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Dynamic analysis of hybrid basalt and carbon fiber reinforced Bismaleimide composites suited for high temperature structural applications

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Abstract

The main aim of this work is to study the damage tolerance of hybrid basalt and carbon fiber-reinforced composite subjected to low velocity impact (LVI) at different velocities, 2.89 m s\(^{-1}\) and 4.42 m s\(^{-1}\), simulated using a CEAST drop hammer testing machine and Dynamic Mechanical Analysis (DMA) were conducted to characterize the sample. In this article, the detailed failure mechanism of seven composite laminates (Basalt fiber/Bismaleimide (BMI)-diallyl Bisphenol A (DABA), Carbon fiber/BMI-DABA, Basalt fiber/BMI/BMI-DABA) were studied under loading of LVI. Through the experiment, it was also substantiated that the hybrid fiber-reinforced composites possessed better damage tolerance and thermo mechanical properties than the homogenous fiber-reinforced composites. The hybrid fiber composites that were produced vary in the number of carbon fiber to basalt fiber ratio and stacking sequence. The impacted surface was analyzed at macro level by using Image J software. The impact force, the energy absorbed, and the deformation of the laminates under impact load were scrutinized extensively, and it was inferred that the basalt fiber intercalated with carbon fiber with BMI/DABA possessed the highest damage resistance than the other composite laminates under study. The highest peak force 5702 N and 9241 N with the highest elastic energy 4.8 J, 11.7 J and with lower deformation (3.85 mm, 6.09 mm) and deformation area (22.79 mm\(^2\), 28.09 mm\(^2\)) was observed in the intercalated hybrid laminate.

1. Introduction

In recent years, emphasis is laid on developing novel materials counting to the improved properties. Categorization of Hybrid composites under novel material is customary in the field of composites. Basalt fiber, a natural fiber, restored with carbon fiber can revamp the mechanical properties. The limited study in their conglomeration ushered into this work. Basalt fiber has been used for centuries in structural applications. It has good thermal and mechanical properties with a resistance to chemicals and moisture [1]. Low velocity impact test on basalt fiber and carbon-reinforced with BMI/DABA is limited. The incorporation of high deformation resistance Basalt fiber in the matrix along with carbon fiber potentially enhanced the impact resistance of the composite. Tracking the trail of various researches in the field of Hybrid composites under LVI, it is possible to unleash a potential resource of knowledge. Han et al [2] analyzed the failure analysis under LVI and compression after impact (CAI) on the carbon fiber reinforced with different resin (Epoxy, Bismaleimide) experimentally and through finite element analysis. It was concluded that the damage tolerance of epoxy resin composites outweighed the bismaleimide composites due to stronger interlaminar properties of the former than latter. Paine et al [3] reported that the inclusion of fibrous super elastic shape memory alloy into brittle graphite/Bismaleimide composite prevented the perforation caused by the impact energy. It also reduced the delamination of the ply by 25% in the composites. Prabu et al [4] showed that the inclusion of Shape Memory
Alloy (SMA) sheets in the kevlar polymer composites improved the mechanical and impact strength of the kevlar polymer composites without the SMA sheet. Quaresimin et al \[5\] also investigated the effect of laminate thickness and stacking sequence of woven carbon-epoxy composites on energy absorption under impact test and concluded that both the thickness and lay-up influenced the absorption capability. García-Moreno et al \[6\] studied the changes in impact damage parameters due to the thermal aging of Carbon/Epoxy composites. He concluded that, above the glass transition temperature, the service behavior of the composites, were affected due to prolonged exposure to high temperature. Sarasini et al \[7\] conducted LVI test on thermoplastic (polypropylene) and thermoset (epoxy) reinforced with hybrid basalt and flax fibers and found that basalt fiber in thermoplastic laminates exhibited enhanced energy absorption with reduced cracks. Kazemianfar et al \[8\] studied the effect of impactor shape on 3D woven polyester resin and E-glass fiber composites under LVI and concluded that the shape of the impactor affected damage intensity. The volume of z fibers in the composite increased the stiffness of the composite. Hence various studies have been conducted on thermoplastic and thermoset resin reinforced with fiber in developing hybrid composites. The limited study on basalt and carbon fiber in BMI/DABA made researchers develop these hybrid composites, with improved properties suitable for structural application.

Extensive studies on DMA on Bismaleimide composites \[9–21\], provided insight into the stiffness, interfacial bonding, toughness, damping properties, and thermal stability between the matrix/fiber is reinstated in this study as an effort to study the dynamic properties of the hybrid fiber composites suitable for high-temperature application.

