with the combination of other fibers like carbon [**8**], glass [**9**], aramid [**10**], flax and hemp [**11**]. They observed that the addition of basalt to carbon, aramid and glass fibers resulted in better impact resistance than all other combinations. The effect of hybridization on aramid/glass hybrid composites under high velocity impact was studied by Muhi *et al.* The experimental results revealed that the hybridization of glass with aramid fibres improves the performance of laminates under dynamic penetration [**12**].

S2 glass based composites are known to have better impact and structural properties than their E glass counterparts due to superior strength, modulus and failure strain (**Table 1**). However, the cost of S2 glass is much higher (8-10 times) as compared to E glass. Over the years, efforts to reduce the cost of S2 glass based composites have not yielded results. Therefore, the objective of the present study is to develop cost effective S2 and E glass based hybrid composites for armour applications in order to get advantages of both fibres *i.e.*, superior impact properties and reduced cost. While in true sense it cannot be termed as hybrid composite, we feel it is quite appropriate to call it hybrid as there is a significant difference in properties of the two types of fibres. In the present work, hybrid composites with different volume ratios of E glass and S2 glass were fabricated. Low velocity impact experiments were conducted to determine their force-time histories and energy absorption capabilities. Ballistic tests on the composites were carried out against 7.62 mm mild steel (MS) projectile in the velocity range of 320±25 $ms^{-1}$ to determine the absorbed energy at high velocity impact. Post ballistic impact observations were also carried out to estimate the damage volume in these laminates. Finally, new performance indicator called damage energy density has been adopted for ranking these composites.

## Experimental

### *Materials*

Epoxy resin (Epofine™556, 97 % purity) and Diamine hardener (Finehard™1972, 97 % purity) supplied by M/s. Fine Finish Organics (P) Ltd., India were used as a matrix in the present study. These materials were used in as received condition without further purification. Commercially available E glass woven roving having 0.22mm thickness with 360 GSM and S2 glass woven roving having 0.5 mm thickness with 815 GSM supplied by M/s. BGF industries, USA were used as reinforcements. Composition and properties of both the glass fibres are given in **Table 1**.

**Table 1**. Composition and properties of E glass and S2 glass fibres [**13**].

| Ingredient | E glass | S2 glass |
|---|---|---|
| $SiO_2$ | 52-54 | 60 - 65 |
| $Al_2O_3$ | 12 - 15 | 23 - 25 |
| CaO | 21 - 23 | -------- |
| MgO | 0.4 - 4 | 6 - 11 |
| $B_2O_3$ | 4 - 6 | -------- |
| F | 0.2 - 0.7 | -------- |
| $Fe_2O_3$ | 0.2 - 0.4 | 0 - 0.1 |
| $TiO_2$ | 0.2 - 0.5 | -------- |
| $Na_2O$ | 0 - 1 | 0 - 0.1 |
| **Properties** | | |
| Density ($kg/m^3$) | 2.54 | 2.49 |
| Strength (GPa) | 3.5 | 4.65 |
| E-Modulus (GPa) | 73.5 | 86.5 |
| Failure strain (%) | 4.5 | 5.3 |

### *Fabrication and evaluation methods*

Fabrication of composite laminates: Laminates were prepared through hand layup technique followed by hot pressing at 80 °C under 40 bar pressure for 180 min. Thickness of the prepared laminates was 2 mm and 6 mm for low and high velocity impact tests respectively. Three varieties of hybrid composite laminates were prepared by varying the volume ratio of two fibers in the ratio of 75:25, 50:50 and 25:75. Composites with individual fibres *i.e.*, E glass/epoxy (E 100) and S2 glass/epoxy (S 100) were also prepared for comparison purpose. Hereafter these composites shall be referred to E 100, ES 75-25 (E glass: 75 % and S2 glass: 25 %), ES 50-50, ES 25-75 and S 100 throughout this manuscript. Physical properties of hybrid laminates were determined as per ASTM standards and are given in **Table 2**.

