DYNAMIC RESPONSE OF A CARBON FIBER - EPOXY COMPOSITE SUBJECT TO PLANAR IMPACT

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Abstract
Unidirectional carbon fiber reinforced epoxy composite samples were tested to determine the response to one dimensional shock loading. The material tested had high fiber content (68% by volume) and low porosity. Wave speeds for shocks traveling along the carbon fibers are significantly higher than for those traveling transverse to the fibers or through the bulk epoxy. As a result, the dynamic material response is dependent on the relative shock – fiber orientation. Shocks traveling along the fiber direction in uniaxial samples travel faster and exhibit both elastic and plastic characteristics over the stress range tested; up to 15 GPa. Results detail the anisotropic material response which is governed by different mechanisms along each of the two principle directions in the composite.

1 Introduction
Fiber reinforced composites are widely used in automotive, aerospace, and other high performance construction applications where both light weight and high strength are critical design elements. In their simplest form, composite materials consist of high strength fibers embedded in a light weight binder matrix. Under shock loading, fibers can exhibit different response along versus across the fiber direction. Thus, the reinforcing fibers in composite materials necessarily imply an anisotropic response by virtue of imposing directionality in the material. Despite this, most dynamic material models assume isotropic response. In order to develop a generally applicable anisotropic material model for fiber reinforced composites, high quality, experimental data is required to define the material response.

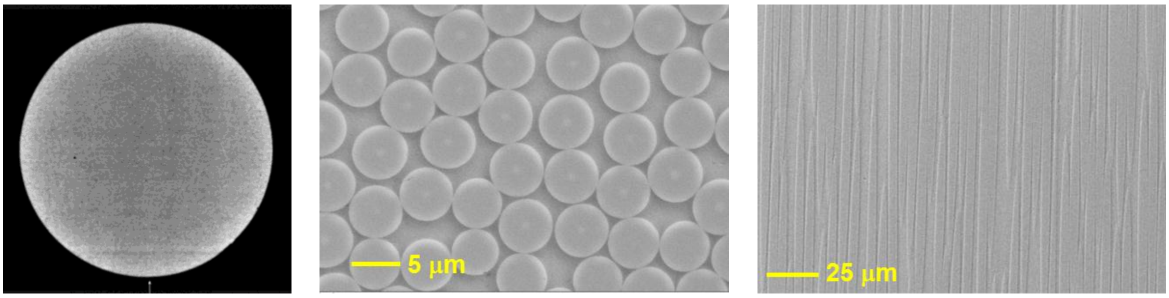
A series of plate impact experiments were conducted to determine the dynamic response of a carbon fiber reinforced epoxy (CFE) composite material. The material tested was selected to have a strong anisotropic response and low porosity. Anisotropy results from orienting the carbon reinforcing fibers in the epoxy matrix. Previous work on carbon fiber reinforced polymers has shown that sound speeds are significantly faster along than across the fibers [1, [2]. Low porosity is important to any shock loading experiment. Pores in the test material lead to localized heating under shock loading and will result in the observation of heterogeneous response. In addition, additional heating may affect the constituent material response. In order to isolate the anisotropic response due to the reinforcing fibers in the composite, samples with extremely low porosity were used.

2 Experimental Details

2.1 Materials tested

The CFE material tested was manufactured by the U.S. Air Force Research Laboratory (AFRL) from a commercially available carbon fiber laminate system; Hexcel IM7/8552. This product consists of epoxy impregnated sheets of 5 μm diameter PAN carbon fibers. The fibers are unidirectional, meaning all the carbon reinforcing fibers were oriented in a single direction (defined as 0°). The composite is made by stacking a large number of these sheets, applying pressure, and heating to cure the epoxy. The number of sheets used dictates the final thickness of the composite. For these tests, samples were produced between 3 mm and 25 mm thick with an average density of 1.579 g/cm^3. With this technique, the fibers always lie in the plane of the plate being produced. The process is similar to that used in the production of aerospace components and results in extremely low porosity. The carbon fibers comprised 68% of the total volume. All of the test samples were assembled to maintain the unidirectional fiber orientation; no cross-ply material was tested. Thus, there are two principle directions in these materials; the fiber direction (0°) and transverse to the fibers (90°). Testing was performed along each of these directions. For shocks traveling along the fibers (0°) samples were cut from the thick plates resulting in 3 and 6 mm thick, 25 mm diameter disk shaped samples. For shocks traveling transverse to the fibers (90°), 75 mm diameter samples were cut from 3 and 6 mm thick plates.

