Stress Wave Damage in Graphite/Epoxy Laminates

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ABSTRACT

A series of unidirectional graphite/epoxy laminates of various fiber moduli have been subjected to uniaxial-strain shock loading to assess their resistance to dynamic loading. All of the laminates were found to exhibit nearly identical values of wave attenuation and shock hardness, and the resistance to impact in the through-thickness direction was ascribed primarily to the response of the epoxy matrix.

INTRODUCTION

THE RAPID DEVELOPMENT of advanced composite materials in the past two decades has been due principally to their excellent strengths and stiffnesses at low density, making them attractive candidate materials for a wide variety of weight-critical structures. Many of these structures also require considerable resistance to dynamic loading effects, and the brittleness of certain composites has been problematic in this regard. A wide range of impact rates must often be considered, from relatively low rates corresponding to a dropped wrench or specimen, to very high rates of the sort which may be encountered in supersonic collisions or explosive blast situations.

The dynamic stress state generated by these impacts is in general very complex, and is dependent on such parameters as the projectile shape, the constitutive material properties, and the material geometry. One relatively convenient means of quantifying the resistance, or "hardness", of materials to these high loading rates is to employ a planar loading configuration in which uniaxial strain waves are propagated in the specimen through-thickness direction. This paper reports the results of such a characterization, applied to graphite/epoxy laminates of a type often employed in structural applications.

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Advanced composites are inherently attractive for structures requiring shock hardness, as they provide means of strengthening against the action of the dynamic tensile stresses and also of attenuating the stress pulses as they propagate so as to lessen the stress intensity the material must withstand. Herrmann [1, 2] has reviewed the literature of wave propagation in solids, and Peck [3, 4] has written reviews specifically for wave propagation in fiber-reinforced composite materials. This literature demonstrates that wave attenuation in composites is enhanced by several mechanisms, among which are geometric wave dispersion due to wave reflections and refractions at the fiber-matrix interfaces, crushup of the porosity normally found in composites, and viscous loss due to the viscoelastic response of the matrix. The attenuation mechanisms act in addition to those also found in homogeneous materials, such as "hydrodynamic" attenuation arising from nonlinear constitutive response (in which the unloading portion of the wave overtakes and attenuates the leading portion). The importance of wave attenuation causes a shock hardness study of composites to consist of two distinct phases: the measurement of the material's ability to mitigate a compressive wave before the tensile components arise, and the material's ability to withstand dynamic fracture once the tensile components do arise.

MATERIALS

Since choice of fiber type is the principal material parameter available to the user of graphite/epoxy composites, laminates were fabricated for this study to reflect the wide range of fiber moduli available. Fiber modulus is also a natural material available for a shock hardness study, since important wave propagation phenomena, notably on wavespeed and geometric dispersion, depend principally on fiber modulus. Three types of carbon or graphite fibers were impregnated with American Cyanamid BP907 epoxy resin and partially cured ("B-staged") to yield thin sheets of composite. Nominal strengths and stiffness of the constituent materials, obtained from the manufacturers, are listed in Table 1 below.

Table 1. Constituent Materials.

Material	Modulus, GPa	Strength, MPa
BP907 epoxy	3.66	64.0
Pluton carbon fiber	41.4	828
Hercules HMS graphite	379	1930
Celanese 70 graphite	483	2070

These sheets of "prepreg" composite were stacked to produce unidirectionally reinforced laminates approximately 3.2 mm thick, and then autoclave cured for one hour at 350°F and 345 kPa pressure. Principal physical and mechanical properties of the cured laminates are listed in Table 2 below.

Table 2. Laminate Properties.

	Pluton	Hercules	Celanese
Density (Mg/m^3)	1.51	1.78	1.83
Volume % fibers	58.5	47.5	51.5
Volume % voids	5.7	0.1	1.0
Modulus (GPa)	26.9	177	248
Strength (MPa)	522	461*	432*

The listed mechanical properties are in the longitudinal (fiber) direction. The two strength values denoted by asterisks represent lower bounds only, since valid gage-section fractures could not be obtained during tensile testing of these materials. The other strength and modulus values agree well with those predicted theoretically by the rule of mixtures. The volume percentage of fibers and voids was measured by quantitative microscopy [5]. As is evidenced by the high void content, impregnation of the Pluton laminates was less satisfactory than of the other two materials. The nature of the Pluton void content can be seen in the micrograph shown in Figure 1.