**Table 2**: Physical properties of composites.

| Property | E 100 | ES 75-25 | ES 50-50 | ES 25-75 | S100 |
|---|---|---|---|---|---|
| Resin content (wt %) | 19.7 | 20 | 19.4 | 19.7 | 21.8 |
| Fibre volume fraction ($V_f$) | 0.642 | 0.637 | 0.646 | 0.642 | 0.612 |
| Specific gravity | 1.99± 0.03 | 1.96± 0.02 | 1.92± 0.02 | 1.91± 0.02 | 1.83± 0.02 |

Low velocity impact tests: Low velocity impact tests were conducted as per ASTM D-3763 [**14**] by using instrumented drop weight impact tester of Ceast-Instron make (CEAST - 9350). The drop weight impactor is equipped with a pneumatic clamping facility to prevent the specimen slippage during impact and an anti-rebound mechanism to avoid multiple impacts on the specimen. A hemispherical steel impactor of 12.7 mm diameter and 5.266 kg mass was used. The impactor is fitted with a force transducer of 45 kN capacity which measures the resistance offered by the specimen to the impactor during the impact. Data acquisition system with a sampling rate of 500 kHz was used to record the force–time history. Specimens having the dimension of 120 mm × 120 mm were impacted with incident energy in the range of 60 - 150 J. Using the force-time data, parameters like contact duration, absorbed energy and displacement were calculated through the application software integrated with the equipment [**15**]. Initial experiments were conducted to determine the effect of strike face by subjecting the specimens to 110 J impact energy (which is the threshold value for E glass laminates). Damage tolerance of these composites was determined by impacting the laminates repeatedly below the threshold value and a value of 60 J was chosen for the purpose. Another set of experiments was conducted with E glass strike face for different hybrid composite laminates and hybridization effect with respect to peak force, displacement and absorbed energy was studied by subjecting the specimens to incident impact energy of 110-150 J.

Ballistic impact test: Ballistic impact tests were carried out using 7.62 × 39 mm MS core service ammunition. The projectile was fired from an AK- 47 rifle at a distance of 10 m from the target at normal impact angle. Details of the experimental setup and projectile are discussed elsewhere [**16**]. Impact velocity of 320 ± 25 $ms^{-1}$ was selected for carrying out the tests in the present study. Targets in size of 150 mm × 100 mm were cut from the composite laminates by using diamond wheel cutting machine and minimum five specimens were tested for each type. Striking and residual velocities of the projectile were measured and absorbed energy of laminate was calculated (Eq. 1).

$$E_{abs} = \frac{1}{2} m\left(V_i^2 - V_r^2\right) \quad (1)$$

where, $E_{abs}$- Energy absorbed by the laminate (J)
$V_i$ - Striking velocity ($ms^{-1}$), $V_r$ - Residual velocity ($ms^{-1}$) and m - Mass of the projectile (g).

