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High Strain-Rate and Shock Response of Carbon Supercomposite™

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Abstract

This study focuses on assessing the dynamic behaviors of carbon Supercomposite™ laminates when subjected to high strain-rates and air blast loads, using a shock tube for testing. The investigation aims to understand the response of these advanced materials under extreme conditions, which is crucial for applications in aerospace, military, and other high-performance industries. Supercomposite™ (CZE) prepreg, made up of a 3K plain weave carbon fabric with milled carbon fibers as interlaminar reinforcements impregnated with epoxy, is used to create Supercomposite™ (CZE) laminates. A woven carbon composite (CBE) laminate was also created using 3K plain weave Carbon/Epoxy (CBE) prepreg. Both types of laminates were designed and fabricated using the autoclave process. The dynamic behaviors of CZE and CBE laminate under transverse compression loads were evaluated using a modified Split Hopkinson Pressure Bar (SHPB). The study found that the 3D reinforcement with milled carbon fibers significantly affected the dynamic behavior of the CZE laminate. Stereo imaging videos, captured using two SHIMADZU high-speed video cameras in shock tube experiments, recorded the time history of back surface deflection. The plate specimens exhibited low deflections without any visible damage. The experimentally observed center point deflections of the CZE plates decayed sooner than those of the CBE laminates, indicating an improvement in damping due to the presence of 3D reinforced milled carbon fibers. This research shows that optimized utilization of milled carbon fibers as 3D reinforcement can withstand high stress in the thickness direction and higher energy absorption when subjected to impact and high strain-rate loading.

Keywords

Supercomposite™, GOM Software, 3D Reinforcement, Milled Carbon Fibers, Split Hopkinson Pressure Bar (SHPB), Air-Blast Loads

1. Introduction

Composite materials made of unidirectional fibers or woven fabrics have superior in-plane specific strength and specific stiffness properties compared to metals and ceramics. However, the use of 2D composite laminates in aircraft and automobile applications is limited due to low impact damage resistance and weak through-thickness mechanical properties when compared to conventional materials such as aluminum alloys and steel. Absence of reinforcements in the third direction is the reason for low delamination resistance and weak out-of-plane properties. To improve the interlaminar properties of the 2D laminates, 3-dimensional textile preforms are being developed using various manufacturing techniques like weaving, knitting, braiding and stitching. Also, the undulations or crimps in the yarns may reduce mechanical properties such as tension or compression strengths. However, 3D reinforced composite materials are specially designed to withstand high stress in the third direction, impact, crash, energy absorption, and multiaxial fatigue, overcoming the disadvantages of standard laminated composite materials.

Research work is directed towards evaluating specially designed 3D reinforced composite materials under dynamic compression, and air-blast loads in a shock tube. The literature review focuses on the dynamic behavior of 3D composites, experimental studies and results of computational modeling reported by other researchers. Hosur *et al.* [1] reported critical findings on stitched and unstitched woven carbon/epoxy laminates under high strain rate compression in a modified compression split Hopkinson pressure bar. Stitched/unstitched laminates are fabricated with aerospace grade plain and satin weave fabrics with room temperature curing SC-15 epoxy resin using affordable vacuum assisted resin infusion molding process. For stitching a 3-cord Kevlar thread was used. Dry fabric preforms were stitched in a lockstitch pattern with a stitch pitch of 6 mm. During dynamic loading, both stitched and unstitched plain and satin weave samples showed higher peak stress, greater modulus, and lower strain at peak stress compared to static loading conditions. The peak stress and modulus increased with the strain rate for both unstitched plain and satin weave samples. Unstitched satin and plain weave laminates exhibited higher peak stress and modulus than stitched satin and plain weave laminates for both in-plane loading directions. Additionally, satin weave samples displayed higher peak stress and modulus compared to plain weave samples. This is because the straighter fabric architecture of satin weave results in a lower crimp angle.

Hosur *et al.* [2] studied the impact response of stitched S2-Glass/SC-15 Epoxy composites under both low and ballistic loading. They conducted low-velocity impact tests using an instrumented impact testing machine, and ballistic impact testing using a gas gun facility. The results showed that stitching significantly improved the damage resistance of the laminates by limiting the size of the damage and increasing the ballistic limits.

Baucom *et al.* [3] conducted a study on the damage accumulation in twodimensional (2D) and three-dimensional (3D) woven glass-fiber-reinforced composite panels under repeated transverse drop-weight impact loading conditions. The 2D composite consisted of four layers 2D plain-woven S-2 Glass fabrics, while the 3D composite had a 3D orthogonal weave with approximately the same areal density as the 2D laminate. The study revealed that the 3D composites exhibited better damage tolerance and were able to dissipate more total energy compared to the 2D laminate. This was attributed to the unique energy absorption mechanisms of the crimped portion of z-tows in the 3D composites.

