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ANISOTROPIC SHOCK RESPONSE OF UNIDIRECTIONAL COMPOSITE MATERIALS

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Abstract

This work presented in this paper summarizes an experimental and analytical program focused on characterizing the anisotropic equation of state behavior of unidirectional composite material systems. A carbon/epoxy composite material system is shock tested in both the longitudinal and transverse orientation at various impact velocities and combined with on- and off-axis shock test data for other composite materials systems from literature. Compilation of the data shows that the bulk shock response of traditional unidirectional fiber reinforced composite materials is isotropic and similar to that of the neat resin constituent. The precursor wave response is shown to be anisotropic and varying in wave velocity according to basic transformation relationships. Analytical predictions using a shock physics hydrocode are compared with the experimental data for various orientation angles. These analytical results are shown to be in excellent agreement with the experimental data throughout all material orientations.

1 Introduction

The use of fiber reinforced composite materials in applications where hypervelocity impacts and shock are design drivers have become more prevalent over the past decade. To optimize the design and material selection process for these applications, engineers often times utilize hydrocodes, which are well suited to handle large deformation, high strain-rate and high-energy problems. For traditional isotropic materials such as steel or aluminum, hydrocodes split the material response into a hydrostatic or pressure response and a deviatoric or strength response. However, for an anisotropic material such as fiber-reinforced composites, the deviatoric and hydrostatic responses are coupled and therefore cannot be separated. Likewise, the equation of state (EOS) relationship that characterizes the pressure response of a composite material system is also anisotropic.

The most common form of the EOS Hugoniot relates the shock velocity (U_s) to the particle velocity (u_p) of the material. Experimental observations have shown that the U_s vs. u_p Hugoniot is a linear relationship for most isotropic materials and can be characterized by two constants, C_o and s. The functional form of the U_s vs. u_p Hugoniot is given in Equation (1).

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$$U_s = C_o + su_p \tag{1}$$

For anisotropic materials the shock response cannot be represented by a single set of constants due to the directional nature of the material. Instead, a Hugoniot relationship would incorporate material parameters that are a function of the wave propagation direction relative to the material orientation. The functional form of this type of Hugoniot is given in Equation (2), where C_o and s are functions of θ and θ represents the angle of wave propagation relative to the material orientation.

$$U_s = C_o(\boldsymbol{\theta}) + s(\boldsymbol{\theta})u_p \tag{2}$$

The consequence of incorporating a Hugoniot of the form shown in Equation (2) is that a very large suite of shock tests would be required to provide the necessary experimental data for fitting each of the constants as a function of orientation. Typically, the costs associated with performing these suites of tests for a composite material system would be prohibitive for practical application. These costs combined with the need to test each candidate material system of interest, makes this approach impractical. Therefore, an analytical expression that utilizes basic constituent (fiber and resin) shock properties is necessary.

For this work, we performed experimental shock testing on a unidirectional carbon/epoxy material (IM7/8552) and studied various other experimental shock test data for carbon/epoxy and aramid/epoxy unidirectional composite materials from the literature. For the testing performed for this work an IM7/8552 composite material was tested in both the longitudinal (on-fiber) and transverse directions to study the corresponding wave structure and shock response. Testing data from the literature was also examined to understand the directional shock response of other composite material systems. Finally, the experimental data from this work and the data from the literature were combined to formulate and validate a directionally dependent relationship for the shock response of a unidirectional composite material that is only a function of the constituent's shock properties.

2 Shock Structure in Unidirectional Composites

To understand the directional shock response of unidirectional composite materials it is first necessary to understand the structure of a shock along each of the principal material fiber directions. These principal directions are termed the longitudinal or on-fiber direction and the transverse or perpendicular direction. Figure 1 illustrates each of these orientations relative to the shock propagation.

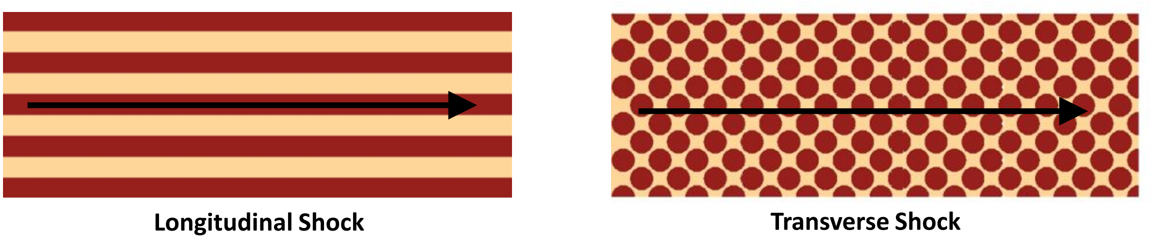


Figure 1. Longitudinal and Transverse Shock Directions of a Unidirectional Composite.

