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Experimental impact study on unidirectional glass-carbon hybrid composite laminates

Abstract: In this experimental study, the impact response of unidirectional hybrid composite laminate was investigated. Hybrid laminates with different stacking sequences were fabricated, using unidirectional glass and carbon fiber as reinforcement and epoxy resin as matrix. ASTM standard D5628 was followed to conduct the experiment using the instrumented drop weight impact test apparatus. All the square specimens were tested at an impact velocity of 3.43 m/s and the time histories of force and energy absorbed were recorded. The impacted specimens and their X-ray images were visually inspected to understand the failure pattern. The experimental results showed that the addition of carbon fiber increases the impact strength by absorbing more force and energy. Furthermore, the laminate can be stiffened with the carbon fiber layers by interfacing glass fiber layers on either side.

Keywords: drop impact; hybrid; unidirectional; X-ray image.

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1 Introduction

In the last decade, researchers focused on materials that support weight reduction with enhanced strength for implementation in all the fields of engineering application. Composite materials with high strength and low specific weight characteristics have attracted research attention because such materials can be used in various structural applications, which range from aerospace to automobiles. Many studies are being undertaken in this area using metal, synthetic, and natural fibers as reinforcement materials. However, the use of high strength

carbon fiber-reinforced composite is largely restricted in the automobile industry due to its higher cost. However, low cost products can benefit from the advantages of carbon fiber by combining it with low cost materials, such as glass fibers, through hybrid composites of interply or intraply type. During operation, any structure is subjected to accidental impact loads. Hence, the response of these composite structures to such unexpected impact loads should be understood.

Impact studies on composites in the past decades have been well documented by Abrate [1]. The damages induced by impact consist of fiber breakage, matrix cracking and delamination, depending on impact parameters including material properties, projectile characteristics, and fiber lay-up. Hybrid effect in E-glass/carbon fiber-reinforced epoxy has been studied by Marom et al. [2] who found that hybrid effect may be positive or negative based on the relative volume fraction of the two types of fiber and the construction pattern of layers. The impact response of unidirectional glass/epoxy laminates have been investigated by Mehmet et al. [3], considering energy profile diagrams and associated load-deflection curves. The authors observed that, for lower impact energies (<25 J), the main damage modes were delamination and matrix cracks. However, for the higher impact energy, fiber failures proved to be the dominant damage mode.

Metin et al. [4] studied the penetration and perforation thresholds of hybrid composites using energy profiling method and load-deflection curves. The perforation threshold of hybrid composites impacted at carbon fiber surface is approximately 30% higher than that of laminates with glass fibers as surface. They observed minor matrix cracking and some delaminations on the glass surface, while only observing indentations and matrix breaks on the carbon surface of the impacted side of specimens. Ercan et al. [5, 6] examined the effect of repeated impact on the response of plain woven hybrid and non hybrid composites using instrumented drop-weight impact tester and nonlinear finite element approach. They visually inspected the damaged specimens using the ultrasonic C-scan method and found that damage accumulations could be slowed down using hybridization.

Hosur et al. [7] tested different combinations of hybrid laminates with low-velocity impact loading. They found

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improvements in the load carrying capability of hybrid composites as compared with carbon/epoxy laminates with slight reduction in stiffness and enhancement in damage tolerance of structures by hybridization. Naik et al. [8, 9] have published various works on the impact of polymer matrix woven fiber composites, reporting that the maximum displacement and duration of impact decreases with increase in in-plane modulus of elasticity. They also reported that the delamination mode is the first possible mode of failure, and that failure is often initiated at the top interface [7].