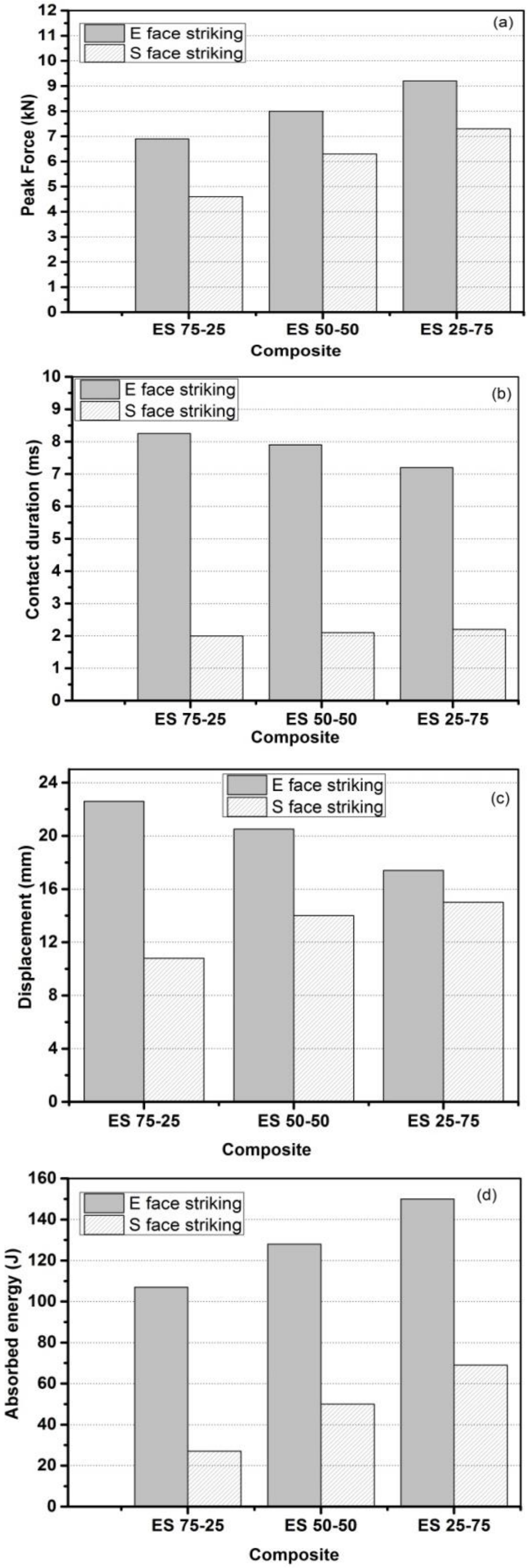

**Fig. 1**. Comparison of (a) peak force, (b) contact duration, (c) displacement and (d) absorbed energy of hybrid composites impacted at two different faces.

## Results and discussion

### *Behaviour of the laminates under low velocity impact*

Effect of striking face on laminate performance: Initially, experiments were carried out to know the effect of striking face for different combinations of hybrid composites. **Fig. 1(a-d)** present a comparison of parameters like peak force, contact duration, displacement and absorbed energy for different combinations of hybrid composites having E and S2 glass strike face respectively. It is clear from **Fig. 1(a-d)** that the hybrid laminates having E glass strike face exhibit better performance in terms of increased peak force, contact duration, displacement and absorbed energy than S2 glass strike face for all the combinations. Peak force (**Fig. 1a**) is found to be in the range of 7-9 kN for E glass strike face whereas for S2 glass strike face it lies in the range of only 4.5-6.5 kN for different combinations of hybrid composite laminates. Contact duration is found to be 7-8 ms (**Fig. 1b**) for E glass strike face laminates while for S2 glass strike face laminates, it is only 2-3 ms. Displacement values are also higher (**Fig. 1c**) when laminates were impacted on E glass strike face than on S2 glass strike face. The results indicate that hybrid composites when impacted on E glass strike face, offer more resistance by undergoing increased deformation prior to their complete perforation. **Fig. 1d** compares the absorbed energy of hybrid composites. All the composites tend to show higher energy absorption when impact occurs on E glass strike face. For instance, while ES 75 - 25 is shown to absorb 107 J of energy when impacted on E glass strike face, it absorbs only 27 J when impacted on S2 glass strike face.

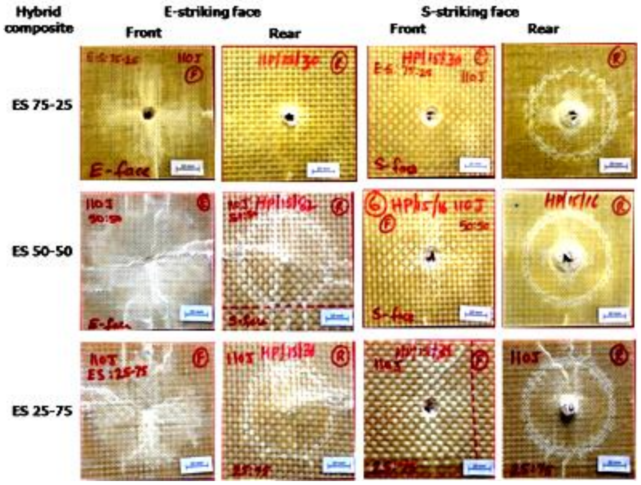

**Fig. 2.** Photographs of impacted hybrid composites.

This is a very significant difference and suggests that high tensile strength and high failure strain of S2 glass fibres at rear side where the elongation and stretching of fibres contribute for increased energy absorption, ductile failure etc [**17**]. Hence hybrid laminates having E glass strike face with S2 glass rear side show better performance.