2.1 Longitudinal (on-fiber) Shock

A longitudinal shock in a unidirectional composite occurs when the wave propagates parallel to the fibers as shown previously in Figure 1. For shock waves propagating in this direction, these materials exhibit what is called a two-wave or elastic-plastic structure. In a two-wave structure a higher velocity, lower amplitude wave preceeds a slower bulk wave with a higher amplitude. Figure 2 shows the shock response for an IM7/8552 material system subjected to three (3) different longitudinal impact velocities. Researchers such as Millet *et al.* [1], Bordzilovskii *et al.* [2], Hazel *et al.* [3] and Hereil *et al.* [4] have all shown a similar longitudinal shock structure for other composite materials.

Figure 2 illustrates the two-wave structure where the lower velocity precursor wave (arriving at ~ 0.5μs) can be seen prior to the slow bulk shock wave (at > 1μs). It is noted that the precursor wave has the same velocity for all impact levels, while the trailing bulk shock velocity is a function of the impact velocity or shock level.

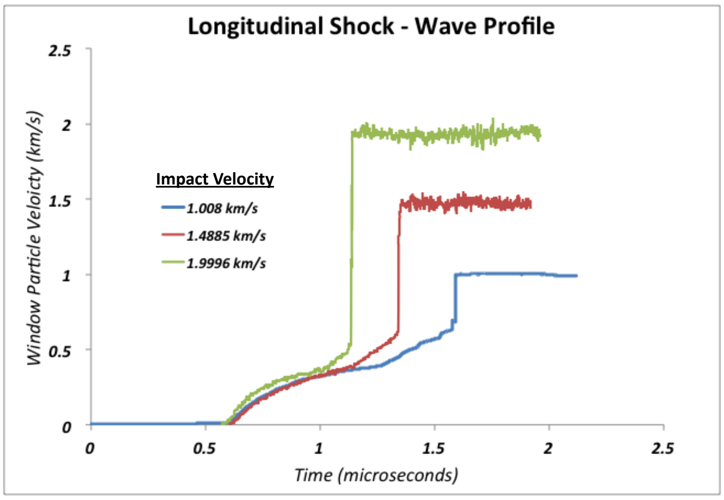


Figure 2. Wave Structure for Longitudinal Impact.

Physically, the shock wave structure observed in Figure 2 is a result of the stiffer fibers carrying the faster precursor wave in front of the bulk shock in the resin. This behavior is illustrated in Figure 3 where through shock hydrocode simulations the higher velocity pressure wave travelling in the fibers can be seen ahead of the bulk shock. It is noted that the small pressure observed in the resin out in front of the bulk shock wave is a result of the interaction of the faster traveling wave in the fibers and the Poisson's effect of the fibers on the resin.

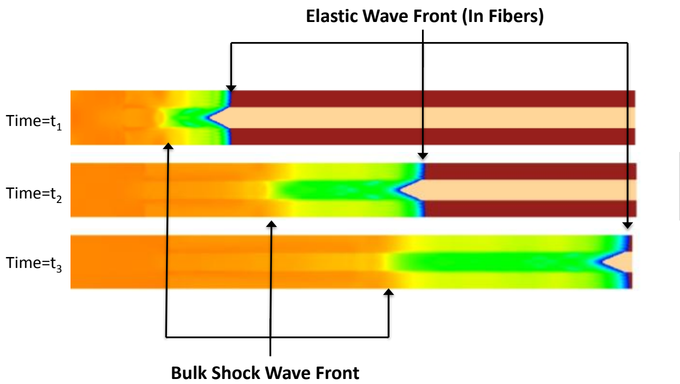


Figure 3. Pressure Profile in a Simplified Unidirectional Composite Subjected to a Longitudinal Shock

2.2 Transverse Shock

A transverse shock occurs in a composite material when the shock propagates perpendicular to the fibers as shown previously in Figure 1. Unlike the two-wave structures observed for a shock propagating in the longitudinal direction of these materials, shock waves travelling in a transverse orientation to the fiber have a single wave structure. Figure 4 shows the transverse shock responses for the IM7/8552 material subjected to five (5) different impact velocities. Figure 4 shows the single bulk shock wave in this orientation and how it varies in velocity as a function of the impact velocity.