Changgan *et al.* [4] conducted a study on the damage of a 3D orthogonal woven composite circular plate. They subjected the plate to quasi-static indentation using a Materials Test System (MTS) and transverse impact using a modified split Hopkinson bar (SHPB) apparatus. The 3-D orthogonal woven fabric is made up of E-glass filament tows as warp and weft yarns with E-glass filament tows as binder yarns in the Z-direction. The fabric is then impregnated with unsaturated polyester resin using vacuum assisted resin transfer molding. They developed a unit-cell model to analyze the damage of the composites. Finite Element simulation was carried out using the unit-cell model and user material subroutine in ABAQUS/Explicit. The results obtained from FEM simulations aligned with the data obtained from impact experiments.

In their study, Grogan *et al.* [5] examined the ballistic resistance of sandwich composite structures designed for vehicle armor panels. Each sandwich structure included a core material comprising a layer of tiled alumina ceramic, combined with a layer of 2D/3D S-2 glass-based woven composite laminate. These layers were sandwiched between 2D plain weave composite skins. The 2D composite backing was made of plain-woven fiberglass, with the fiber orientation predominantly in the direction of the weave plane. The 3D backing had a similar in-plane fiber preform structure but also included an integral through-thickness fiber, creating a 3D structure. The study found that armor panels with 3D woven backing exhibited fewer instances of delamination and complete penetrations, indicating a higher ballistic efficiency compared to the 2D baseline panels.

Muñoz *et al.* [6] studied the damage caused by low-velocity impacts on a 3D woven hybrid composite material. The 3D composite was manufactured by infusing epoxy vinyl ester resin into a 3D orthogonal woven preform. The preform consisted of multiple layers of woven carbon and S2/glass fiber fabrics with Dyneema fiber as a Z-yarn binder. The 3D woven hybrid composite exhibited improved performance due to the confining effect of the Z-yarns, which helped distribute damage throughout the entire specimen.

Hart *et al.* [7] conducted a study on the post-impact mechanical response of 2D and 3D woven glass/epoxy composite plates and beams with equivalent areal density. The composites with 3D woven reinforcement were created from a single layer S2-glass orthogonal weave fabric comprising of 3 warp and 4 weft layers held together by a through-thickness penetrating Z-tow traveling in the warp direction. On the other hand, the composites with 2D woven reinforcement were made from 5 layers of plain woven S2-glass fabric arranged in a $[0]_5$ configuration, resulting in the same fiber areal density as the 3D woven composites. Epoxy resin was infused into the preforms using vacuum-assisted resin transfer molding (VARTM). When both 3D and 2D composites were subjected to low-velocity impacts, it was observed that the delamination length and opening of the 3D woven composites were less compared to the 2D composites impacted at the same energy level. The 3D woven composites demonstrated better post-impact mechanical performance due to the through-thickness Z-tow.

The blast mitigation characteristics of sandwich structures with composite face sheet materials were previously reported by several investigators. However, few 3D reinforced designs were employed to enhance the impact and damage resistance in composite laminates. The novel 3D reinforced face skin materials proposed in this research are not reported elsewhere in the open literature. The study of the dynamic behaviors of 3D reinforced face sheet materials under high strain rate and blast loading revealed both potential benefits and drawbacks of using milled fibers between laminas in a composite laminate. The lightweight and hard milled carbon fiber shown in **Figure 1** is a black powder made by finely grinding carbon fibers about 200-micron (0.2 mm) long that can be used as a reinforcing material in composites. The dry milled fiber easily dissolves and spread uniformly in resin.

Figure 1. Chopped vs milled carbon fibers (https://www.m-chemical.co.jp/carbon-fiber/en/product/mid/).

The primary objective of this research is to investigate the dynamic behaviors and energy absorption characteristics of 3D reinforced face sheets used in sandwich composite structures. Studies on 3D reinforced composite face sheets were conducted to evaluate the effect of 3D reinforcement with milled fibers, fabric type, and matrix materials on the blast response. The response of these novel 3D reinforced face sheet materials under low-velocity impact and air blast load in a shock tube was used to study the effect of 3D reinforcement on delamination properties and fracture energy characteristics. Dynamic tests employed in this research included dynamic transverse compression on a modified Split Hopkinson Pressure Bar (SHPB), low-velocity impact on a CEAST 9450 drop-weight test system, and air blast loading in a shock tube. Preliminary results on dynamic flexural modulus and response to low-velocity impact are reported by the authors in [8].

The outcome of this research enhances the understanding and utilization of 3D reinforced composite face sheets to improve the energy absorption of sandwich structures for blast and impact hazard mitigation.

2. Materials

3D Reinforced composite laminates with a novel type of reinforcement using milled carbon fibers in Z-direction were considered for this research. The research aims to evaluate two types of face sheet materials for their application in lightweight sandwich structures, namely, Supercomposite™ (CZE) and Control (CBE) Panels. For this research, six CBE and six CZE panels were designed and fabricated using the autoclave process. Both CBE and CZE prepregs utilized T300 3K plain weave carbon fabrics as fiber material, with an areal weight of 205 gsm (grams per square meter). The "T300" means that it typically exhibits a tensile strength of around 3000 MPa and a modulus of approximately 230 GPa. A 3K plain weave carbon fabric, with 3000 filaments in each strand, is produced by interlacing fill and warp strands (1 × 1) at right angles as shown in **Figure 2**.

