Improved understanding of the dynamic response in anisotropic directional composite materials through the combination of experiments and modeling

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Abstract

Recently there has been renewed interest in the dynamic response of composite materials; specifically low density epoxy matrix binders strengthened with continuous reinforcing fibers. This is in part due to the widespread use of carbon fiber composites in military, commercial, industrial, and aerospace applications. The design community requires better understanding of these materials in order to make full use of their unique properties. Planar impact testing was performed resulting in pressures up to 15 GPa on a unidirectional carbon fiber - epoxy composite, engineered to have high uniformity and low porosity. Results illustrate the anisotropic nature of the response under shock loading. Along the fiber direction, a two-wave structure similar to typical elastic-plastic response is observed, however, when shocked transverse to the fibers, only a single bulk shock wave is detected. At higher pressures, the epoxy matrix dissociates resulting in a loss of anisotropy. Greater understanding of the mechanisms responsible for the observed response has been achieved through numerical modeling of the system at the micromechanical level using the CTH hydrocode. From the simulation results it is evident that the observed two-wave structure in the longitudinal fiber direction is the result of a fast moving elastic precursor wave traveling in the carbon fibers ahead of the bulk response in the epoxy resin. Similarly, in the transverse direction, results show a collapse of the resin component consistent with the experimental observation of a single shock wave traveling at speeds associated with bulk carbon. Experimental and simulation results will be discussed and used to show where additional mechanisms, not fully described by the currently used models, are present.

1. Introduction

With the increasingly common use of fiber reinforced composites in automotive, aerospace, and other high performance construction applications [1], it is important to understand and be able to model their complex dynamic material response. In traditional isotropic materials, such as metals, the stress and strain response of the material can be represented by separable hydrostatic (pressure) and deviatoric (strength) responses. However, in anisotropic composite materials, the components are coupled and must be considered together.

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Composite materials generally consist of high strength fibers embedded in a light weight binder matrix. The fibers, which exhibit different responses along different directions, imply an anisotropic response by virtue of imposing directionality in the material. By studying high quality composite samples, experimental data is used to define the material response and combined with micromechanical simulations to further the understanding of the response to shock loading. Ultimately, this is expected to lead to better models to describe this class of materials under dynamic loading.

2. Experimental Testing

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 manufactured by the U.S. Air Force Research Laboratory at Kirkland Air Force Base from a commercially available carbon fiber–epoxy 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°). For these tests, samples were produced with 62% carbon fiber by volume between 3 mm and 25 mm thick with an average density of 1.560 g/cm³. The manufacturing process resulted in uniform samples of extremely low porosity as verified by ultrasonic and x-ray imaging.

Prior to shock loading, ambient sound speeds were measured along the principal directions. Measurements were made using both longitudinal and shear transducers on both 0° and 90° oriented samples. Shear measurements were made while rotating the transducer to find the maximum shear velocity. A measurement was also made orthogonal to this direction. Averaged results of tests on multiple samples are summarized in table 1. The significant anisotropy observed in these results is consistent with other CFE composites [2, 3].

| Orientation (degrees) | Measurement direction | Average wave speed (km/s) |
|-----------------------|-----------------------|--------------------------|
| 0                     | Longitudinal          | 10.76                    |
|                       | Shear (maximum)       | 2.18                     |
|                       | Shear (orthogonal)    | 2.16                     |
| 90                    | Longitudinal          | 3.04                     |
|                       | Shear (maximum)       | 2.07                     |
|                       | Shear (orthogonal)    | 1.53                     |

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. Experiments consisted of single or multiple CFE targets impacted by copper plates nominally 6 mm thick. Targets were backed with PMMA windows and monitored with VISAR [4]. Samples were oriented such that the fibers were either perpendicular to (0°), parallel to (90°), or intermediate to (7, 14, or 21°) the shock propagation direction. Samples other than 0° orientations were backed with thin PMMA buffers to protect the VISAR reflector. Additional details of each experimental configuration are provided in table 2. Supplementary windows were mounted in the impact plane to record time of impact via additional VISAR beams. Wave profiles from these tests are shown in the following section.