A variety of evaluation methods was used to ensure low porosity in the test samples. Samples were x-rayed to look for large voids. None were found in any of the test samples. A representative image is shown in Figure 1a where the contrast uniformity indicates no void presence. SEM microscopy was also used to evaluate the uniformity of the fiber arrangement. Results showing the impact surface of 0° and 90° samples are shown in figure 1b and 1c respectively. The images show uniform fiber spacing and no evidence for voids or fiber poor regions in the samples.



(a) (b) (c)

Figure 1. Results of select non-destructive testing to ensure sample quality prior to testing. Shown are (a) an x-ray image, and SEM micrographs of the impact surface of (b) 0° and (c) 90° samples.

Prior to shock testing, samples were evaluated via ultrasonic testing to determine ambient sound speeds along each of the principle directions. Results of tests on multiple samples indicate sound speeds of 10.763 km/s along the fibers (0°) and 3.042 km/s transverse to the fibers (90°). All transverse directions (through thickness or within the plane of the original manufactured plate) were found to be equivalent.

2.2 Experimental design

Plate impact experiments were conducted utilizing the 89 mm bore powder driven gas gun and the 100 mm bore compressed gas gun facilities at Sandia National Laboratories. Shock experiments were conducted in two different configurations, shown in figure 2, based on the fiber orientation. For shocks traveling along the fibers (0°, figure 2a) two samples, nominally 3 and 6 mm thick, are used. Each sample is backed by a PMMA window and monitored with a single velocity interferometer system for any reflector (VISAR) [3] probe (indicated by arrows in the figure). PMMA was used as the shock impedance is closer to that of the CFE than other window choices minimizing wave interactions at the CFE – PMMA interface. In addition, three LiF windows, coated on the impact surface with a thin Al reflector, are monitored with VISAR and used to determine the time of impact for each sample. For shocks traveling transverse to the fibers (90°, figure 2b), a single, larger diameter sample is used. This is done to account for the increased wave speed along the fibers in the now transverse direction to avoid loss of the one dimensional shock conditions due to edge release during the experiment. As before, the sample is backed with a PMMA window. In this orientation it was found to be necessary to use a thin PMMA buffer to protect the optical reflector from abrasion. The sample in this configuration is monitored with three VISAR probes arranged at the center and set at a fixed radius at 0 and 90 degrees in the plane of the sample. Four LiF windows equally spaced around the periphery are used to determine the time of impact at each VISAR location.