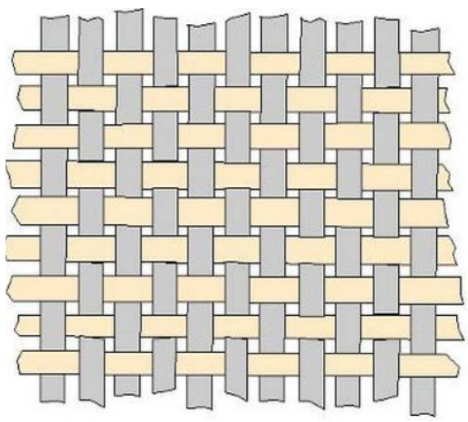


Figure 2. Schematic of plain weave fabric.

A CBE ply is a T300 3K plain-weave carbon fabric impregnated with 42% of 250˚F cure epoxy (Newport NB 301) resin and has an areal weight of 351 gsm. A CZE ply is a 3D prepreg with dense interlaminar reinforcement, is formed by coating T300 3K plain-weave carbon fabric with Z-axis milled carbon fibers and impregnated with a 42% 250˚F cure epoxy (Newport NB 301) resin. The Z-axis fibers used are of the milled PX 30 - 150 μm type. Areal weight of CZE ply is 667 gsm. These Z-axis milled fibers mechanically pin the layers of a laminated composite together as shown in **Figure 3(a)** and **Figure 3(b)**, effectively increasing the interlaminar fracture toughness. This patented mechanism for toughening the interlaminar region distributes multi-axial loads throughout the entire composite, making it possible to produce impact-resistant and durable components that are ideal for high-stress and high-temperature applications [9]. Boston Materials, LLC supplies the CZE prepregs that are suitable for all automated tape laying and roll wrapping manufacturing methods. The Z-axis milled fiber reinforcements enhance toughness by approximately 300%, strength by 35%, and Z-axis thermal conductivity by 300% under quasi-static loading conditions, without compromising stiffness.

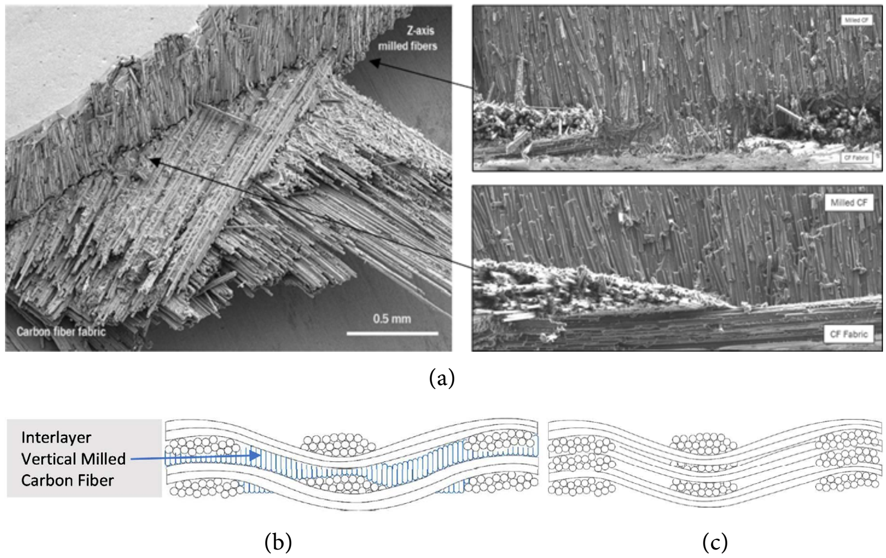
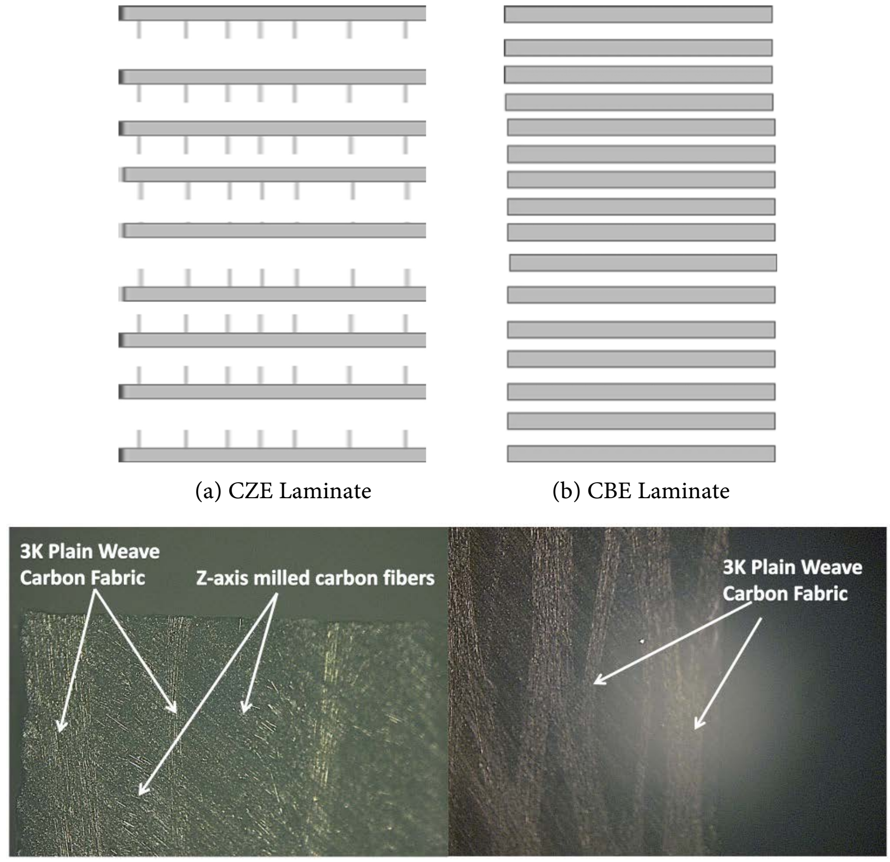