Photographs of impacted hybrid composite laminates with different striking faces are given in **Fig. 2**. It clearly indicates that composites are perforated easily when impacted with S2- glass strike face and diameter of perforation is higher as compared to E glass strike face.

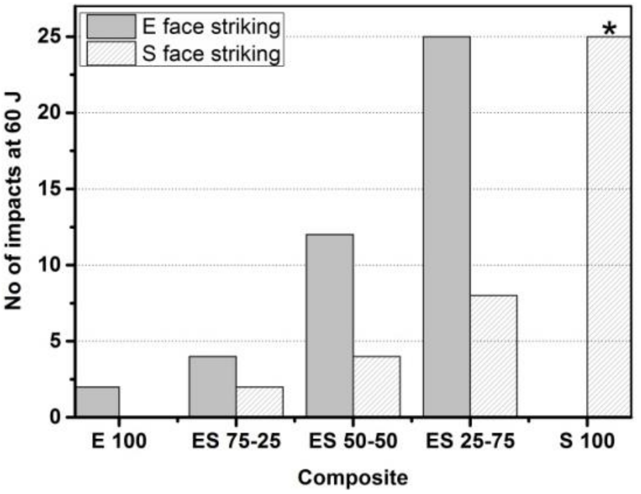

**Fig. 3.** Number of repeated impacts for complete perforation of laminates having E and S2 glass strike face (* not perforated after 25 hits).

Effect of strike face on damage tolerance: Damage tolerance of laminates can be represented by number of repeated impacts required for complete perforation. **Fig. 3** shows the number of repeated impacts for all the laminates. From the figure it is seen that laminates of E glass strike face have shown high damage tolerance by undergoing more number of impacts prior to complete failure than S2 glass strike face laminates. For instance hybrid composite with ES 75-25 combination was perforated completely after 4 hits while ES 50-50 and ES 25-75 panels were perforated after 12 and 25 hits respectively when impacted on E glass strike face. The same composites were perforated within 2, 4 and 8 hits respectively when impacted on S2 glass strike face. For comparison purpose E 100 and S 100 laminates were also subjected to repeated impacts and found that E 100 perforated after just 2 impacts, while S 100 laminate did not perforate even after 25 hits.

Effect of hybridization: Based on the results from previous sections, studies on hybridization effect were carried out with E glass strike face. **Fig. 4** shows the force-time curves, displacement and energy-time curves for different combinations of hybrid laminates. It is seen from **Fig. 4a** that peak force for E 100 is 6.6 kN and increases progressively as the amount of S2 glass is increased in the composite. Peak force for ES 25-75 and S100 is found to be similar (9.0 kN). It is also observed that slope of force-time curve which indicates the stiffness of the laminate increases with increase in S2 glass [**14**]. **Fig. 4b** represents the comparison of displacement values at 110 J impact energy for all the laminates. It is seen from **Fig. 4b** that E100 laminate has undergone displacement of 18 mm before it got perforated, whereas ES 75-25 has shown 22.6 mm displacement due to addition of S2 glass. One could have expected continuation of upward trend in displacement with further increase in S2 glass content. However, with further increase in S2, the displacement was found to reduce as the impact energy of the impactor was not sufficient for complete perforation of laminate and impactor rebounded before the laminate could stretch to its full potential and resulted in reduction in displacement. Therefore, it can be assumed that impact resistance of hybrid laminates with E glass strike face improves with increase of S2 glass content in hybrid composite laminate.