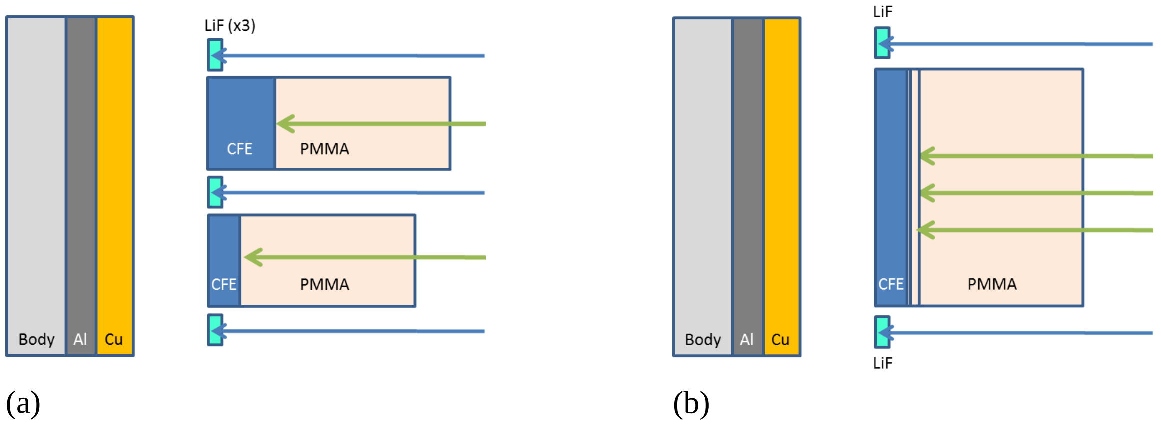
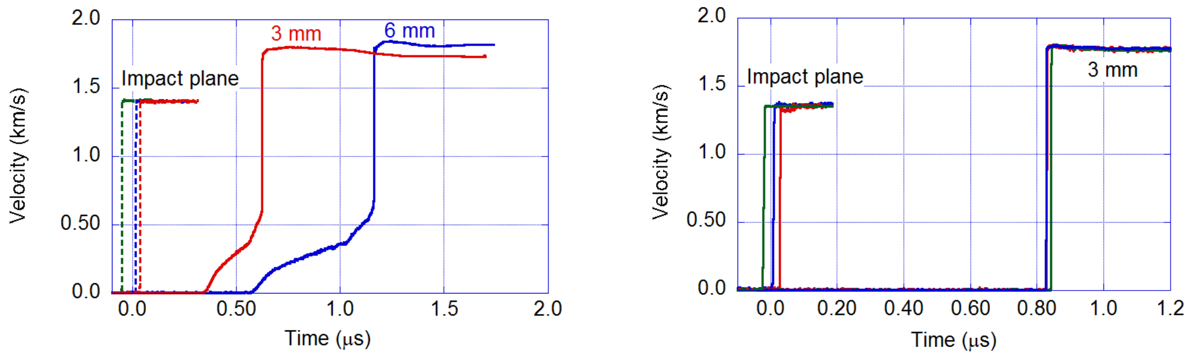


Figure 2. Schematic diagrams of the experimental configurations used for (a) 0° and (b) 90° samples.

3 Results and discussion

A series of 10 shots was conducted on the CFE material; four shots in the 0° orientation, six in the 90° orientation, as detailed above. Representative VISAR profiles are shown in figure 3. It is immediately evident from the figure that an elastic precursor is measured in the 0° orientation (figure 3a). This feature was evident in all tests regardless of the impact velocity. Following the precursor, a bulk shock is observed. A slight relaxation is also evident behind the shock. In the 90° orientation (figure 3b), only a bulk shock is observed in all cases. Again there is a slight relaxation behind the shock front.



(a) (b)

Figure 3. Representative VISAR profiles for select (a) 0° and (b) 90° experiments.

Wave speeds were determined by Lagrangian analysis. The sample thickness divided by transit time of a wave through the sample gives the Lagrangian shock wave speed (U_S). For the 90° experiments where three probes were used, the tabulated values below for shock wave speed are an average of the three measurements. In the 0° experiments where two samples were present, the analysis can also be completed by measuring the difference in thickness divided by the difference in transit time. This method was used to determine the wave speeds as a function of particle velocity reported here although the results were consistent independent of the method used. Impedance matching was used to determine the particle velocity (u_p). Stress was determined by applying the Rankine-Hugoniot conservation relations. The results for all tests are listed in Table 1.

Shot ID	Orientation (°)	u_p (km/s)	U_S (km/s)	Stress (GPa)
CFE-1	90	0.095	2.775	0.416
CFE-2	90	0.428	3.510	2.371
CFE-3	90	0.813	3.942	4.831
CFE-9	90	1.469	4.927	11.422
CFE-10	90	1.160	4.326	7.917
CFE-11	90	1.754	5.533	15.333
CFE-7	0	0.825	3.652	6.335
CFE-8	0	1.632	5.055	13.317
CFE-30	0	0.403	**	4.292
CFE-31	0	1.297	4.470	10.350

** It was not clear from the data that a steady shock had developed in shot CFE-30. Values shown are for the peak stress state. No shock velocity is given.