Figure 3. (a) Z-axis milled fibers provide through thickness & interlaminar reinforcement; (b) 2 in-plane milled carbon CZE layers; (c) 3 in-plane CBE layers (Courtesy: Boston Materials, LLC).

Both CBE and CZE laminates of approximate equal thickness and areal weight density are designed and fabricated using CBE plies and CZE plies. In the CZE laminate, 8 CZE plies and 1 CBE ply are stacked together at 0˚/90˚ orientation to be symmetric by placing the CBE ply at the center location. To ensure mid-plane symmetry, the Z-axis milled fibers on top four CZE plies and bottom four CZE plies are oriented towards the CBE ply located at middle surface, as in **Figure 4(a)**. In the CBE laminate, 16 CBE plies are stacked together at 0˚/90˚ orientation to be symmetric with respect to the middle surface as in **Figure 4(b)**.

Both CBE and CZE laminates are cured in an autoclave at 90 Psi for 3 hours. Temperature inside the autoclave is ramped linearly from room temperature up to 250˚ F in the first 100 minutes, maintained at 250˚ F for next 50 minutes and ramped down to room temperature in the remaining time. Average volume density (Kg/m^3) and areal density (Kg/m^2) of CBE specimens were 1434 and 5.56 respectively. Average volume density (Kg/m^3) and areal density (Kg/m^2) of CZE specimens were 1432.66 and 5.62 respectively. Average thickness of CBE and CZE specimens was 3.88 mm and 3.92 mm respectively. Cross-sectional view of CZE with Z-axis milled carbon fibers and CBE laminates captured using a KEYENCE digital microscope are shown in **Figure 4(c)** and **Figure 4(d)**, respectively.



(c) cross section of CZE Laminate (d) cross section of CBE Laminate

Figure 4. (a) CZE laminate with 1 CBE ply at center and eight CZE plies; (b) CBE laminate with 16 plies of 3K plain woven carbon/epoxy (CBE) prepregs; (c) Cross section of CZE laminate with Z-axis milled carbon fibers; (d) Cross section of woven carbon/epoxy CBE laminate.

3. Experiments

3.1. Dynamic Behavior of CZE Laminate Using SHPB

The dynamic response and energy absorption characteristics of CBE and CZE specimens subjected to dynamic compression at high strain-rate in a modified Split Hopkinson Pressure Bar (SHPB) apparatus are presented in this section. SHPB, or Kolsky bar, first developed by Kolsky [10] in 1949, is a well-known test method for characterizing materials at high strain-rates. All tests were carried out on the modified SHPB in the Blast and Impact Dynamics Lab at the University of Mississippi, MS. Maraging steel bars of 19.02 mm diameter were used as striker, incident and transmission bars for conducting experiments on CBE and CZE specimens. A thin elastic-plastic disc made of copper is placed in between the incident and striker bars so that a ramping stress wave pulse is generated to assure a constant stress rate in the sample or specimen. Frew *et al.* [11] have discussed this pulse shaping technique in detail for SHPB compressive test of brittle materials.

Square specimens measuring 3/8” × 3/8” were precisely cut for dynamic compression experiments on SHPB. Incident bar in SHPB is fired by a compression chamber in which air is compressed to various pressure levels. A typical plot of incident, reflected, and transmitted stress pulses are shown in Figure 5(a). Dynamic stress equilibrium was ensured for each specimen during the compression loading using three wave analysis, as shown in Figure 5(b). Experiments were conducted at two compression chamber pressure levels of 30 and 45 psi to achieve two impact velocities of incident bar and to verify the range of strain rates achieved in specimens. Three specimens of CBE and CZE were tested at two pressure levels. Two strain rates of ~950 s^{-1} and ~1150 s^{-1} were achieved in CBE specimens. Two strain rates of ~950 s^{-1} and ~1550 s^{-1} were achieved in CZE specimens. So, material behavior of CBE and CZE was compared at ~950 s^{-1}. An HPV-2 High-Speed Video Camera (Shimadzu Scientific Instruments) with a fixed resolution of 312 × 260 pixels and recording speed of 250,000 fps was used to capture the deformation/failure process during SHPB compression loading. Images of the specimen at initial time point (0 s), initial failure (140 μs) and final fracture (260 μs) are shown in Figure 6.