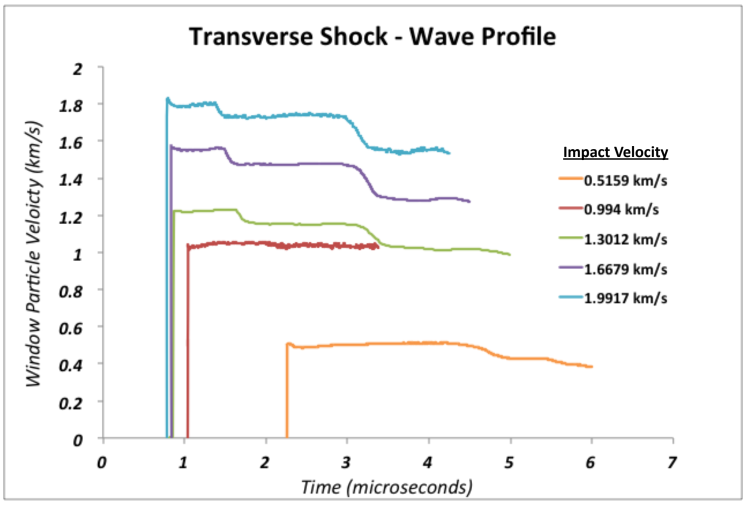


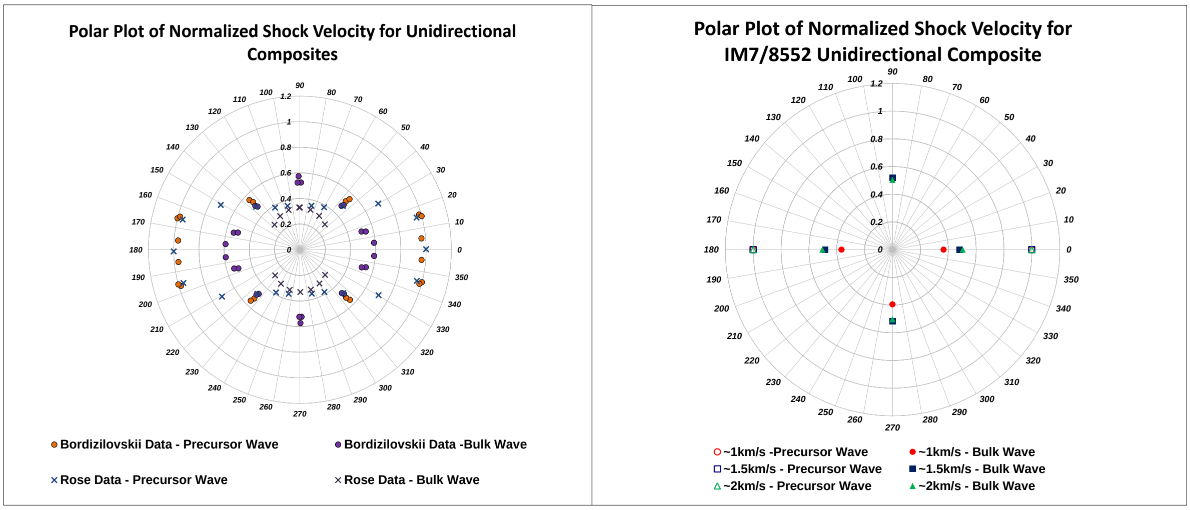
Figure 4. Wave Structure for Transverse Impact.

3 Directional Dependent Shock Responses

3.1 Experimental Data

The body of work for off-axis shock testing of composite materials to date is very limited. Rose *et al.* [5] and Bordzilovskii *et al.* [2] are the only known experimentalists to present shock data for composite materials at varying orientation angles. Rose presented wave velocity data for a graphite/epoxy composite material from 0° (longitudinal) to 90° (transverse) in 15° increments. However, the experimental method used by Rose only allowed for measurement of the wave speed, with no information about the wave structure. Therefore, the bulk wave (second) velocity was not able to be determined in all cases. Bordzilovskii performed a similar set of tests on an aramid/epoxy composite material system at orientation angles of 0°, 5°, 15°, 45° and 90°. Bordzilovskii did use experimental techniques that allowed for visualization of the wave structure and hence calculation of both the precursor and bulk shock wave velocities.

Figure 5(a) shows the experimental data from Rose and Bordzilovskii, while Figure 5(b) shows the experimental data collected for this current program for IM7/8552. The current IM7/8552 testing presented herein is only a subset of the data to be collected. In the coming year, off-axis testing for this material system will be performed. In the plots from Figure 5, all wave speeds have been normalized by the longitudinal precursor wave speed and plotted in a polar coordinate system. The data was plotted in this manner to better visualize and understand the directional shock behavior of these materials.