In this study, the hybrid (carbon and basalt fiber) laminates reinforced with BMI/DABA with different stacking sequence and fiber ratio (in terms of varying number of basalt fiber to carbon fiber) was produced. The laminates produced were characterized by LVI test and DMA test to find its impact resistance and viscoelastic behavior respectively and a correlation between the two tests was studied. The inadequate amount of work on hybrid basalt and carbon fiber with BMI contrasted with the abundance of work with other resin system like epoxy connotes the curiosity of this work.

2. Materials and methodology

The matrix used was recrystallized BMI modified with DABA and the reinforcement was plain bidirectional weave basalt fiber (450 gsm) and carbon fiber (400 gsm) (figure 1). The recrystallized BMI had a sharp melting point at 154 °C. The resin to modifier stoichiometry ratio was 1:1, constituting 54% by volume fraction in the composite and the remaining 46% constitutes the fiber. BMI with DABA was heated to 60 °C and the preform obtained was coated over the fiber by hand lay-up method. The resulting Prepreg (250 mm × 250 mm × 4 mm) was stacked in the desired sequence (table 1) adopting design guidelines \[22\] and referring related articles.

![Figure 1. (a) Basalt fiber, (b) Carbon fiber.](image_url)

Table 1. Laminate stacking sequence.

| Laminates | L1  | L2  | L3  | L4  | L5  | L6  | L7  |
|-----------|-----|-----|-----|-----|-----|-----|-----|
| Stacking Sequence | [B/B/B/C]/Bjs | [C/C/C/C]/Cjs | [C/C/C/B]/Bjs | [C/B/B/C]/Bjs | [B/B/C/C]/Cjs | [B/C/B/C]/Cjs |
| Hybrid fiber Ratio (B:C) | — | — | 1:3 | 2:2 | 3:1 | 2:2 | 2:2 |
This prepreg was consolidated in a hydraulic press having a suitable strip heater for heating it to the required temperature. The temperature was gradually increased from 100°C to 180°C with contact pressure. At 180°C, a pressure of 10 bar was applied and maintained in that temperature for an hour. The laminate was cured at 200°C for 2 h and 250°C for 5 h in an oven. The laminate was cooled to room temperature and removed from the furnace. The cure cycle followed was provided by the supplier (ABR organics India).

3. Dynamic tests

The LV1 test was carried at room temperature on the CEAST Fractovis drop weight impact tower. It consists of a hemispherical striker of size 25 mm diameter with a weight of 1.926 kg. The apparatus had a provision of circular enclosure of 79 mm diameter with 50N clamping force for holding and positioning the specimen rigidly without any lateral movement. The test was conducted at two different velocities 2.89 m s\(^{-1}\) and 4.42 m s\(^{-1}\) on an average of 3 times with standard deviation of ± 4. The velocities were chosen referring to related articles [2–4]. These nominal velocities impart standard Energy level (8 J and 18.8 J) specific for impact penetration resistance rather than perforation resistance.

The impact energy, impact force, deformation, and rebounding were recorded using a data acquisition system incorporated with the impact tester. The piezoelectric sensor in the striker records the impact force and energy during the test. The laminates were prepared to ASTM D5628- D standards. The sample size of 90 mm × 90 mm × 4 ± 0.3 mm was used for the test.

DMA tests were conducted according to ASTM D4065 to determine the viscoelastic behavior of laminates subjected to three-point bending mode at a constant frequency of 2 Hz in a Nitrogen atmosphere with a heating rate of 5°C/min within 30°C and 300°C. The sample size was 50 mm × 12 mm × 4 mm for the test.

[23–25].
4. Results and discussion

The determinants of Impact resistance are absorbed impact energy, peak force, peak deformation, duration of impact contact, type, and extent of deformation. The records of force-time, force-displacement, and absorbed energy-time elucidate the damage response criterion, which is detailed in the discussion below.
4.1. Impact Force versus deformation

The graph in figures 2(a), (b) depicts the impact force versus deformation of the laminates under LVI. The force history provided the damage initiation and propagation of the laminates. The threshold force is the force causing the first material damage with sharp changes and oscillations in the curve. The sharp changes and oscillations observed before the major impairment caused by the peak force was the threshold force (figure 2). The higher peak force indicates the maximum force that a laminate can endure before any major impairment. It indicates the delamination with the reduction in stiffness due to the first abrupt drop in force [26]. It is inferred from the figures 3(a), (b) that the laminate L7 at two different velocities endured the highest impact force (5700 N, 9210 N) as well as threshold force (5620 N, 9050 N) compared to the other laminates due to the high tough basalt fiber [27] at the outermost layer, intercalated with high stiff carbon fiber. The deformation caused by discrete velocities were depicted in figure 4 showing that it was minimum for laminate L7 (3.85 mm, 6.09 mm) due to the presence of impact resistance basalt fiber in it.