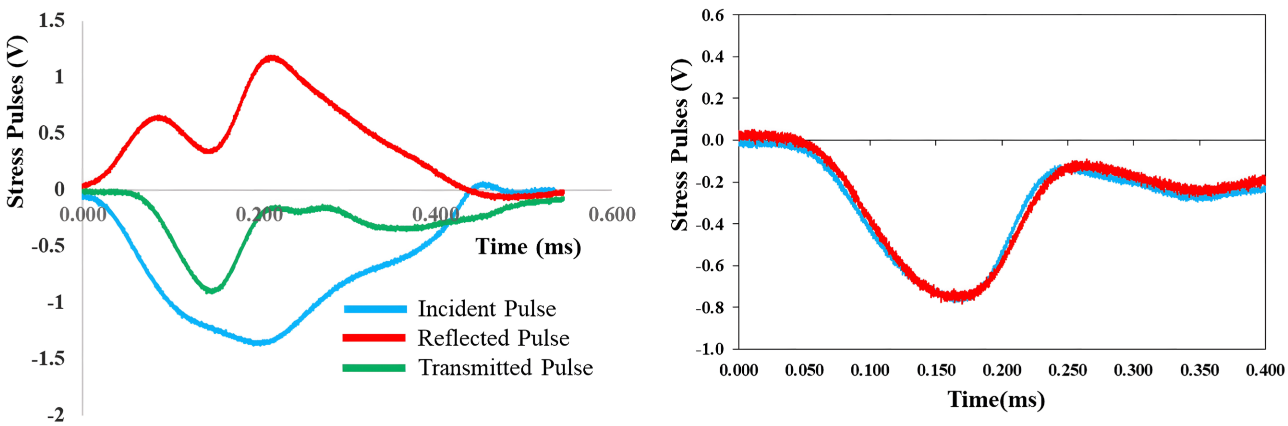


Figure 5. (a) Typical stress pulses of CBE and CZE specimens under dynamic compression; (b) Dynamic stress equilibrium using 3-wave analysis.

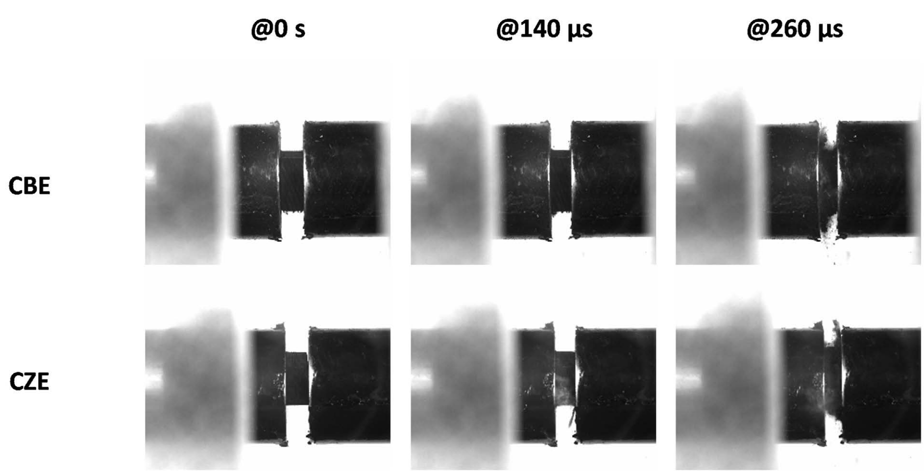


Figure 6. Dynamic compression of CBE and CZE specimens at various time points.

Figure 7 shows typical stress-strain behavior for CBE and CZE specimens. All curves are plotted up to a fracture strain of 20%. It was observed that peak stress of CBE specimens increased with an increase in strain rate. However, in contrast, the peak stress of CZE decreased with strain rate. For both CBE and CZE specimens, specific energy absorption up to 20% strain increased with strain rate. Overall peak stress sustained by CZE specimens was less than CBE specimens. At a strain rate of 950 s^{-1}, both induced peak compressive stress and specific energy absorption capacity of CBE specimens are higher than CZE specimens. The percentage drop of peak stress and specific energy absorption in CZE specimen is approximately 27% even after removing 50% of carbon plies from a CBE specimen. This provides solid evidence that optimization of number of carbon plies in a CZE laminate up to 12 may provide resisting capability to sustain same peak stress and have specific energy absorption capacity as that of a CBE specimen with 16 plies of plain weave carbon fabric. **Figure 8(a)**, **Figure 8(b)** and **Table 1** show the values of maximum stress induced during dynamic compression and specific energy absorption up to 20% strain for both CBE and CZE specimens.