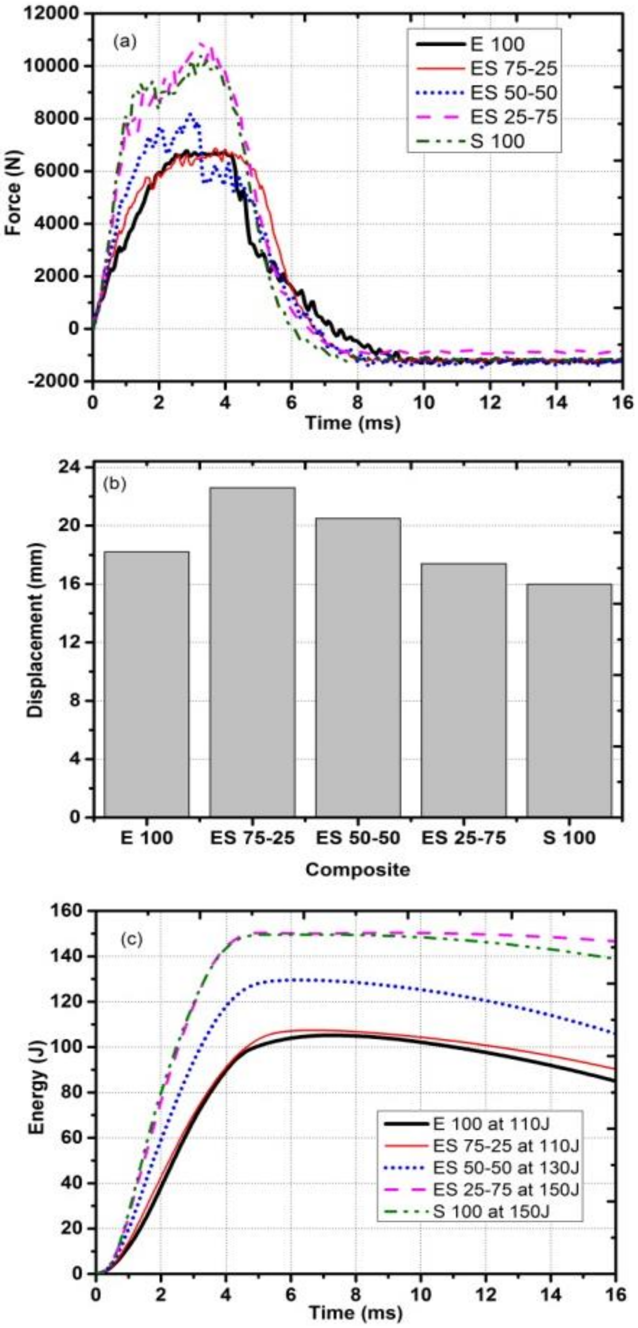

**Fig. 4.** Comparison of (a) force –time curves and (b) displacement of all composites impacted at 110 J energy (c) Energy-time curves at impact of threshold energies.

**Fig. 4c** shows energy-time history for different hybrid composites and explains how the given energy is dissipated during the impact event. It can be seen that E 100 and ES 75-25 laminates absorbed lowest energy (only ~110 J) and resulted in full perforation. Remaining laminates did not perforate at incident energy of 110J. Therefore, in another set of experiments incident energy was enhanced incrementally until perforation, to determine the threshold energy *i.e.*, minimum energy required for complete perforation. ES 50-50 was found to perforate at 130 J by completely absorbing the energy, while ES 25-75 and S 100 did not show full perforation even at 150 J impact energy. Experiments were stopped at 150 J impact as initiation of rupturing was observed at boundaries of clamped laminate. From the figure it is also clear that rate of absorption of energy is highest in case of ES 25-75 and S 100 laminates.