Table 1. Experimental results.

The elastic precursor evident in the 0° orientation was analyzed up to the bulk shock arrival. The Hugoniot elastic limit (HEL) is the maximum stress supported by a material before plastic deformation occurs. Generally this corresponds with the material state just prior to the bulk shock wave arrival. Using this approach, significant variation was observed in the HEL as a function of peak shock pressure. However, it is noted that there is a change in the slope of the precursor shortly before the bulk arrival. It is assumed that the steeper portion of the wave profile ahead of the bulk shock is due to an as yet unidentified inelastic deformation mechanism and that the HEL corresponds to the point of this slope change in the wave profiles. In the following discussion, it will be seen that the data points derived from the wave profile just before the bulk shock arrival form a smooth transition from linear elastic response to bulk plastic deformation. The HEL is determined to be 3.5 GPa by using an elastic – perfectly plastic analysis finding the intersection of linear elastic response and plastic response in the data of figure 4.

The dynamic response of the CFE is shown in figure 4 in the stress – particle velocity plane. The response of the epoxy matrix without reinforcing fibers, tested independently of the composite material[1], is also shown for comparison. The anisotropic nature of the response is clear. The 0° orientation shows a stiffening of the matrix at pressures up to around 10-12 GPa. Above this range, the response appears to become isotropic although to be certain, additional testing at higher pressures is required. This range is reasonable as epoxies generally dissociate in the 10-20 GPa range and with the loss of the binder, it is expected that the fibers will quickly fail resulting in a homogenized mixture of constituents.

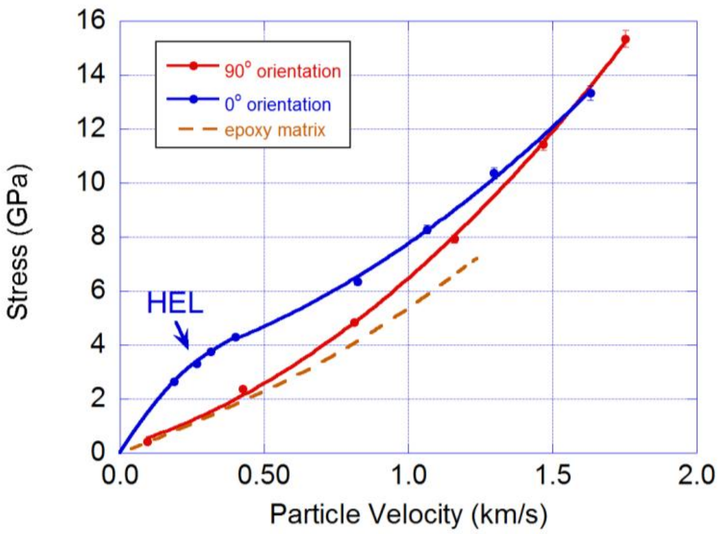


Figure 4. The dynamic response of the CFE in the stress – particle velocity plane. Lines shown are guides to the eye. Also shown is the response of the epoxy matrix without the reinforcing fibers.

In order to gain insight into the mechanisms underlying the observed response, the two orientations are considered separately. The 90° orientation is considered first. In this orientation, the response is observed to be slightly stiffer than the unreinforced epoxy. A reasonable assumption would be that the fibers do not provide additional support to the matrix when transverse to the shock loading and the composite might be expected to behave as a mixture of epoxy and carbon. This was shown to be the case for a particular glass fiber reinforced polymer by Dandekar *et al*. [6]. Figure 5 shows the 90° orientation data along with the response of epoxy and also Hugoniot data for graphite (carbon) which was pressed to a density of 1.77 g/cm^3, a close match to the composite material density (1.58 g/cm^3). From the figure, it is clear that the response of the composite is in good agreement with the response of carbon at this density. Hence, there is no mixture dependence; rather the response of the carbon component of the composite dominates.

