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Dynamic Response of Pultruded Glass-Graphite/Epoxy Hybrid Composites Subjected to Transverse High Strain-Rate Compression Loading

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Abstract

In a previous study, the energy absorption and dynamic response of different combinations of cylindrical fiber-reinforced pultruded hybrid composite samples made of unidirectional glass and graphite fiber/epoxy, were investigated under longitudinal compression loading. It was found that placing glass fibers in the inner core of composites resulted in a higher ultimate compressive strength and specific energy absorption. In this study, the dynamic responses of pultruded glass-graphite/epoxy hybrid specimens with rectangular cross-section subjected to transverse compression loading are reported. Crack initiation and propagation was monitored using a high-speed video camera, and the effects of hybridization were analyzed. It was found that the location of glass or graphite fibers inside the pultruded composites has no significant effect on the ultimate compressive strength under such transverse compression loading. The energy absorption in all the hybrid specimens was almost identical. Graphite/epoxy composite showed higher specific energy absorption due to its lower density, and glass/epoxy composite had the lowest specific energy absorption.

Keywords

Pultruded Composites, High Strain-Rate Compression Loading, SHPB, Energy Absorption, Transverse Loadings

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1. Introduction

Composites are utilized because they have desired properties which cannot be attained by other types of constituent materials. Fibrous composites, including reinforcing fibers embedded in a matrix material, are commonly used in different applications. Fiber-reinforced composite materials present different features in terms of stiffness, specific strength, deformation etc. Their usage encompasses a wide range of applications in automotive, aerospace and marine.

The two most common reinforcing fibers are glass and graphite. Glass fibers have high tensile strength and low tensile modulus. On the other hand, graphite fibers possess very high tensile modulus, low weight and low impact resistance. A number of investigations have been carried out on pultruded composites [1]-[13]. Their results illustrate that hybridization with different percentages of glass and graphite within the same epoxy matrix has a significant effect on the mechanical properties.

In many applications, composite materials are subjected to dynamic loading, which is produced by vibration or wave propagation [14]. Therefore, it is necessary to investigate the strain rate sensitivity, failure modes and other behaviors under dynamic loading. Several studies have been performed on strain rate sensitivity [15]-[17]. Ochola *et al.* [18] tested a glass fiber reinforced polymer at different strain rates. The results show that the value of mean ultimate compressive stress for this composite increased by 20.9% as the strain rate is increased from 10^{-3} to 450 s^{-1}. Various set-ups like drop-weight and Split Hopkinson Pressure Bar (SHPB) have been used [19] [20].

Furthermore, direction of loading and fiber orientation play an important role in dynamic behavior of composite materials. Yokoyama *et al.* [21] investigated cubic specimens of carbon/epoxy laminates behavior in all three principal material directions under high strain rate compression test and discussed the failure mechanism of composites. They show that by increasing strain rate, while the compression is along the fiber direction, ultimate strength increases, and energy absorbed up to failure strain decreases. In a previous investigation by the authors [22], the energy absorption and dynamic response of different combinations of glass and graphite pultruded composites under longitudinal compression loading was studied. It was found that locating glass fibers in the inner core raises the ultimate compressive strength and results in better dynamic behavior of the composite. Since there are many applications where loads are applied in transverse direction, optimization of pultruded composite materials from this point of view is necessitated.

The purpose of this study is to analyze the dynamic behavior and energy absorption of pultruded glass-graphite/epoxy hybrid composites by applying transverse compression load at high strain-rate. A modified SHPB test system has been used for producing dynamic load. Additionally, a high-speed camera was deployed to record the events and monitor crack initiation, propagation and failure of samples during the tests.

2. Specimen Details

Samples for SHPB test were cut from long rectangular cross-section composite beams manufactured by the pultrusion process (Pulstar 804 machine). Glass and graphite fibers were used for reinforcement, while volume fraction of epoxy was maintained at 40%. The graphite fibers were AS4W-12K (Hercules), the glass fibers were E-Glass (PPG 2001, #12), and the epoxy was EPON 862/W/537 (Shell Chemical Company, USA). All the SHPB test samples were cut precisely in 6.6 mm × 6.6 mm section from 3.3 mm thick long rectangular beams (**Figure 1**).