The closed-type hysteresis of force-deformation curve, depicted the elastic behavior of the material under impact. It also signified that there was minimum penetration by rebounding energy during impact preventing failure due to perforation [28]. The area under the force-deformation curve gives the absorbed energy transferred from the impactor to the laminate.

4.2. Absorbed energy versus deformation/time

The energy-deformation/time curve of the composites were depicted in figures 5(a)–(d) shows that there was an initial increase of impact energy reaching the peak. The energy after reaching the maximum value dropped until
it became constant, indicating the value of permanent absorbed energy [29]. The end of the curve depicts the plastic energy dissipated in the form of permanent deformation/damage/delamination such as matrix cracking, fiber fracture, and kinking [30]. Hence the damage evolution is the total of plastic energy [30], found highest in laminate (L5) and (L4), lowest in laminate (L7) at both the velocities respectively, depicted in Energy–time curves (figures 5(c), (d)). The part of the elastic energy was given back to the impactor as the rebound energy [27]. The maximum energy at maximum force is the sum of elastic energy (absorbed energy) and plastic energy (dissipated energy) depicted in figures 6(a), (b). It was observed that the elastic energy was the highest for laminate L7 [B/C/B/C]/(4.8 J, 11.7 J) with the lowest plastic energy (7.57 J, 17.05 J) at two different velocities, indicating the damage tolerance as well as lesser damage area of the composite, preventing penetration/damage in the matrix/fiber.

### 4.3. Impact force versus time

The impact force or impact resistance exhibited by the laminates were parabolic (figure 7) during the impact test at different velocities signified the rebounding condition [31]. The partial smooth curve showed that there was less force oscillation in the curve due to impactor velocity. The reduced force oscillation with rapid peak force, seen in laminate (L7), prevented the composite from damage due to penetration and perforation [28], which were characteristics of high impact incidence causing failure of the material. The tests were conducted on the seven laminates and the force borne by them was documented using a data acquisition system. From the force histories, it was observed that the first threshold force indicated the first damage forming small cracks with the second threshold force causing first lamina failure. Figure 7 acknowledge the fact that laminate (L7), with basalt and carbon intercalated in the matrix, generated peak force of 5702 N and 9241 N at discrete impact speeds, and the impact force was engrossed within a short period compared to other laminates. The first threshold force is also high enough in laminate (L7) (5.62 N, 9.05 N) at discrete impact speed delaying the damage of the material. Table 2 provided the details of force borne by the laminates at two different velocities.

### Table 2. Impact Force Analysis of different Specimens.

| Specimen | Force kN at 2.89 m s\(^{-1}\) | Increase/ Decrease (%) | Force kN at 4.42 m s\(^{-1}\) | Increase/ Decrease (%) |
|----------|--------------------------------|-------------------------|--------------------------------|-------------------------|
| Laminate L1 | 4.68 | — | 6.04 | — |
| Laminate L2 | 4.407 | −5.83 | 8.13 | 34.64 |
| Laminate L3 | 4.85 | 3.63 | 8 | 32.46 |
| Laminate L4 | 4.85 | 3.72 | 7.85 | 30.055 |
| Laminate L5 | 3.81 | −18.65 | 7.69 | 27.34 |
| Laminate L6 | 4.59 | −1.99 | 8.97 | 48.55 |
| Laminate L7 | 5.7 | **21.84** | 9.21 | **53.02** |

Figure 8. Impact area Analysis of Laminates (L1 to L7 depicted in (a)–(g)) subjected to the Velocity of 2.89 m s\(^{-1}\) using image J software.
Figure 9. Impact area Analysis of Laminates (L1 to L7 depicted in (a)–(g)) subjected to the Velocity of 4.42 m s$^{-1}$ using image J software.

Figure 10. Deformation area of laminates at 2.89 m s$^{-1}$ and 4.42 m s$^{-1}$.