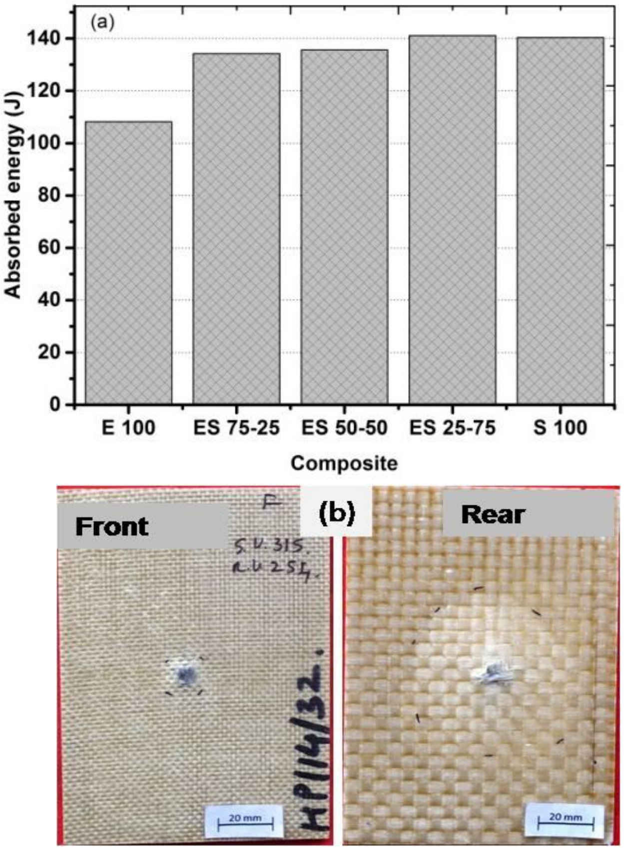

**Fig. 5.** (a) Absorbed energy of all composites during ballistic impact & (b) Photographs of hybrid laminate after ballistic impact.

### *Behaviour of the laminates under ballistic impact*

Hybrid composites were subjected to ballistic impact by using 7.62 mm MS projectile. Energy absorbed by the different composites is calculated using Eq.1 plotted in **Fig. 5a**. It is seen from the figure that E 100 laminate absorbs lowest energy (~110 J) whereas all the other composites are seen to absorb energy in the range of 135-140 J. Energy absorption of laminates is found to increase with increase of S2 glass fibre content and possibly is due to high strength and high failure strain of S2 glass fibre. However, ES 25-75 combination gives maximum energy absorption and is equivalent to the energy absorbed by S 100 composite laminate.

Front and rear face photographs of impacted laminates are given in **Fig. 5b**. Ballistic impact has resulted damage in the shape of a distorted circle at rear side. Maximum diameter of the damage region at front and rear face of the impacted laminates was measured and it was found that damage diameter of front face is lower than the rear face diameter for all the laminates.

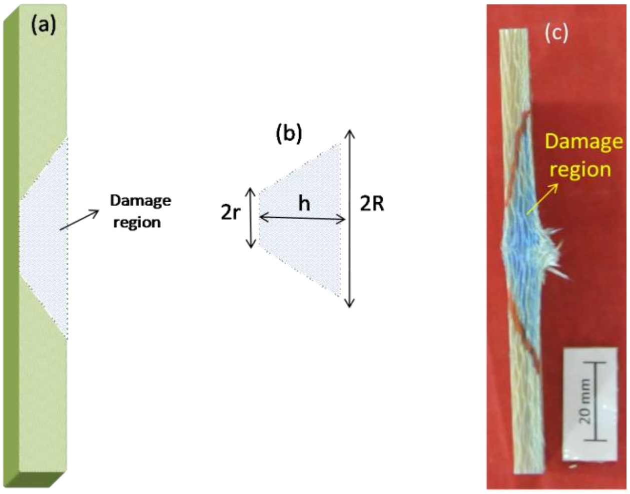

**Fig. 6.** (a) Schematic representation of cross section of impacted laminate, (b) damage region, (c) Photograph of cross sectioned laminate.

In order to get an idea about the damage behaviour of internal plies, impacted laminates were sectioned through the centre of impact point. It was found that damage has taken place through cone formation as represented in the **Fig. 6**. This finding is consistent with reported literature for thin laminates [**18**]. The damage volume (D.V) was calculated by using equation 2.

$$D.V = \frac{\pi h}{3}(r^2 + rR + R^2) \qquad (2)$$

where, D.V is damage volume, *h* is thickness, *r* is damage radius of front face and *R* is damage radius of rear face.

**Fig. 7a** shows damage volume of different hybrid composites. It is observed that damage volume is lowest for E 100 composite and suggestive of their lower energy absorption. Damage volume of ES 75-25 is found to be highest and it decreases with increase of S2 glass content in hybrid laminate even though absorbed energy is increased with increasing S2 content. It suggests that the presence of S2 glass fibre results in increased resistance of the laminate and hence at higher content of S2 glass fibre composites have shown reduction in damage volume.