The six fiber combinations with layup sequence for hybrid composite test samples are shown in **Table 1**. Reference [23] describes more details of the manufacturing process for these pultruded beam samples. The measured bulk densities of the specimens are shown in **Table 2**.

3. Experimental Technique

The high strain-rate testing was carried out using a modified SHPB located at the Blast and Impact Dynamics Laboratory, University of Mississippi. A schematic of SHPB set-up is shown in **Figure 2**. It consists of a striker bar, a strain gaged incident/input bar and a transmitter/output bar. The bars are made of maraging steel. Specimens are sandwiched between the incident and transmission bars. A copper pulse shaper was applied to attain a triangular incident pulse. Petroleum jelly was used to place specimen between the incident and transmitter bars, and also to avoid friction and shear effects on the samples during testing.

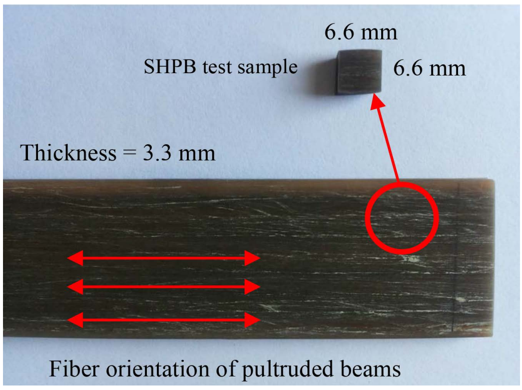


Figure 1. Dimensions of test samples cut from rectangular cross-section pultruded beams.

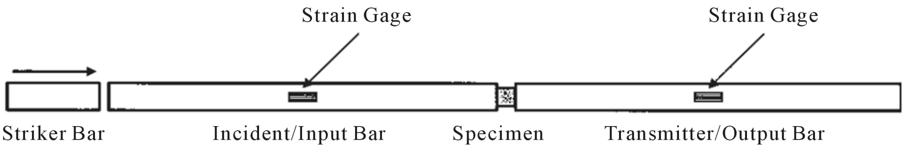


Figure 2. Schematic of a Split Hopkinson Pressure bar [20].

Table 1. Fiber combinations with layup sequence for hybrid composites [23].

Specimen ID	Fiber Volume Fraction (%)		Resin System (%)	Cross Section
	Graphite (AS4W-12)	Glass (PPG 2001, #12)	EPON 862 Resin System	
CFMIX01	60	0	40	
CFMIX02	0	60	40	
CFMIX03	20	20 + 20	40	
CFMIX04	30	15 + 15	40	
CFMIX05	20 + 20	20	40	
CFMIX06	15 + 15	30	40	

Table 2. Measured average bulk densities of the pultruded hybrid specimens.

Density (kg/m^3)	**CFMIX01**	**CFMIX02**	**CFMIX03**
	1569	1924	1807
	CFMIX04	**CFMIX05**	**CFMIX06**
	1809	1749	1784

A high-speed video camera (HyperVision HPV-2, Shimadzu Corporation, Japan) was employed to record the events and monitor the crack initiation, propagation and failure of samples during the SHPB compression loading tests. One hundred and two frames of each event were recorded at a frame rate of 500,000 fps. Two 1000W strobes were used to provide the required lighting.

4. Results and Discussion

Six combinations of pultruded glass-graphite/epoxy hybrid samples were tested under transverse compression loading. **Figure 3** shows typical stress wave pulses including incident, reflected and transmitted pulses. For validating the dynamic equilibrium condition, a test specimen must be in force equilibrium [22]. The stresses in both interfaces of each specimen were calculated to ensure that equilibrium was attained (**Figure 4**).

Five samples were tested for each combination at an average strain rate of 800 s^{-1}. **Figure 5** shows typical stress-strain behavior for all the combinations. All curves are plotted until shattering point of each specimen, with high-speed photography utilized for capturing this moment. They are essentially coincident with each other until ultimate compressive strength with all of them possessing equal initial stiffness. This synchronization appears to be from matrix dominant response for these pultruded composites, with compression load applied in the transverse direction.