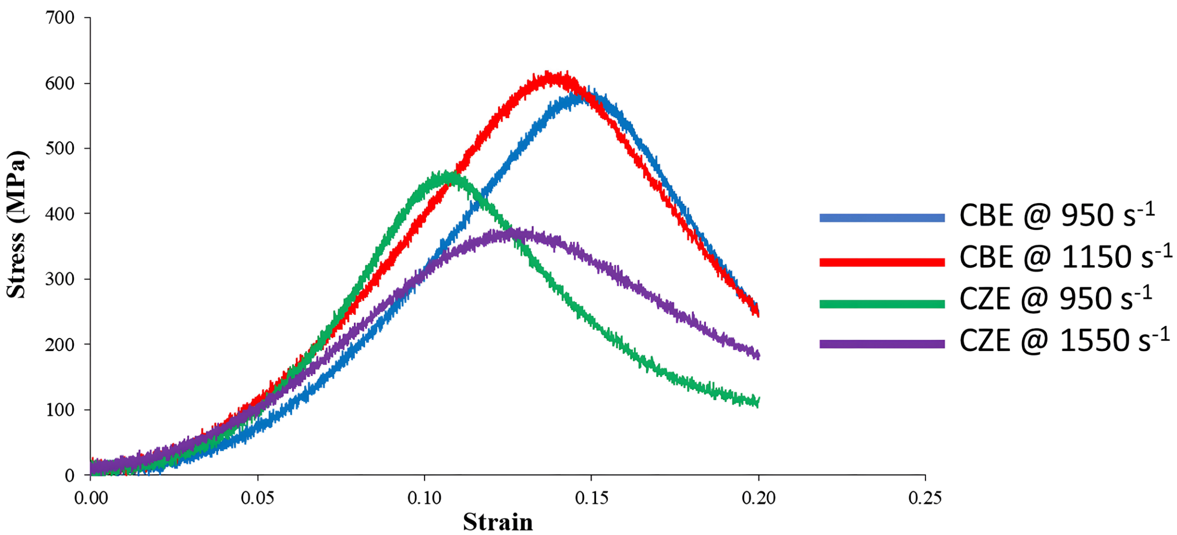


Figure 7. Stress-strain plots of CBE and CZE specimens at different strain rates.

Table 1. Maximum stress and specific energy absorption capacity of CBE and CZE specimens.

Specimen Name	Strain Rate	Maximum Stress	Specific Energy Absorption (SEA)
	s^{-1}	MPa	KJ/Kg
CBE	950	612	43.17
	1150	627	46.34
CZE	950	445	31.07
	1550	361	34.62

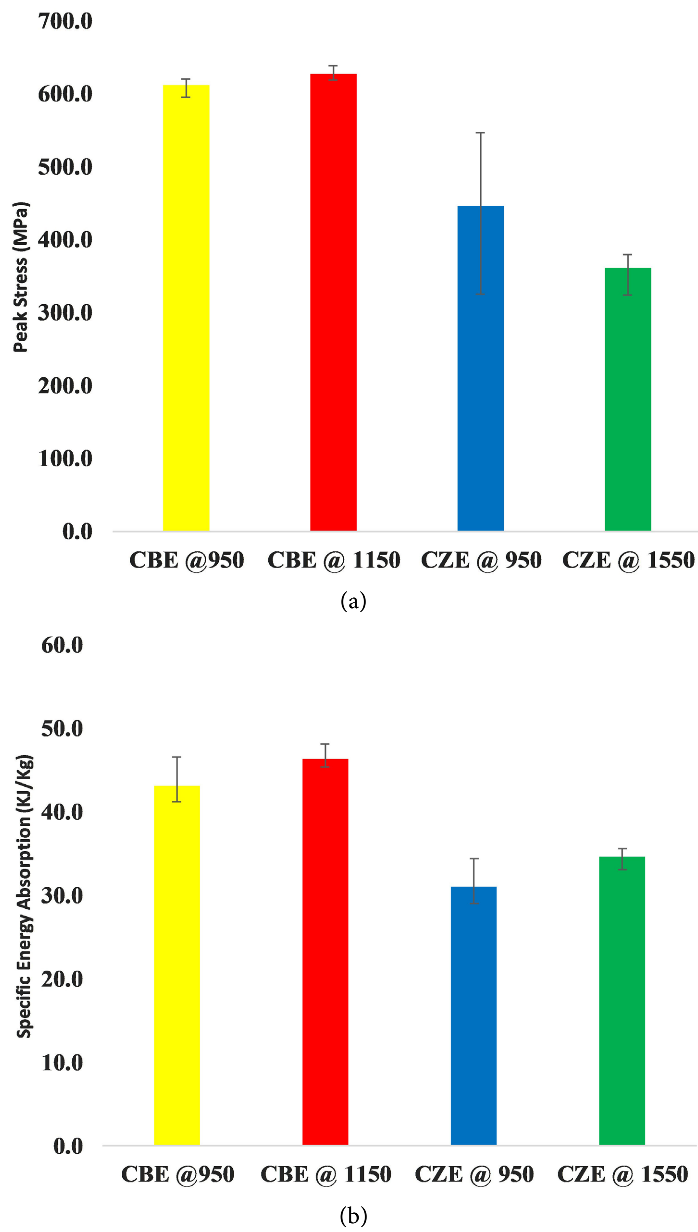


Figure 8. (a) Peak stress (MPa) of CBE and CZE specimens; (b) Specific Energy Absorption capacity (KJ/Kg) of CBE and CZE specimens.