(a) (b)

Figure 5. Normalized Elastic and Plastic Wave Speed vs. Orientation for Data from (a) Literature and (b) the Current Experimental Program.

3.2 Precursor Wave

Studying the precursor wave velocities in Figure 5 (orange dots and blue x's) it can be seen that a precursor wave only exists for material orientations between 0° (longitudinal) and ~ 45°. For material orientations greater than 45° only a single bulk shock wave is observed. Not only does the precursor wave dissipate at 45°, but it also decreases nonlinearly in velocity from 0° to 45°. The nonlinear decrease in precursor wave velocity is similar to the traditional vector transformation relationship given in Equation (3).

$$\begin{Bmatrix} C_L' \\ C_T' \\ C_S' \end{Bmatrix} = \begin{bmatrix} cos^2\theta & sin^2\theta & cos\theta sin\theta \\ sin^2\theta & cos^2\theta & -cos\theta sin\theta \\ -2cos\theta sin\theta & 2cos\theta sin\theta & cos^2\theta - sin^2\theta \end{bmatrix} \begin{Bmatrix} C_L \\ C_T \\ C_S \end{Bmatrix} \qquad (3)$$

In Equation (3), C_L, C_T and C_S are the longitudinal, transverse and shear sound speeds for the anisotropic fiber, respectively. For the carbon and aramid fibers studied in this work, the sound speeds (which are a function of the stiffness) in the transverse and shear directions are on the order of 5% of the longitudinal sound speed. Therefore, the longitudinal wave speed will vary almost entirely as a function of $cos^2\theta$. Figure 6 shows the precursor wave speed from Rose and Bordzilovskii versus $cos^2\theta$ from 0° to 45° where the precursor wave diminishes. This figure shows good agreement between the transformation relationship and the experimental data.

Figure 6 highlights the first fundamental behavior needed in order to simulate the directional response of a shock wave. Specifically, a numerical model/method must have the ability to retain the identities and orientations of each individual lamina. This capability allows for the orientation of the shock relative to the lamina to be determined and hence appropriately calculate the precursor wave velocity in the elastic fiber constituent.

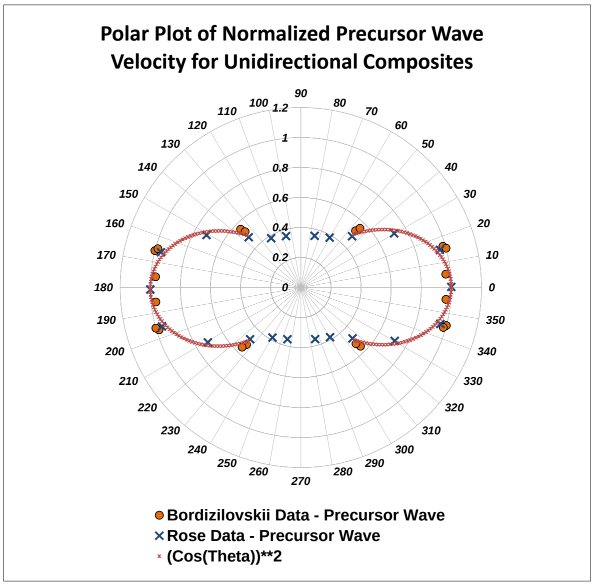


Figure 6. $\text{Cos}^2\theta$ vs. Experimental Precursor Wave Velocities.

3.3 Bulk Shock Wave

Based on the data presented in Figure 5, the bulk shock velocity for a unidirectional composite material is isotropic or independent of material orientation. Figure 7 shows the bulk shock velocities for Rose and Bordzilovskii plotted against two constant radius dashed-line circles representing isotropic behavior. In this figure, the outer circle is a fit to the bulk shock wave velocity data for the aramid/epoxy while the inner circle is fit to the bulk shock wave velocity for the graphite/epoxy.

Each of these composites showed that the bulk response of the composite was similar to that of the response of the in-situ resin constituent when comparing the experimentally measured bulk shock velocities and the known shock response of the neat epoxy resin system. Therefore, if each of the material systems had been shocked to the same level, the bulk shock response would be similar (equal radii) as they all were fabricated with an epoxy resin system.