Figure 6 illustrates the average ultimate compressive strength for six specimens of each combination. CFMIX01 with 60% graphite possess the highest ultimate compressive strength and CFMIX02 with 60% glass has the lowest. The compressive strength of hybrid with 40% graphite in the outer layer and 20% glass in the

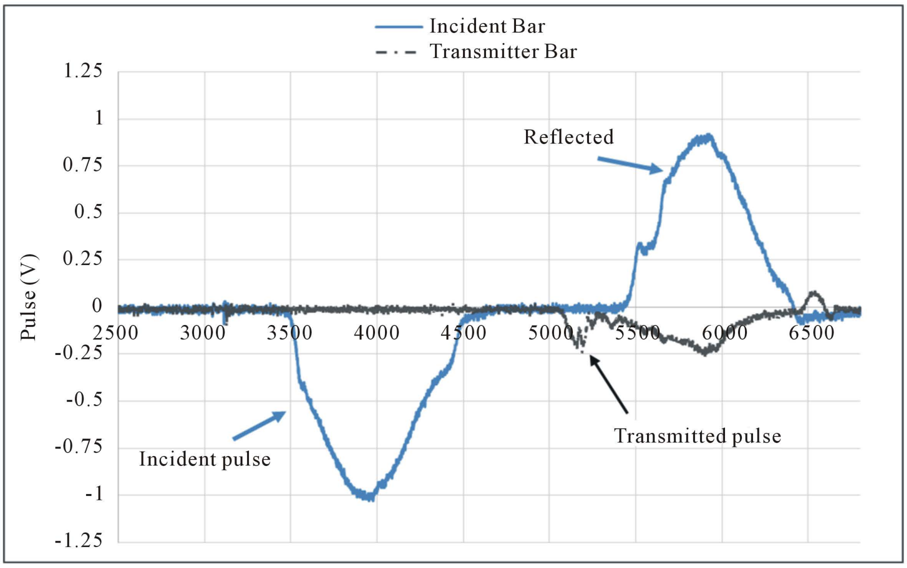


Figure 3. Typical incident, reflected and transmitted pulses from SHPB test of a pultruded hybrid composite sample.

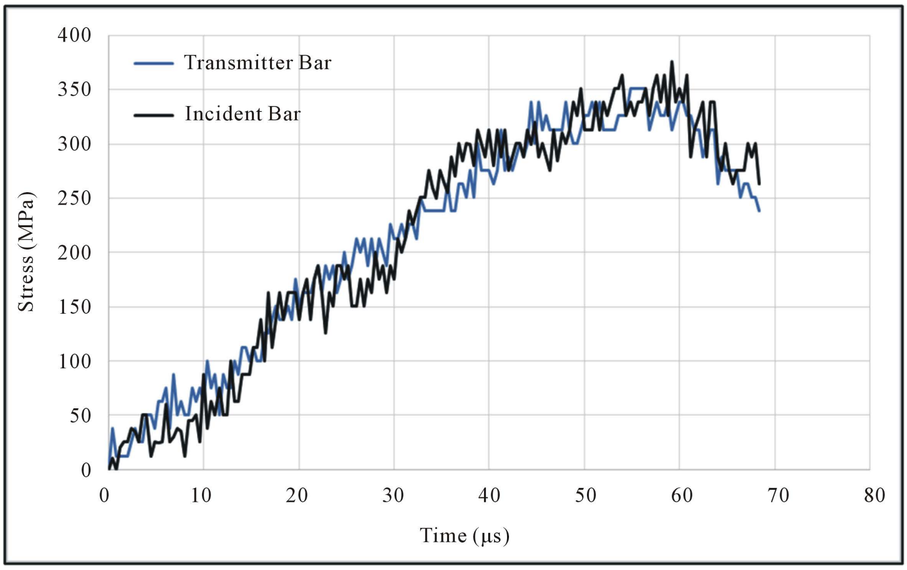


Figure 4. Validation of stress equilibrium for tested pultruded hybrid composite sample.