Mitrevski et al. [10] investigated the effect of impactor shape (hemispherical, ogival, and conical) on the impact response of woven carbon/epoxy laminates. They found that the specimens impacted by the conical impactor absorbed more energy as a result of local penetration, whereas the hemispherical impactor produced the highest peak force and lowest contact duration. Caprino et al. [11] found that the maximum force and penetration energy increased to the power of approximately 1.5 times with increase in plate thickness. Belingardi et al. [12] compared the impact response to repeated loading of glass laminates manufactured by hand lay-up and vacuum infusion methods. Their results demonstrate that hand lay-up specimens survived more number of impacts before perforation and absorbed more total energy than vacuum-infused specimens. Meanwhile, Harding [13] discussed the techniques for determining the mechanical behavior of fiber-reinforced composites. Sugun et al. [14] conducted a repeated drop test on glass-epoxy composite to study the impactor mass effect. They found that, at low incident energies, heavier impactors cause more damage to the laminate which, in turn, diminishes gradually at relatively higher incident energies.

Perez et al. [15] studied the high velocity impact performance of woven carbon and glass fabric hybrid laminates, and their results have been used to describe the role played by glass-fiber hybridization on the fracture micromechanics and on the overall laminate performance. Marino et al. [16] investigated the behavior of composite laminates under low velocity impact, with the aim of determining the influence of stacking sequence and laminate thickness on contact loads, absorbed energy, and delamination. Sket et al. [17] studied the onset and evolution of damage using X-ray computed micro-tomography in a notched glass fiber/epoxy cross-ply laminate subjected to three-point bending. They found that the damage starts with the formation of intraply cracks in the 90° plies followed by intraply cracking in the 0° plies. Finally, Batra et al. [18] analyzed the damage initiation, progression, and failure of a laminated composite impacted by a low speed rigid sphere, and compared their results with the experimental findings in the literature.

2 Materials and methods

In this study, 400 gsm unidirectional glass fiber and 300 gsm unidirectional carbon fiber supplied by Harsh-Deep industries, Ahmedabad, Gujarat, India were used as reinforcement materials, while epoxy resin LY556 supplied by Javanthee enterprises, Chennai, India was used as matrix material along with the hardener HY951. The mixing ratio for resin-to-hardener in weight was taken as 10:1. The hybrid fiber reinforced polymer (FRP) composite laminates were manufactured by hand lay-up technique in an open mold. The prepared laminates were cured in atmospheric condition for 4 h and post cured by compressing in a compression molding machine for 10 min, at 70°C with a constant pressure of 8 bars. The laminates were then allowed to cool in an open atmosphere for 24 h to allow them to completely cure. Two different set of laminates were proposed for evaluating the impact response based on energy absorbed by each laminate.

The layer configuration of composite laminates without carbon fiber and another with carbon fiber in the midplane is given in Table 1A. Three different laminates designed by changing the carbon mat position from the midplane outwards are given in Table 1B. The schematic representations of one half of the laminates are shown in Figure 1. The nomenclature adopted for different configurations are listed below.

1. G is a fully glass laminate having two unidirectional glass fiber layers at the middle and quasi-isotropic stacking of glass fiber layers on either side.
2. GC1 is a hybrid laminate with unidirectional glass and carbon fiber in the middle of the laminate as well as quasi-isotropic stacking of glass fiber layers on either side.
3. In GC2, two cross-ply carbon fiber mats are placed in the middle and quasi-isotropic stacking of glass fibers layers are stacked on either side.

Table 1: Layer configuration of the composite laminate.

Nomenclature	Lay-up	Fiber volume fraction%	
		Glass	Carbon
(A) Laminates with and without carbon fiber in the midplane			
G	$[G_0/G_{135}/G_{90}/G_{45}/G_0/G_0]_S$	62	0
GC1	$[G_0/G_{135}/G_{90}/G_{45}/G_0/C_0]_S$	50	12
(B) Changing position of carbon fiber from the midplane outwards			
GC2	$[G_0/G_{135}/G_{90}/G_{45}/C_0/C_0]_S$	38	24
CG1	$[C_0/C_{90}/G_0/G_{135}/G_{90}/G_{45}]_S$	38	24
GCG	$[G_0/G_{90}/C_0/C_{90}/G_{135}/G_{45}]_S$	38	24

Figure 1: Schematic representation for top half of symmetric laminates.