[1] The response of the epoxy matrix was determined via isentropic compression experiments using the Veloce small pulse machine [4] at Sandia National Laboratories. The response shown is an isentrope, however, due to the extremely low strength of the epoxy this is also a good approximation of the Hugoniot. Excellent agreement was seen between this data and a single shock loaded Hugoniot point. Comparison with the Hugoniot determined from shock loading experiments [5] on a similar epoxy (Epon 828) shows good agreement within the scatter of the shock results.

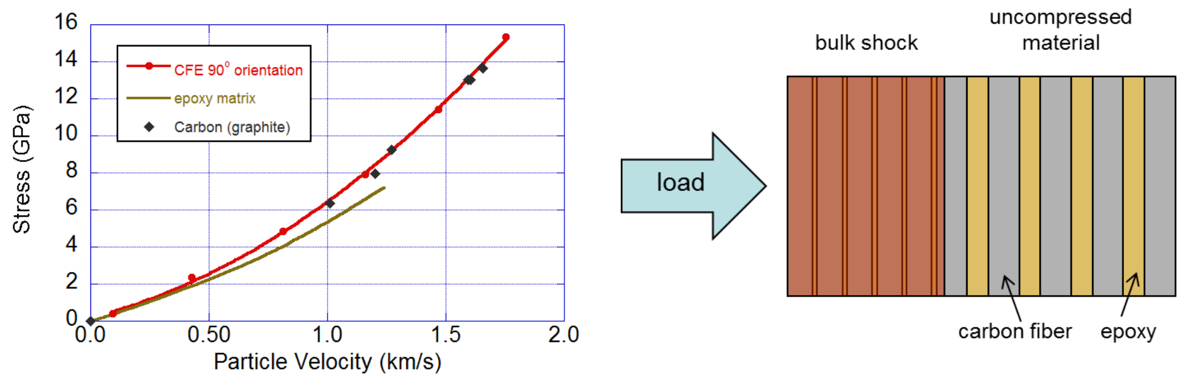


Figure 5. The results of figure 4 shown for the 90° configuration along with the response of graphite (left). Also shown is an illustration (right) of the response in the CFE material.

To understand this result, consider the schematic drawing in figure 5 showing the composite material when the shock wave has propagated through a portion of the composite. Compressed material, indicated by the red shading, is shown on the left with uncompressed material on the right. As the shock propagates, the epoxy, which is more compressible than the carbon fibers, undergoes a greater volume compression resulting in fiber-fiber contact with the compressed epoxy occupying gaps around the cylindrical fibers. This is not unlike what will occur in a pressed graphite sample where the epoxy is replaced by air or void. Given fiber-fiber contact, the bulk response is expected to be dominated by the carbon as observed.

The 0° orientation response is more complex due to the elastic precursor. One might expect the material to behave similarly to the 90° orientation here but with the Hugoniot shifted upward to higher stress to account for the elastic response. However, it is clear from the data of figure 4 that the 0° orientation bulk response cannot be described by shifting the 90° orientation curve upward. Therefore additional mechanisms must be considered.

Consider a decoupled response where the elastic portion is governed by the carbon fibers and the bulk response depends on the epoxy binder. Such response has been observed previously in carbon-carbon composites by Hereil *et al*. [7]. Figure 6 shows the 0° orientation data along with the response of the epoxy binder. The dashed portion of the epoxy curve has been extrapolated from the data (indicated by the solid curve). The extrapolated response is consistent with other epoxy data (see for example Epon 828 [5]) recorded at higher pressure although no further justification is provided for the extrapolation. The epoxy curve is shifted up by 2.6 GPa such that it is a best fit to the bulk shock data. Ideally the shifted curve would be required to pass through the HEL, however, the non-distinct nature of the measured HEL makes such an approach difficult. Instead, using the best fit approach for the bulk response and assuming a linear elastic response, we find an HEL of 3.5 GPa at the intersection of the two curves. This approach results in a reasonable fit to the experimental data over both the elastic and plastic response regions. Thus the response is consistent with the proposed decoupling. Elastic waves will travel in the fibers with the bulk response in the epoxy. Small discrepancies between the composite data and the decoupled response indicate a slight coupling between the fibers and the matrix.