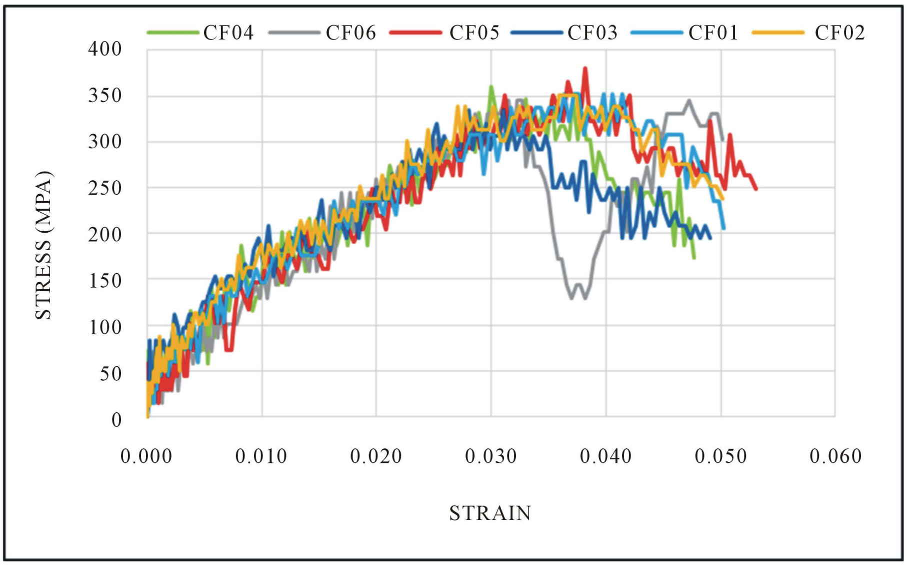


Figure 5. Typical stress-strain curve for all hybrids tested by SHPB transverse compression loading.

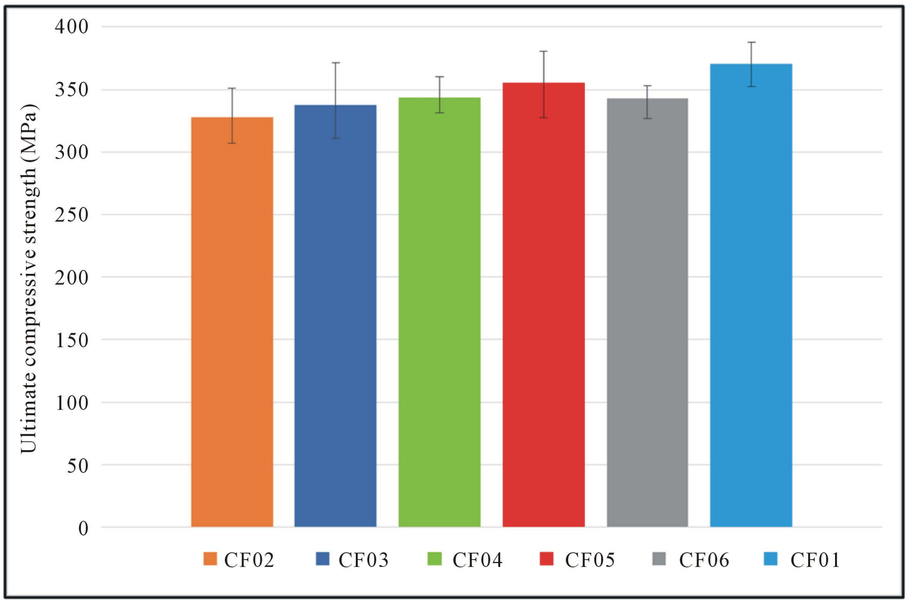
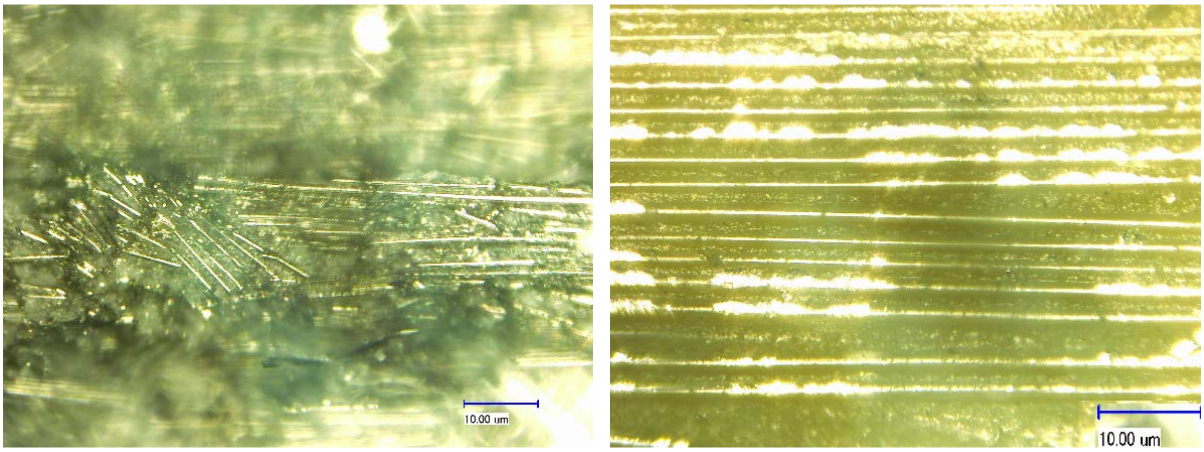