4. In CG1, the cross-ply carbon fiber mat is moved to the exterior and quasi-isotropic stacking of glass fiber layers are placed inside.
5. GCG is a special laminate, in which carbon mat is placed in the middle of the upper half and the lower half with cross-ply glass fiber mat as skin and $135^\circ/45^\circ$ oriented glass fiber mat near the midplane.

A sophisticated instrumented drop weight impact testing machine, Ceast 9350 (Fractovis Plus) was used to study the impact response of hybrid FRP laminates. This testing machine has a dropping crosshead with its accessories guided by two smooth columns, pneumatic clamping fixture to fix the specimen, and pneumatic rebound breaking system to prevent repeated impact of specimens. The drop weight impact test uses kinetic energy of the free falling weight, which depends on the mass and height of the impactor to break the plate specimen. The energy absorbed by the specimen can be calculated using Equations (1) and (2) given by

$$U = \frac{m}{2}(u_1^2 - u_2^2), \quad (1)$$

$$u_1 = \sqrt{2gh}, \quad (2)$$

where

m refers to the mass of the falling impactor, u_1 is the velocity of the impactor just before impact, g refers to the acceleration due to gravity, h is the drop height of the impactor, and u_2 represents the velocity of the impactor after impact.

The weight of crosshead could be adjusted by changing the drop mass and tub of the impactor. In this study, the total mass of the impactor with its accessories was taken as 13 kg and the striker used was a 12.7 mm diameter hemispherical nose aligned to impact at the center of the specimen. The specimen was clamped with a clamping force of 100 N, and the test was conducted at atmospheric conditions according to ASTM standard D5628 with

geometry “FD” (square specimen 89 mm×89 mm). The clamping fixture used to hold the specimen had an outer diameter of 100 mm and an inner diameter of 76 mm. The specimen clamped to the fixture is shown in Figure 2.

The objective of this study was to determine the behavior of the laminates at low velocities, which might lead to internal cracking and delamination. Hence, a low velocity impact test was conducted by dropping a 13 kg impactor from a height of 600 mm, which accelerated to an impact velocity of 3.43 m/s with a kinetic energy of 76 J when it impacted the specimen. Impulse data acquisition system was used to record the time histories of impact force and energy absorbed. A total of 5000 data points were recorded for force and energy absorbed by the specimen at a time interval of 0.001 ms.

3 Results and discussion

All the specimens were tested at same velocity and drop height. Repeated impact of specimen was avoided with the help of pneumatic break, which caught the striker if it rebounded. Four samples were tested for each type of specimen, and the average value was reported.

Figure 2: Specimen clamping fixture.

3.1 Laminates with and without carbon fiber in the midplane

To understand the effect of hybridization, the carbon fiber volume ratio was increased from 0% in specimen G to 12% in specimen GC1. The time histories of impact force and energy absorbed by specimens G and GC1 are shown in Figure 3A and B, respectively.

The graph showing impact force indicates clearly that the addition of the carbon fiber layer in the midplane in specimen GC1 enhances impact resistance even after the failure of the glass fiber layer on the impacted side. The impact force increases quickly and drops down to the lowest value for specimen G, whereas the impact force does not drop down drastically for the specimen GC1 with the carbon fiber layer in the midplane. The energy absorbed during impact is found to be greater in case of specimen GC1 compared with that of specimen G. Furthermore, the laminate with carbon fiber in the midplane absorbed more energy than the fully glass laminate in the later stage of impact. This can be attributed to the fact that the carbon fiber layers can absorb the impact more effectively in specimen GC1 than the fully glass fiber layers in specimen G.