Performance of the laminates can be compared either in terms of absorbed energy or damage volume. From the **Fig. 5a** it is clear that while ES 25-75 and S 100 composites are better in terms of energy absorption, E 100 laminate seems to be better in terms of damage volume as it shows the lowest damage volume among all. It appears to be more appropriate to unify the effect of both the parameters into a single parameter termed as damage energy density to indicate the performance of the studied composites. It can be defined as amount of energy consumed to generate unit damage volume. These values for all the laminates are plotted in the **Fig. 7b**. The figure clearly suggests that performance of the composites increases with increase in S2 glass content in hybrid laminate. However, ES 25-75 composite is found to possess same damage energy density as that of S 100 laminate. Hence it can be inferred that ES 25-75 composite exhibits performance similar to S 100 laminate in terms of energy absorption as well as damage volume. And finally it can also be concluded that, for ballistic applications, a minimum of 25 % S2 glass fibres can be replaced with cost-effective E glass fibres for equal performance.

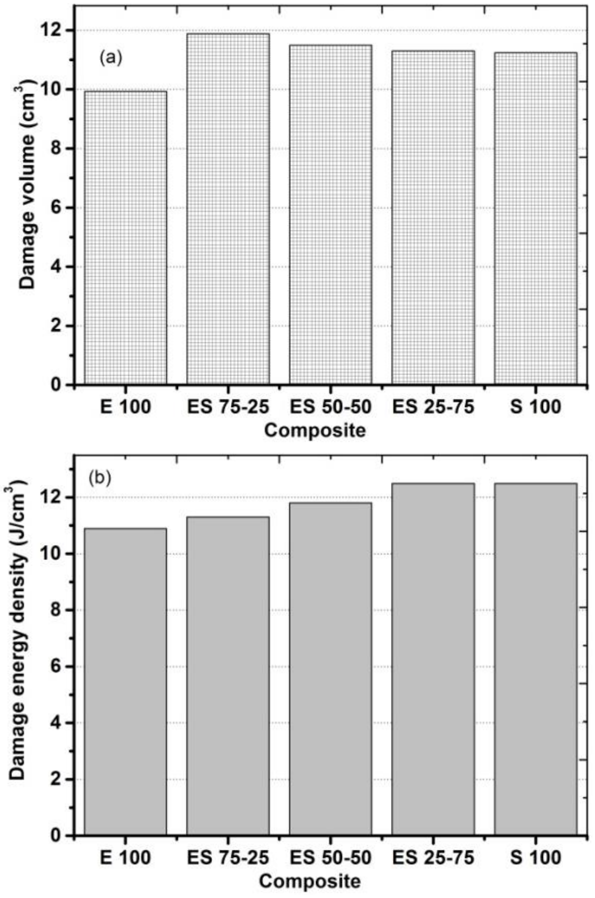

**Fig. 7.** (a) Calculated damage volume and (b) Damage energy density values of all the composites.

## Conclusion

Three hybrid composites based on E glass and S2 glass in the volume ratio of 75:25, 50:50 and 25:75 were fabricated using epoxy matrix. Composites with individual fibres *i.e.*, E glass/epoxy and S2 glass/epoxy were also prepared for comparison purpose. Low velocity impact tests show that composites perform better when impacted on E glass strike face than on S glass strike face for similar ratio of E and S2 glass. While hybrid laminates having ES 50-50 combination has shown to perform less in terms of peak force, energy absorption and damage tolerance as compare to S 100, ES 25-75 composite has shown equal performance to that of S 100 laminate. Ballistic evaluation also proved that performance of hybrid composites increases with increase in S2 glass content and ES 25-75 composite performs similar to 100 % S2 glass/epoxy (S 100) laminate in terms of energy absorption as well as damage volume. Hence, it can be concluded from both low velocity and ballistic impacts that a minimum of 25 % S2 glass can be replaced with low cost E glass without compromising performance. Further potential of this approach may be explored by studying effect of laminate thickness, projectile velocity, geometry and testing temperature on performance of these laminates. These hybrid composites may potentially find applications not only in armour field but also in aerospace and automobile sector.

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