Figure 6. Ultimate compressive strength (MPa) for all hybrids tested by SHPB transverse compression loading.

core, CFMIX05, is slightly nearer to graphite/epoxy. The small difference between the highest and lowest ultimate compressive strength demonstrates that using different portions of glass and graphite fibers does not dramatically change the compressive strength under transverse compression dynamic loading. This small difference results from the stronger bond between graphite fiber and epoxy matrix compared to the bond between glass fiber and epoxy matrix, perhaps due to the sizing of graphite fibers for improving adhesion during pultrusion manufacturing. As can be seen in **Figure 7**, graphite fibers (**Figure 7(a)**), have mostly disintegrated after the compression event while glass fibers (**Figure 7(b)**), remained almost intact.

As can be seen in **Figure 5**, all the specimens absorbed almost equivalent amounts of energy (integration of area under stress-strain curve) during the dynamic compression tests, with specimens having greater volume fraction of graphite fibers absorbing marginally more energy. CF06 samples showed a distinct drop towards the



(a) (b)

Figure 7. Micrograph view of specimens after transverse compression event (500×). (a) Graphite fibers; and (b) Glass fibers.

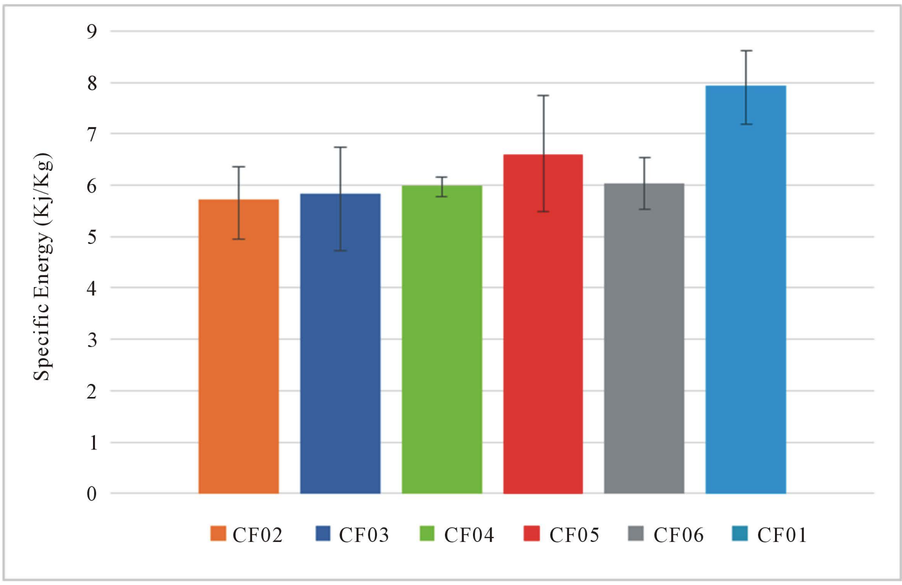


Figure 8. Specific energy absorption for all hybrid specimens tested by SHPB under transverse compression loading.