The front side, back side photograph, and X-ray image of specimens G and GC1 are shown in Figures 4 and 5 respectively. As can be seen, the impactor have penetrated the fully glass laminate G in the front side (Figure 4A) by breaking the fiber without any damage to the surrounding area, which is due to the brittleness of the glass fiber layers. The back side of specimen G (Figure 4B) shows horizontal delamination, which is due to the bending that took place at the bottom layers of the laminate during impact. Similar horizontal delaminations have been reported in the literature [3, 4]. The X-ray image in Figure 4C also shows the breakage of fibers and penetration of the impactor. In the

Figure 3: Time history plots of force and energy for the laminates with and without carbon fiber.

case of specimen GC1, the impactor breaks the fibers in the front and back sides without any delamination, as shown in Figure 5A and B, respectively. The damage is localized in specimen GC1 due to the presence of the carbon fiber layer, which has increased the bending resistance of the laminate, thus allowing the impactor to penetrate without delaminating the back side. Meanwhile, the X-ray image in Figure 5C shows lesser fiber breakage in specimen GC1 than that of the fully glass laminate. From the above results, it can be concluded that a small quantity of high

Figure 4: Photographs of impacted specimen G.

Figure 5: Photographs of impacted specimen GC1.

modulus carbon fiber – when hybridized with glass fiber – can increase the impact resistance of a laminate.

3.2 Changing position of carbon fiber from the midplane outwards

The impact strength of a laminate increases when hybridized with carbon fiber layer compared with a laminate having only glass fiber layers. Given the importance of identifying the optimum position of the carbon fiber layer in the stacking sequence, three different laminates were tested by changing the carbon mat position from the midplane outwards. In the first laminate GC2, two cross-ply carbon mats were placed in the center above and below the midplane. In the second laminate CG1, one cross-ply carbon mat was placed as skin on either side of the laminate. The third laminate GCG was a special laminate with two layers of carbon fiber placed in between glass fibers on the top half and at the bottom half from the midplane.

The time histories of impact force and energy absorbed by the laminates are shown in Figure 6A and B, respectively. As can be seen, the impact force of specimen GC2 increased and dropped slowly to the lowest value, whereas in specimen CG1, the impact force increased and then dropped suddenly after reaching the maximum value, indicating the failure of the carbon fiber layer in the skin. As the carbon fiber layer failed initially, the force dropped down and reached the value close to GC2. The impact force of specimen GCG is similar to that of specimen CG1 up to the maximum value, but the specimen GCG maintained the force of resistance due to the carbon fiber layers in the middle. Energy absorbed is almost similar for all the laminates, with the lowest value of energy absorbed by the specimen GC2. The rate of energy absorption is greater for the specimen CG1 at the initial stages,

although it dropped down after the carbon fiber failed. In comparison, the laminate GCG absorbed more energy, increasing steadily at the later stages of the impact.

From the above graphs of laminates GC2, CG1 and GCG, it can be assumed that specimen GCG with carbon fiber mat placed in between glass fiber mat resulted in greater resistance to impact compared with specimens GC2 and CG1. However, laminates with carbon fiber layer placed as skin also showed better resistance to impact than the laminates with carbon fiber layer placed near the

Figure 6: Time history plots of force and energy for different carbon fiber position.

Figure 7: Photographs of impacted specimen GC2.

midplane. The photographs and X-ray images of impacted specimens GC2, CG1, and GCG are shown in Figures 7–9, respectively.

Matrix damage occurred in the front side of specimen GC2, as shown in Figure 7A. The damage can be attributed to the transfer of force from the point of impact at the skin layer to the subsequent layers, causing the damage of the matrix to widen. The laminate failed with radial crack formation in the back side of specimen GC2, as shown in Figure 7B. The bending resistance of the laminate increases with the addition of carbon fiber layer, which then leads to radial crack. The X-ray image in Figure 7C also shows matrix damage with less fiber breakage.

The failure in the front side of specimen CG1 is due to the crack that spread perpendicular to the orientation of the fibers in the outer layer (Figure 8A). This can be attributed to the weakness of the layer in perpendicular direction to the fiber on the impacted side. In the back side of specimen CG1, the damage is due to high tensile bending stress, which caused the peeling of the layer (Figure 8B).

Two carbon fiber layers on the back side of specimen CG1 peeled off due to the damage occurred in the glass fiber layers present above it during impact. The X-ray image in Figure 8C shows the fiber split-up with less penetration of the impactor. Similar layer split-ups have been observed in earlier studies [4].