Wave speeds were determined by Lagrangian analysis of the recorded particle velocity profiles after which stress was determined by applying the Rankine-Hugoniot conservation relations. Results of testing along the principal directions are summarized in figure 1. The anisotropic nature of the response is immediately evident with the 0° orientation exhibiting a stiffer response up to 10-12 GPa. The response appears to become isotropic above this pressure range although additional testing to confirm this has not been conducted.
Table 2: Summary of experimental parameters.

| Shot ID | Impact Velocity (km/s) | CFE Orientation θ (degrees) | Target Thickness (mm) | Buffer Thickness (mm) |
|---------|------------------------|----------------------------|-----------------------|-----------------------|
| CFE-22  | 0.994                  | 90                         | 3.20                  | 0.99                  |
| CFE-23  | 1.301                  | 90                         | 3.21                  | 1.01                  |
| CFE-24  | 1.668                  | 90                         | 3.18                  | 1.02                  |
| CFE-25  | 1.992                  | 90                         | 3.23                  | 0.93                  |
| CFE-27  | 1.008                  | 0/0                        | 3.03/6.05             | N/A                   |
| CFE-28  | 1.489                  | 0/0                        | 3.03/5.84             | N/A                   |
| CFE-29  | 2.000                  | 0/0                        | 3.02/6.05             | N/A                   |
| CFE-32  | 1.013                  | 7/14/21                    | 1.52/1.52/1.52        | 0.53/0.54/0.52        |
| CFE-33  | 1.512                  | 7/14/21                    | 1.52/1.53/1.52        | 0.53/0.54/0.52        |
| CFE-35  | 2.078                  | 7/14/21                    | 1.52/1.58/1.51        | 0.51/0.55/0.51        |

Figure 1: Dynamic response of CFE in the stress – particle velocity plane. Lines shown are guides to the eye. Also shown are previous results on the epoxy matrix and carbon [5].

Additional testing was performed on off-principal axis orientations at 7°, 14°, and 21° orientations. For these tests, samples were machined from existing 0° orientation material. Due to geometric constraints, the samples tested were thinner and of smaller diameter in the off-axis configurations. Sample dimensions were maintained such that edge waves would not affect the results. All other test aspects were similar to the principal axis tests described above. Wave profiles are shown and discussed in the following section.
3. Micromechanics Simulations

To gain a better understanding of the mechanisms and constituent interactions that occur during shock loading of unidirectional composite materials, shock micromechanics models were constructed and analyzed using the shock physics hydrocode CTH [6]. These micromechanics models resolved the unidirectional microstructure down to the fiber and matrix level. Micromechanics models were built for the principal (longitudinal and transverse) directions of the composite microstructure and the off-axis orientations discussed previously. Figure 2 shows 2D images of the principal orientation micromechanics models, where the maroon regions are the carbon fibers and the tan regions are the epoxy resin. Due to the geometric scale difference between the individual fibers (~5 microns in diameter) and the experimental specimens (3-6 mm thick), it was numerically infeasible to model the entire experimental specimen. Therefore, as shown in figure 2 a representative section of the test specimens were modeled in order to capture the basic features of the microstructure and still allow for complete development of the shock wave profile.

![Figure 2: CTH shock micromechanics models.](image)

For each of the micromechanics models, the fiber and matrix were modeled using an elastic perfectly-plastic strength model with a Von-Mises yield surface. Likewise, each constituent’s equation of state (EOS) response was modeled using the Mie-Grüneisen EOS. It is important to note here that the carbon fibers in the composite material are anisotropic due to their fabrication method. Therefore, separate strength and EOS properties are defined for the fiber according to the direction of shock loading. Table 3 lists the strength and EOS properties for both principal orientations of the anisotropic carbon fiber and for the matrix.

| Constituent | Epoxy Matrix | Carbon Fiber (Longitudinal) | Carbon Fiber (Transverse) |
|-------------|--------------|-----------------------------|---------------------------|
| Mie-Grüneisen EOS | \( \rho_0 = 1.305 \text{ g/cc} \) | \( \rho_0 = 1.694 \text{ g/cc} \) | \( \rho_0 = 1.694 \text{ g/cc} \) |
| \( C_0 = 2.35 \text{ km/s} \) | \( C_0 = 5.20 \text{ km/s} \) | \( C_0 = 2.35 \text{ km/s} \) |
| \( S = 1.604 \) | \( S = 1.478 \) | \( S = 1.478 \) |
| Elastic-Perfectly Plastic Strength | \( \nu = 0.393 \) | \( \nu = 0.050 \) | \( \nu = 0.352 \) |
| \( Y_0 = 0.1 \text{ GPa} \) | \( Y_0 = 3.5 \text{ GPa} \) | \( Y_0 = 3.5 \text{ GPa} \) |