3.2. Shock Response of CZE in a Shock Tube

Along with the low velocity impact response and dynamic behavior of carbon composites, response to an air blast loading in a shock tube is also required for using these materials as face sheets in sandwich structures. Carbon CBE and CZE circular plate specimens of 4" diameter as shown in **Figure 9** were cut to be tested under air blast load in a shock tube. Consistent air blast loads were generated in a shock tube with a high-speed valve actuating system. Two Kulite HKS-HP-375-5000SG pressure transducers were used to capture the incident and reflected pressure profiles. Repeatable pressure profiles on three specimens each of CBE and CZE specimens are plotted in **Figure 10(a)** and **Figure 10(b)** respectively.

Figure 9. Circular plate specimens of control (CBE) and CZE materials.

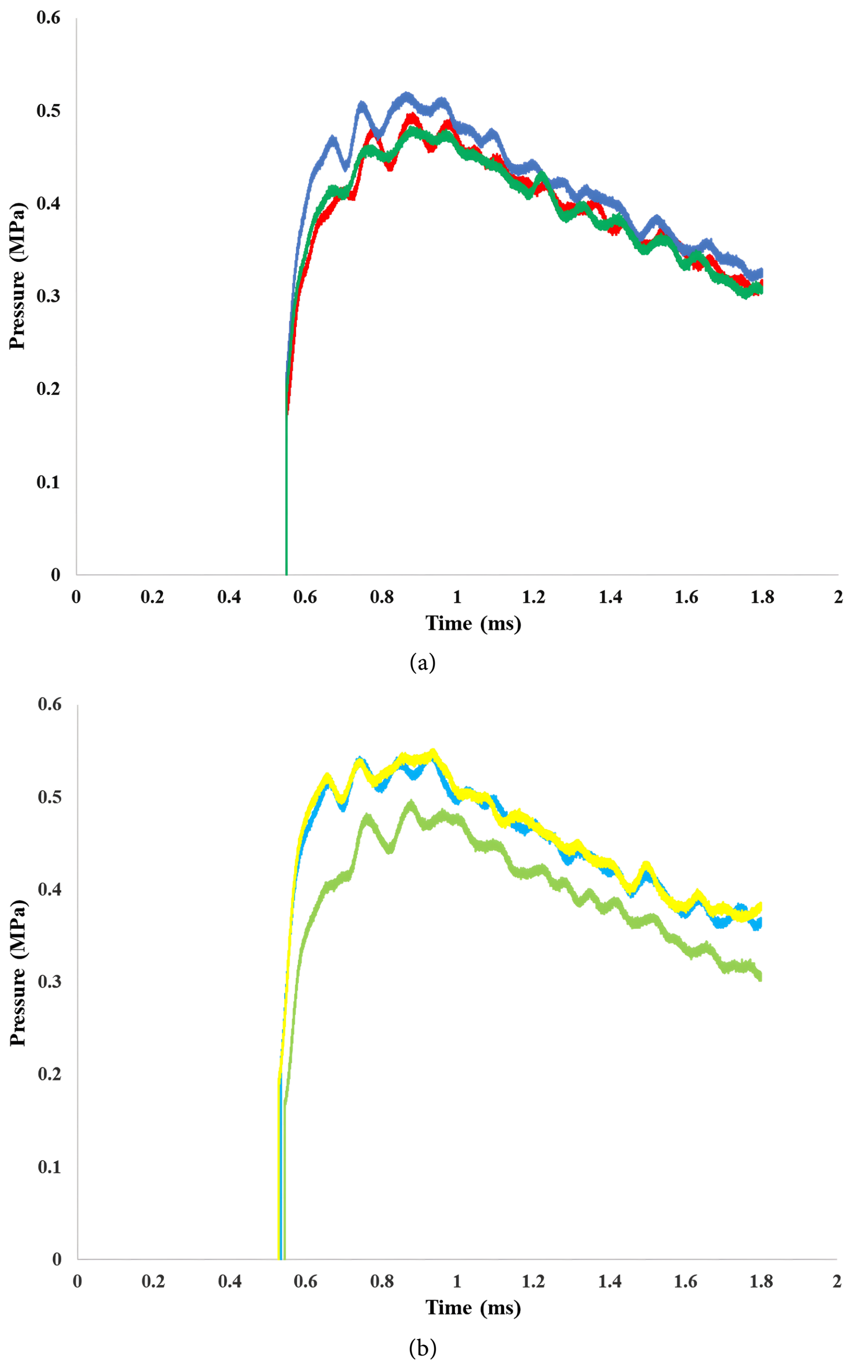
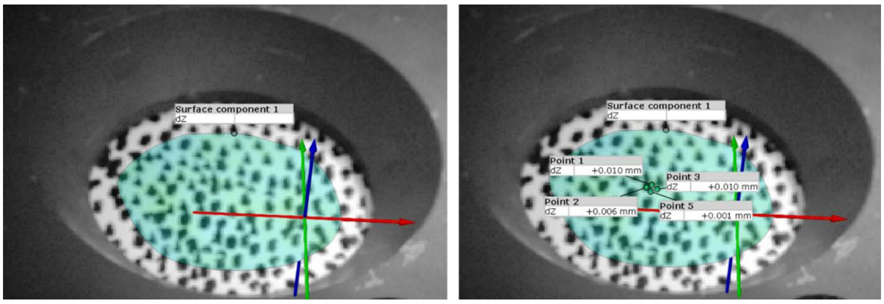


Figure 10. (a) Pressure profiles of air blast wave subjected on CBE specimens (b) Pressure profiles of air blast wave subjected on CZE specimens.