In the front side of specimen GCG, the failure is localized with matrix damage and crack formation perpendicular to the fiber direction (Figure 9A). At the back side of specimen GCG, shown in Figure 9B, only the matrix is damaged. As can be seen, the matrix damage spread uniformly throughout the entire specimen without any fiber breakage or delamination. Thus, the stresses developed during impact have been distributed to all the layers. The X-ray image in Figure 9C shows overall matrix damage without any fiber breakage or penetration of impactor. Furthermore, the specimen GCG has better resistance to impact than other specimens because the carbon fiber layers placed near the skin glass fiber layer protect the laminate from failure by absorbing more energy.

Figure 8: Photographs of impacted specimen CG1.

Figure 9: Photographs of impacted specimen GCG.

3.3 Area of penetration

Understanding the amount of penetration or damage done by the indenter in the specimen is important. When glass fibers are used, light is projected on the impacted specimen to measure the area of damage or penetration, but carbon fiber used in this work, such as glass fiber, is not transparent. Hence, the X-ray image of the impacted specimen was inserted into autocad software and the damage area was plotted by drawing free form curve along the damage boundary. From the closed curve, the area of penetration was measured using area measurement tool in autocad. The measurements are shown in Table 2.

The area of penetration is wider for the fully glass laminate G, in which 87% of the area of impactor penetrated the specimen. Whereas the percentage area of penetration with respect to impactor reduced to 42% and 19% when two carbon fiber layers are added near the midplane in specimen GC1 and four carbon fiber layers are added in specimen GC2, respectively. However, it slightly increased to 22.5% for specimen CG1 when the four carbon fiber layers are placed as outer skin layers. The percentage area of penetration with respect to the impactor is the lowest at 8.75% for the specimen GCG, in which the carbon fiber

layers have been placed in between cross-ply glass fiber layers.

The comparisons of maximum resistive force and energy absorbed by the specimens with standard deviation for each value are shown in Figures 10 and 11, respectively. As the carbon fiber volume fraction increased to 24%, the impact force increased by 15% and energy absorbed increased by 20.5% in the specimen GC2 with respect to that of the specimen G. Similar trends have been observed in earlier studies [4–6]. However, the impact

Figure 10: Maximum resistive force offered by the laminates.

Figure 11: Energy absorbed by the laminates.

Table 2: Area of penetration for the laminates hybridized with glass and carbon fibers.

S.No	Laminate	Area of penetration (mm ²)	Percentage area of penetration with respect to the area of the impactor
1	G	110.02	86.86
2	GC1	53.49	42.23
3	GC2	24.38	19.25
4	CG1	28.51	22.51
5	GCG	11.08	8.75

force increased by 25% and energy absorbed increased by 26.8% in specimen GCG compared with that of the fully glass fiber specimen G. In addition, the specimen GCG also resisted peeling of layers at the back side, which occurred in specimen CG1; hence, the hybrid specimen GCG is selected as the best specimen for impact applications.

4 Conclusion

The impact response of glass-carbon hybrid laminates has been investigated in this experimental study, and several conclusions have been made.

- Hybridization of unidirectional carbon fiber layers with glass fiber layers can increase impact resistance by absorbing more force and energy, resulting in reduced area of penetration.
- The failure mode of the laminate changed from breakage of fibers and delamination in the case of fully glass fiber-reinforced laminate to matrix damage and crack formation when carbon fiber volume fraction increased to 24%.
- The bending effect can be reduced by changing the cross-ply carbon fiber mat position from the mid-plane outwards as observed in specimens GCG and CG1.
- When carbon fiber is placed as skin, the impact resistance dropped suddenly after the carbon fiber failed, and layer separation occurred in the non-impacted side.
- Maximum hybridization effect can be obtained by placing the carbon fiber layers alternatively along with the glass fiber layers.
- Finally, in the specimen GCG, when cross-ply carbon fiber mat has been stacked next to the skin glass fiber layers, the impact force increased by 2 kN and energy

absorbed increased by 15 J, with less area of damage compared with fully glass laminate. Hence, such layer configuration can perform as the best hybridized laminate for impact applications.

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