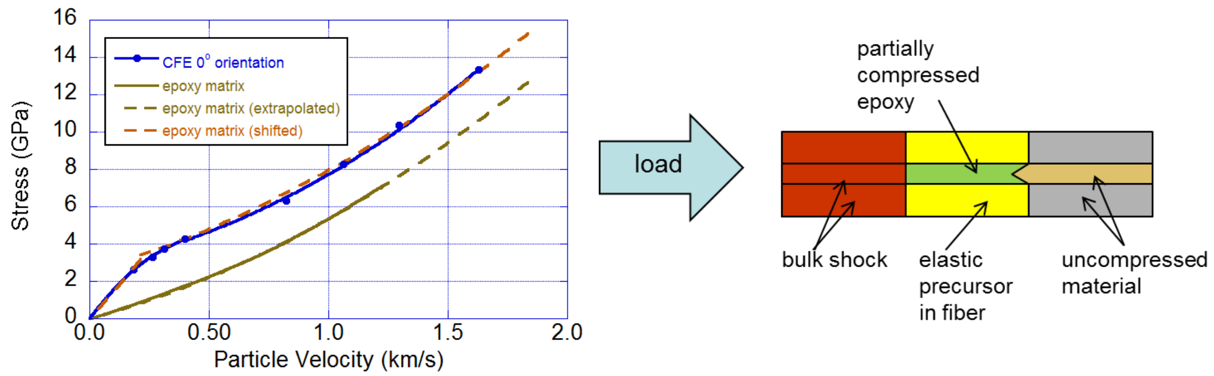


Figure 6. The results of figure 4 shown for the 0° configuration along with the response of the epoxy binder (left). Also shown is an illustration (right) of the decoupled response in the CFE material.

In order to understand the underlying mechanisms in this case, consider the illustration in figure 6 which again shows the composite material after both the elastic and bulk waves have propagated partway through the sample. The elastic wave, traveling in the carbon at a greater speed than the bulk wave will result in the carbon fibers being loaded to their HEL (indicated in the figure by yellow). As this wave moves only in the fibers, it is reasonable that the response is dictated by fiber. These loaded fibers will begin to release into the surrounding uncompressed epoxy resulting in a partial compression of the epoxy (indicated by green). The fibers never truly unload as additional wavelets continue to outrun the bulk shock maintaining the HEL pressure in the fibers until arrival of the bulk wave. The resulting pressure profile in the epoxy is similar to a Mach wave [8] formed under shock loading. The bulk wave (indicated by red) moves uniformly through the composite with the response dictated by the bulk properties of both the slightly precompressed epoxy and the elastically loaded fibers. That the composite bulk response is well modeled by shifting the bulk epoxy curve argues that either the bulk responses are similar (as shown) or that the bulk wave will travel slower in the compressed fibers than in the epoxy resulting in the dominant epoxy response observed.

4 Summary

The dynamic response of a carbon fiber reinforced polymer system with low porosity has been measured utilizing planar shock loading. The results show that the response in anisotropic up to 10-12 GPa highlighting the need for advanced constitutive models for this class of material. Shocks traveling transverse to the reinforcing fibers show only a single wave bulk response which is determined by the fiber material (carbon) response. Conversely, when shocked along the fiber direction, an elastic precursor is observed in addition to the bulk response. The elastic portion is described by the fiber elastic properties while the bulk response is dominated by that of the polymer binder. These results can be described by a proposed micromechanical description of the process.

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