(a) (b)

Figure 11. (a) Image of speckle coated plate specimen inside a shock tube imported into GOM software (b) Inspection points at the center for evaluating out of plane deflection.

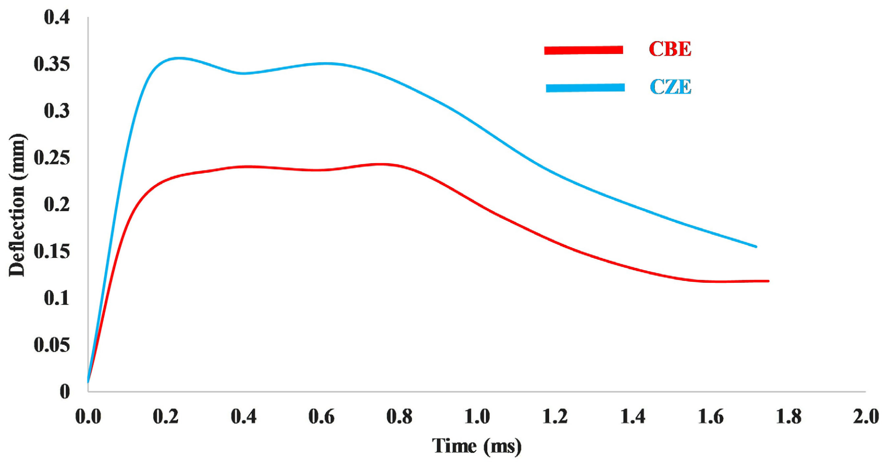


Figure 12. Out of plane maximum deflection with respect to time at the center of three CBE and CZE plate specimens subjected to air blast load.

Two Shimadzu HPV2 high speed digital imaging cameras were used to capture the back surface of the plate specimen during the shock event. 3D Digital Image Correlation technique based GOM software was used to obtain full field strain and out of plane deflection at the center point of the plate specimens coated with speckle coating. Inspection points were created in GOM software at the center of the plate. Out of plane deflection at the center of the plate specimen is extracted using the inspection points and are shown in Figure 11. Out of plane deflections of 0.24 mm and 0.36 mm were observed in CBE and CZE plate specimens as shown in Figure 12. CBE specimens with 16 plain weave carbon fabrics offered more resistance to shock load leading to a less out of plane deflection at center. CZE specimens with 9 CZE plies offered lesser resistance to the shock load and had higher deflection at the center. Out of plane deflection and in-plane full fields were very fluctuating all over the plate specimen due to the anisotropic nature of the composite plates during the load transfer across the laminas. Deflection in the plate specimens was evaluated up to 1.8 milliseconds of the shock loading in the shock tube. Due to the low-pressure blast load, center point deflections of plate specimens were observed to be very minimal in value without any visible damage. Center point deflection of CZE plate specimens dampened out soon, as they have higher damping properties than CBE specimens as seen [8]. Also, Magnitude of center point deflection did not double even after removing 50% of carbon fabric material in the CZE laminate.

4. Conclusions

Summary of findings based on the experimental data from the split Hopkinson bar and shock tube is as follows:

- Peak stress increased with an increase in strain rate for CBE specimens.
- Peak stress of CZE decreased with strain rate.
- Overall, peak stress sustained by CZE specimens was less than CBE specimens.
- The percentage drop of peak stress and specific energy absorption in CZE specimens is approximately 27%, even after removing 50% of carbon plies from the CBE specimens.
- Specific energy absorption up to 20% strain increased with strain rate for both CBE and CZE specimens.
- CBE specimens with 16 plain weave carbon fabrics offered more resistance to shock load, resulting in less out-of-plane deflection at the center.
- CZE specimens with 9 CZE plies offered less resistance to the shock load and had higher deflection at the center.
- Out-of-plane deflection and in-plane full fields were very fluctuating across the plate specimen due to the anisotropic nature of the composite plates during load transfer across the laminas.
- Due to the low-pressure blast load, center point deflections of plate specimens were observed to be very minimal in value without any visible damage, even after removing 50% of carbon plies from the CBE specimen.
- Center point deflection of CZE plate specimens dampened out soon when compared to CBE specimens. This is due to increase in damping in Z-direction along the axis of milled carbon fibers.

This study provides evidence that optimization of number of carbon plies results in CZE laminate to withstand same peak stress and specific energy absorption (SEA) similar to that of a CBE laminate with higher number of carbon fabric layers. So, optimized utilization of milled carbon fibers as 3D reinforcement can withstand high stress in the third direction and higher energy absorption when subjected to impact and high strain-rate loadings. Thus, by utilizing the milled carbon fibers obtained as a by-product of machining carbon composites and by reducing 16 to 9 plies in the carbon fabric (~50% reduction), best economic lightweighting option and sustainable material solution can be obtained for structural applications without compromising mechanical behavior at high strain-rate.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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