end of the compressive event, perhaps due to the larger portion of glass fibers located in the central region. However, the specific energy absorption (energy absorbed per unit mass) for each specimen is distinct due to their different densities (**Figure 8**). As shown in **Table 2**, specimens with more graphite fibers have lower density, which resulted in higher specific energy absorption. Specimens with 60% graphite (CFMIX01) and 40% graphite (CFMIX05) show the highest specific energy absorption; while 60% glass (CFMIX02) exhibits the lowest specific energy absorption.

As mentioned, a high-speed video camera was deployed to monitor the crack initiation, propagation and failure of samples during the SHPB compression loading tests. For these samples, the event (from time zero to crack initiation of specimen) takes 55 µs -75 µs. Four stages of specimen CFMIX05 deformation are shown in **Figure 9**. The stress versus time history of this specimen is depicted in **Figure 10**. Three red dots show starting point, ultimate strength point and crack initiation point. The maximum load (ultimate strength) occurs at 51 µs and crack initiates at 66 µs. The image at 79 µs shows that the fiber glass in the specimen core detaches from epoxy matrix. The results indicate that the entire sample has not been completely damaged at the peak stress. It should be noted that the compression load is applied transverse to the fiber direction, *i.e.*, load is perpendicular to the fiber orientation for each of the tested hybrid composites.