3.4 Shock Wave Summary

The results shown in Figure 7 combined with the results shown in Figure 6 for the elastic precursor wave velocity provide the following conclusions for modeling the anisotropic shock response of unidirectional composites. First, to model the elastic precursor wave of a unidirectional composite, a lamina level definition and material orientation must be retained during the simulation to allow for calculation of the shock orientation relative to the principal material directions of the lamina. This allows for the material moduli, which are directly related to the precursor wave velocity, to be utilized in the appropriate orientation relative to the shock propagation. Second, in order to model the bulk shock response of a composite, the isotropic shock response of the neat resin must be known.

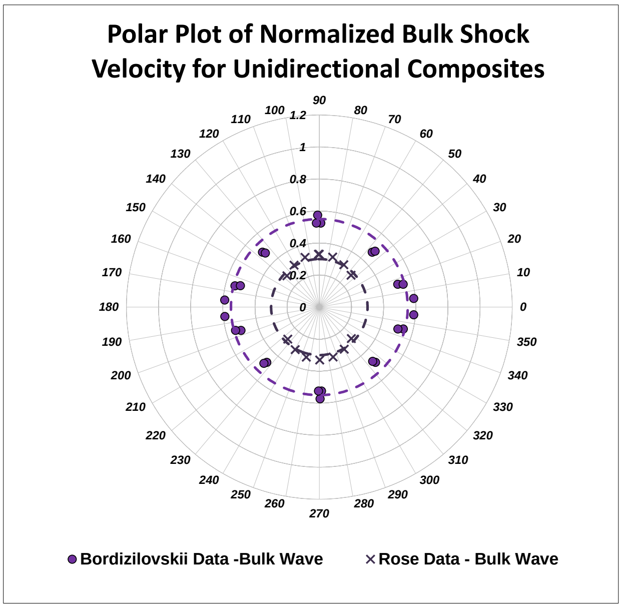


Figure 7. Circular Fit of the Bulk Wave Velocity.

4 Shock Hydrocode Predictions

To demonstrate the previously discussed method for modeling the anisotropic shock response for a unidirectional composite material, a shock physics hydrocode, which includes a built in layering methodology with lamina orientation definitions [6] was utilized. The composite stiffnesses for the fiber and corresponding composite were then input to control the directional response of the precursor wave through the known material orientations. The EOS parameters for the model were input as those of a neat epoxy resin system. Figure 8 show the hydrocode predictions versus the experimental data for the graphite/epoxy composite subjected to shocks at angles varying from 0° to 90°. This figure shows good agreement between the hydrocode numerical predictions for the precursor and bulk shock wave velocities and the experimental data.

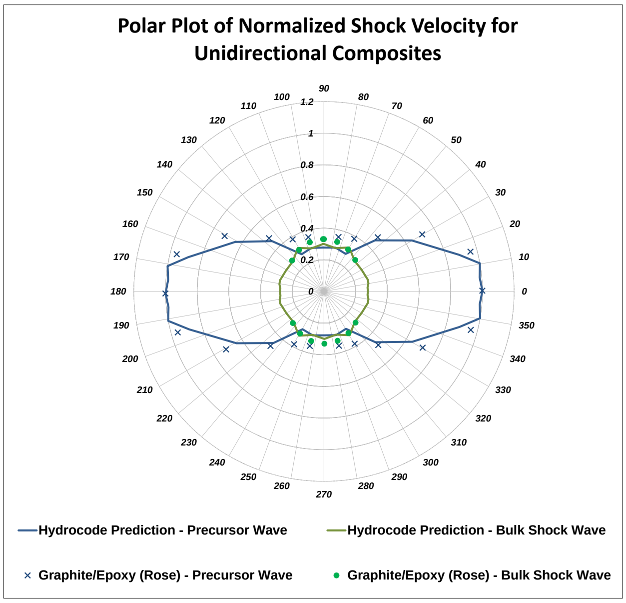


Figure 8. Shock Hydrocode Predictions of Anisotropic Shock Response vs. Experimental Data for a Carbon/Epoxy Composite Material.

5 Conclusions

The data presented in this paper shows that the anisotropic shock response of a unidirectional composite material is a function of both the constituent materials (fiber and resin) and the orientation of the material system relative to the shock wave. For shock propagation directions between 0° and 45° the response is similar to that of an elastic-plastic material where a two-wave structure is generated. However, for the composite material this structure is a function of the material architecture rather than an elastic-plastic constitutive behavior. For propagation directions greater than 45°, the response of the material is a single bulk shock wave with the response similar to the in-situ neat resin response.

The observed relationships for the precursor and bulk wave responses lead to a general modeling approach for unidirectional composite materials. Specifically, through the knowledge of the neat resin shock parameters and the anisotropic elastic material constants the anisotropic composite shock response can be accurately modeled using a shock physics hydrocode.

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