Figure 11. Failure mechanism of laminates: (a) L5 at 2.89 m s$^{-1}$, (b), (c) L4 at 4.42 m s$^{-1}$. 
4.4. Impact area analysis

The impact surface area was analyzed on the seven different laminates depicted in figures 8(a)–(g), 9(a)–(g) with the aid of Image J software. The contact surface of the impacted laminates examined at macro level showed the presence of varying penetration depth and damage intensity ($L_2 > L_5 > L_4 > L_1 > L_6 > L_3 > L_7$) at 2.48 m s$^{-1}$ and ($L_4 > L_5 > L_6 > L_2 > L_3 > L_1 > L_7$) at 4.42 m s$^{-1}$ obtained from the visual inspection, microstructure analysis and area analysis. The area under the impact regime of the post-impact test was calculated for all the laminates under two different velocities shown in figure 10. The Image J software developed by the National Institute of Health, University of Wisconsin is a powerful tool for analyzing Images is used in this study for area analysis.

For all the impacted velocities on the laminates, the minimum area of damage was found in laminate ($L_7$) $[B/C/B/C]$ ($22.79$ mm$^2$, $28.09$ mm$^2$) due to its increased impact resistance capacity and substantiated less or negligible deformation. The inclusion of low modulus basalt fiber at the superficial side with high modulus carbon fiber in laminate $L_7$, reduced the stress concentration on carbon fiber and improved the impact resistance due to the hybrid effect [27]. Hence in $L_7$ laminate the deformation obtained was lesser than $L_1$ and $L_6$.

4.5. Mechanism of failure of hybrid composite laminates

The mechanism of damage was mainly due to matrix cracking, matrix debonding, delamination, fiber breakage, or a combination of the above [32]. The damage severity of the impacted laminates varied at the two specified velocities. The microscopic analysis of the severely damaged laminates ($L_5$ at 2.89 m s$^{-1}$ and $L_4$ at 4.42 m s$^{-1}$) in figures 11(a)–(c) showed the deformation due to matrix cracking (indentation) and fiber breakage and delamination, which was the characteristic of the penetration deformation. The probable reason for variation in damage intensity was due to more layers of carbon fiber as well as its presence at the posterior side. This carbon fiber acted as the site of high-stress concentration with low strain to failure reducing the damage resistance. The
positioning and inclusion of Basalt fiber reduced stress concentration improved high strain to failure in laminate L7 with increased impact resistance[27]. The above results were consistent with the results of peak force analysis.

4.6. Dynamic mechanical analysis (DMA)

DMA calculates force and deflection for varying temperature/frequency responses. In this study, the test was conducted by varying temperatures with a constant frequency. The storage modulus of the hybrid laminates was more than the homogeneous laminates owing to the combined effect of fibers. The higher storage modulus value relates to higher stiffness with shape recovery during loading. The Laminate L3 and L7 possessed a better storage modulus 47 200 MPa and 44 500 MPa respectively, depicted in figure 12(a) than the other laminates and was hence capable of withstanding better impact which was also found during LVI test. The viscous behavior of the polymer was depicted by the loss modulus factor depicted in figure 12(b). The peak Loss modulus shifting to higher temperature indicates the reduction in chain flexibility with energy dissipated as heat [33, 34]. The tan delta peak reflects the rigidity of the materials. The lower Tan delta peak (0.256) with higher Tan delta temperature (Tg)(218 °C) observed in laminate L7 [B/C/B/C] in figure 12(c) indicated that there was lower segmental mobility with lesser relaxation species owing to the high degree of cross-linking. It is hence concluded that the design requirement on high impact toughness can be provided by Laminate L7 and high mobility of polymer chain with inelastic deformation can be provided by laminate (L3) [C/C/C/B] where higher Tan delta peak(0.42) with lower Tan delta temperature (195 °C) was observed.

5. Conclusion

In this paper DMA test and low velocity impact behavior of hybrid woven composites with different fiber ratios and stacking sequences on the energy absorption capability were analyzed. The following conclusions were drawn:

The laminate (L7) intercalated with basalt and carbon [B/C/B/C], in the ratio of 1:1 stood out from the other due to its superior properties enlisted below:

• The generation of the highest peak force of 5702 N and 9241 N at discrete impact speeds engrossed within a short period.

• The minimum area of damage is (22.79 mm², 28.09 mm²) due to its increased impact resistance capacity.

• The highest elastic energy (4.8 J, 11.7 J) with the lowest energy dissipated (7.57 J, 17.05 J) at two different velocities, indicating the better damage tolerance, preventing penetration/damage in the matrix/fiber.

• The minimum deformation (3.85 mm, 6.09 mm) caused by discrete velocities due to the presence of impact resistance basalt fiber in it.

• A further correlation with the DMA test indicated that the high toughness of the laminate (L7) was due to its higher storage modulus, lesser loss modulus with higher Tg, making it suitable for high-temperature structural applications.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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