Using the shock micromechanics models of figure 2 and the constituent strength and EOS properties of table 3, each of the experimental flyer plate tests detailed previously were simulated. Tracer points were placed in both the fiber and matrix regions of the micromechanics models such that a velocity response was measured for each constituent individually. These individual responses were then volume averaged using equation (1) and time shifted according to the location of the tracer and the thickness of the experimental specimen to allow for comparison with the experimental data.

\[
V_{\text{composite}} = \phi_{\text{fiber}}V_{\text{fiber}} + \phi_{\text{matrix}}V_{\text{matrix}}
\]  

(1)

The results of each of these simulations are plotted against the experimental test data in figure 3 and figure 4. Figure 3 shows reasonable correlation for the principal material orientations between the micromechanics simulations (solid lines) and the experimental test data (dashed lines). The micromechanics model for the longitudinal loading condition captures the higher velocity precursor
travelling in front of the bulk shock wave, while the transverse model shows only a bulk shock wave propagating through the microstructure similar to what was observed in the experimental data. Quantitatively, the micromechanics predictions for the particle velocities behind the shock front were within 5% of the experimental values for all orientations. The predicted bulk shock velocities were also within 5% of the experimental values in the transverse orientation. In the longitudinal case, shock velocities were too fast by up to 25% compared to the data. It was possible to soften the matrix EOS to match the experimental shock velocity; however, the model then over predicts the post-shock particle velocity by about 10%. These results suggest that frictional coupling between the fibers and matrix is not being correctly modeled. Results shown have infinite friction (welded contact) present in the calculation. Reducing fiber-matrix friction will reduce the coupling of the elastic precursor and bulk waves, resulting in a slower bulk shock wave as observed experimentally. It should also be noted that the experimentally observed elastic wave reflection (the second precursor wave) is not seen in the micromechanics simulations due to limitations on the dimensions of the calculation domain.

**Figure 3:** Shock micromechanics wave profiles plotted against experimental wave profiles for (a) transverse loading and (b) longitudinal loading.

Figure 4 shows the off-axis micromechanics predictions versus the experimental data for the 7°, 14° and 21° orientations. Similar to the principal material orientations, there is good agreement between the analytical predictions and experimental data both in terms of quantitative agreement (wave speeds and particle velocities agree within 5%) and wave structure. The agreement of the bulk shock wave speed in these orientations suggests that frictional coupling becomes less important as the composite is rotated off the longitudinal axis. However, the simulation results continue to show a dispersed shock and elastic precursor velocities are slower than observed.

**Figure 4:** Off-axis shock micromechanics wave profiles plotted against experimental wave profiles.
As noted previously, one of the primary reasons for developing the shock micromechanics models was to gain insight into the mechanisms that occurred during shock loading of the unidirectional composite material and how these mechanisms influenced the observed experimental profiles. The first mechanism that can be explained through the micromechanics simulations is the observation made previously in the discussion of figure 1 which showed that the shock Hugoniot of the composite material in the transverse direction is very similar to the Hugoniot of homogeneous pressed carbon. Figure 5 shows an example of how as the shock wave travels in the transverse orientation of the composite, the epoxy is compressed significantly more than the fibers. Further, the side view shown in figure 5 shows that as the epoxy is compressed into interstitial space, the fibers start to form a jet-like structure as a result of the different wave speeds of the fiber and matrix. Each of these observations support the previous conclusion from figure 1 that as the composite material is shocked in the transverse orientation, fiber on fiber contact is experienced.

![Top View][Side View]

**Figure 5:** Transverse shock micromechanics material plots.

To better understand the observed shock response in the longitudinal direction of the unidirectional composite, figure 6 is considered. Figure 6 shows a section of the longitudinal micromechanics model taken at three times within the simulation with the pressure contours overlayed. From this figure one can see that there is a faster precursor wave travelling in the fibers ahead of the higher pressure bulk shock wave which travels in both the fibers and the matrix. The higher wave speed in the fibers causes them to act as a “wave guide” to the shock front and therefore produce the observed multi-wave response seen in the experimental results. These results are supported by the observation that the precursor velocity from the numerical predictions and experiments match reasonably well with the estimated shock velocity of the longitudinal fibers, while the overall bulk shock velocity is similar to that of the epoxy matrix.