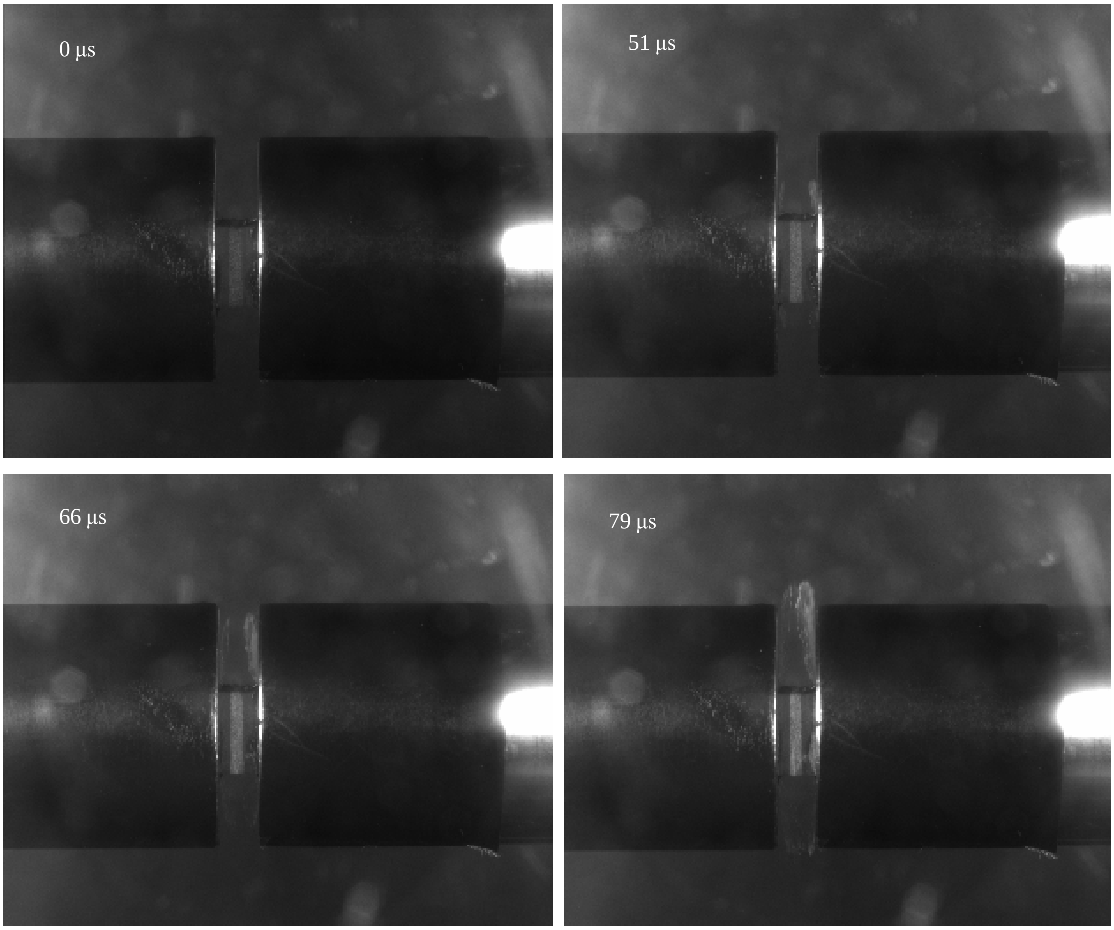


Figure 9. Four stages of specimen CFMIX05 deformation under transverse compression at different times.

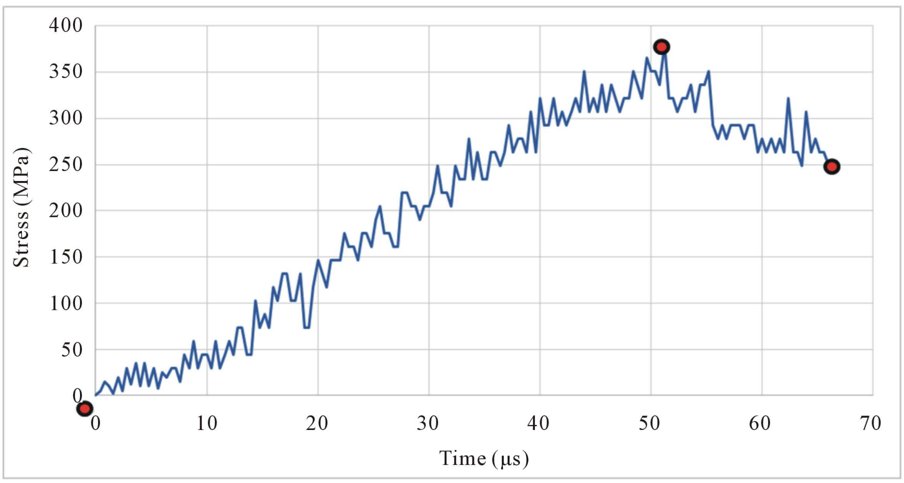


Figure 10. Stress versus time history of CFMIX05 under transverse compression loading. Three red dots show st.

A comparison between this study and previous investigation conducted by the authors on longitudinal compressive loading [22] shows dramatic difference in the dynamic response of graphite-glass/epoxy pultruded hybrids under transverse and longitudinal loading conditions. **Figure 11** and **Figure 12** show the ultimate compressive strength and average specific energy of cylindrical hybrid combinations where GL60, GR60, GL30 and