![Elastic Wave Front (in Fibers)][load]

**Figure 6:** Longitudinal shock micromechanics material and pressure plots. Shown are three distinct time steps from the calculation.
4. Off-Principal Axis Response

In real world applications, shock waves rarely travel only in the material principal directions. Therefore, it is necessary to develop a mathematical model that can capture the shock response of these materials along any given orientation. To understand the effect of orientation on the composite shock response, the data of figure 3 and figure 4 are considered. The elastic precursor velocity and bulk shock wave velocity for each of the off-principal axis tests are plotted in polar space in figure 7. In this figure, the bulk shock wave velocity and elastic precursor velocity are normalized by the 0° (longitudinal) precursor velocity for ease of comparison.

Analytic expressions for both the bulk and precursor wave velocities as functions of the fiber orientation angle (θ) can be determined by studying the experimental data in figure 7. The predicted relationship for the bulk shock wave velocity is indicated by the purple circle. In polar space, a circle represents isotropic behavior. This is expected given that the bulk shock is primarily carried by the isotropic matrix material or the transverse fibers which exhibit a similar response to the matrix. This prediction is validated experimentally as the observed velocity of the bulk shock was independent of orientation under all tested conditions. Finally, the diameter of this circle varies according to the test conditions and the Hugoniot response of the relevant material.

In the case of the composite material, X corresponds to the longitudinal direction (θ = 0), Y to the transverse direction (θ = 90), and Z is orthogonal to both X and Y. Given that the $C_v$ and $C_Z$ are small compared to the $C_X$ in these materials, the initially assumed relationship for the precursor velocity was estimated to be a function of $\cos^2 \theta$ (solid orange line in figure 7). However, upon examining this relationship and the experimental data it was determined that although the $\cos^2 \theta$ relationship has the correct basic shape it does not match the data as well as hoped. This observation led to the revised relationship that the precursor material velocity is a tensor quantity rather than a vector and follows the tensor transformation given in equation (3).

![Figure 7: Polar plot of all experimental shock velocities and the assumed transformation relations.](image)

The relationship for the precursor velocity is more complex than the bulk shock and is based upon assuming the material velocities are a vector quantity and will follow the traditional vector rotation relationship of equation (2) to govern the directional dependence of the precursor velocity.

$$
\begin{bmatrix}
C_x' \\
C_y' \\
C_z'
\end{bmatrix}
= 
\begin{bmatrix}
\cos^2 \theta & \sin^2 \theta & 0 \\
\sin^2 \theta & \cos^2 \theta & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
C_x \\
C_y \\
C_z
\end{bmatrix}
$$

In the case of the composite material, X corresponds to the longitudinal direction (θ = 0), Y to the transverse direction (θ = 90), and Z is orthogonal to both X and Y. Given that the $C_v$ and $C_Z$ are small compared to the $C_X$ in these materials, the initially assumed relationship for the precursor velocity was estimated to be a function of $\cos^2 \theta$ (solid orange line in figure 7). However, upon examining this relationship and the experimental data it was determined that although the $\cos^2 \theta$ relationship has the correct basic shape it does not match the data as well as hoped. This observation led to the revised relationship that the precursor material velocity is a tensor quantity rather than a vector and follows the tensor transformation given in equation (3).
Assuming that the precursor wave speed behaves as a tensor results in the $\eta$ constants given in equation (3) which are analogous to Poisson’s ratio from traditional stiffness mechanics. This parameter specifies the level of coupling between the normal material precursor velocities just as Poisson’s ratio couples the strain response between the normal stiffnesses. By modifying the $\eta$ coupling terms, the predicted precursor response can be made to fit the experimental data. An example of a better fit that can be achieved by altering the $\eta$ parameters is shown in figure 7 as a dashed orange line.

5. Conclusions
The work presented in this paper illustrates the anisotropic shock response exhibited by unidirectional composite materials. Experimental data shows that for shock loading in the transverse orientation, a single bulk shock wave structure is generated while for the longitudinal orientation a two-wave structure composed of a faster precursor wave followed by a higher pressure bulk wave is generated. Analytical shock micromechanics predictions show good agreement with the measured responses in both the principal and off-axis orientations. Examination of the micromechanics predictions confirmed that under the transverse orientation, the more compressible matrix constituent is compressed such that fiber on fiber contact is experienced and results in the observation that the Hugoniot for this orientation is similar to that of homogenous pressed carbon. Also, the micromechanics simulations show that in the longitudinal orientation the fibers carry the precursor wave while the bulk wave was controlled by the matrix resulting in the experimentally observed two-wave structure. Finally, using the off-axis experimental test data a basic relationship is presented which allows for the calculation of the precursor and bulk shock velocities in any given orientation. This relationship also introduces the concept of a coupling parameter between the directional shock velocities of the composite which is similar in behavior to Poisson’s ratio.

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