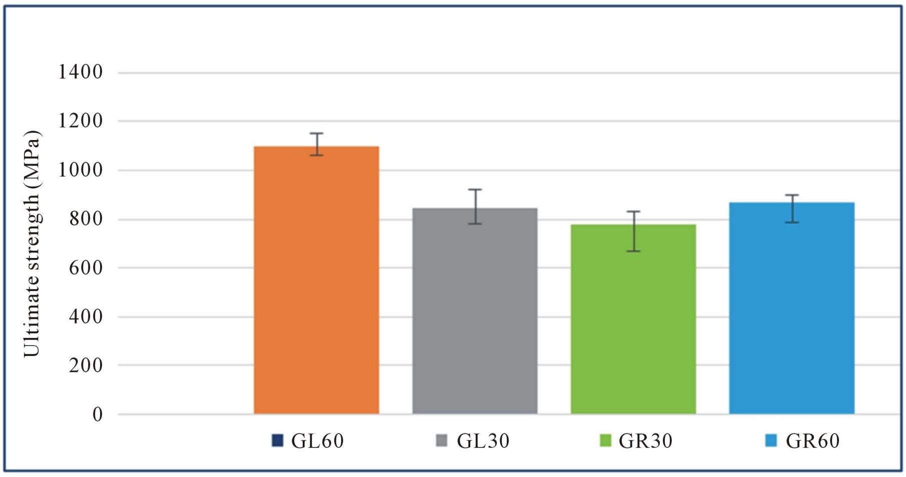


Figure 11. Ultimate compressive strength for different combinations of pultruded hybrids under longitudinal compression loading [22].

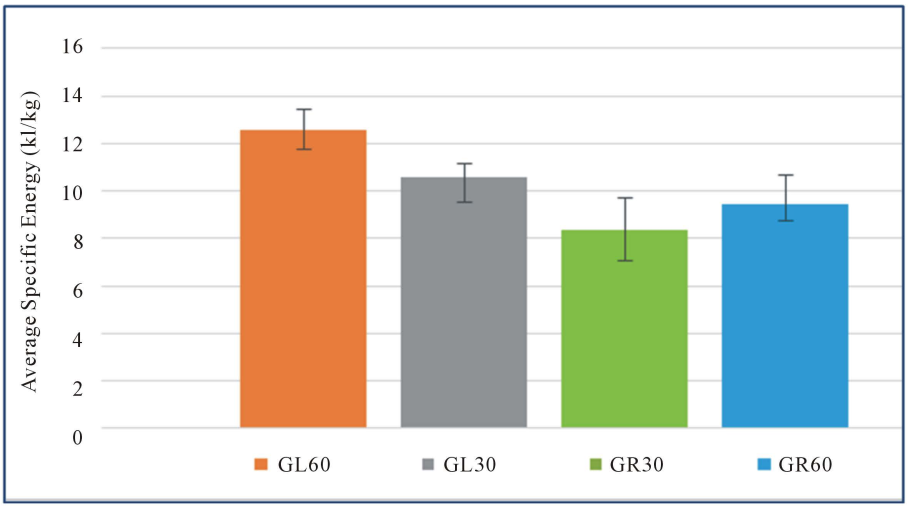


Figure 12. Average specific energy absorption for different combinations of pultruded hybrids under longitudinal compression loading [22].

GR30 have respectively similar hybrid combinations of CF02, CF01, CF06 and CF04 used in this study. It is apparent that under transverse compression dynamic loading, ultimate compressive strength of graphite-glass/epoxy pultruded hybrids is about one-third of that under longitudinal compression dynamic loading. On the other hand, specific energy absorption under longitudinal compression loading shows an opposite trend to the response under transverse compression loading.

5. Conclusion

In this investigation, six combinations of pultruded glass-graphite/epoxy hybrids have been experimentally studied under transverse high strain-rate compression loading, using a modified SHPB. It was observed that failure of specimens loaded along transverse direction was dominated by matrix failure. It was also observed that 60% graphite (CFMIX01) has the highest ultimate compressive strength. The ultimate compressive strength was also marginally greater with higher percentage of graphite. This marginal difference results from the stronger bond between graphite fiber and epoxy compared to that between glass fiber and epoxy, perhaps due to the sizing of graphite fibers for better adhesion. Location of glass or graphite fibers inside the pultruded composites had no significant effect on the ultimate compressive strength under transverse compression dynamic loading. While all specimens absorbed almost equivalent amount of energy, the graphite/epoxy samples demonstrated significantly higher specific energy absorption compared to the other combinations. This was due to its lower density, while glass/epoxy showed the lowest specific energy absorption. Moreover, comparison between this study and a previous investigation conducted by the authors showed significant differences in the response under longitudinal and transverse dynamic loading.

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