EXPERIMENTAL

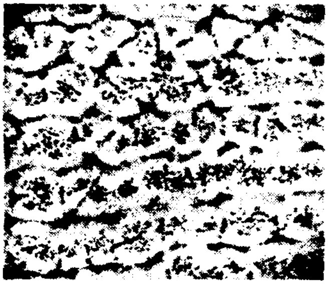

Figure 1. Micrograph of Pluton composite, section perpendicular to fiber direction.

A common means of generating intense uniaxial-strain compressive waves is to propel a flat flyer plate against the specimen. Several means of accelerating the flyer to impact velocity are available, including magnetic repulsion, gas gun propulsion, and exploding foil [6]. The exploding foil method was used in this study, as illustrated in Figure 2. The energy stored in a 12 kJ capacitor bank is allowed to flow through a foil by an ionizing spark gap trigger, and the resulting high amplitude current causes the foil to explode. The pressure pulse causes a flyer plate to shear out of a thin Mylar or Plexiglas sheet, and accelerate toward the specimen through an evacuated free run. Flyer velocity for a given flyer material, foil, and capacitor energy is known by reference to calibration

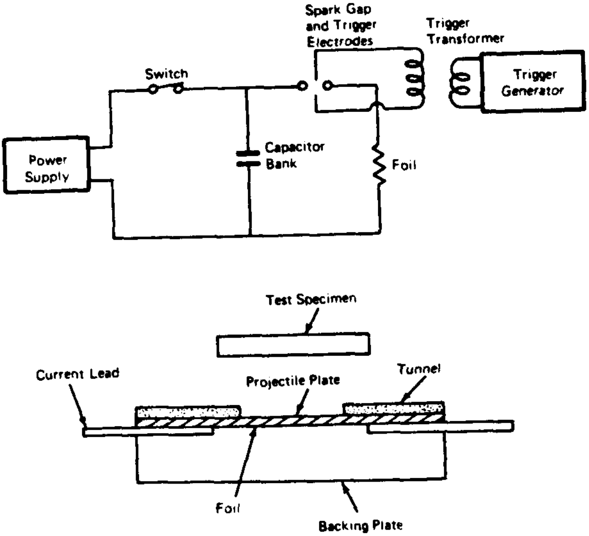

Figure 2. Schematic of exploding-foil plate loading device.

tests in which the flyer motion is monitored by streak photography. Velocities were found to be reproducible from shot to shot within five percent.

A wide variety of configurations based on Figure 2 is possible, enabling one to choose the stress pulse desired for a particular test. In general, a flyer plate impact produces an approximately rectangular waveform whose intensity is controlled by impact velocity and whose duration is controlled by the flyer plate thickness. The rear surface of the specimen is left unsupported if reflected tensile waves are desired, and is backed by a momentum trap if only compressive waves are desired. In many of the tests reported here, stress-time histories were recorded by means of piezoresistive carbon stress gages mounted upon the front or rear of the specimen.

A number of tests were performed using triangular rather than rectangular stress pulses; these were obtained by eliminating the flyer plate and allowing the pressure pulse from the foil itself to load the specimen. The foil was separated from the sample by a Plexiglas moderator which protected the specimen from the direct explosion and allowed the leading edge of the pressure pulse to steepen by shock formation.

RESULTS AND ANALYSIS

Pieces of laminate 5 cm by 5 cm were ground to various thicknesses, then loaded with triangular pulses in the through-thickness direction (wave propagation transverse to the fibers). These samples had stress gages mounted on the front and rear surfaces. By examining the gage records for various sample thicknesses, attenuation as a function of propagation distance can be determined as the ratio of transmitted to incident stress, and wavespeed as the ratio of the propagation distance to the time interval between the leading edges of the incident and transmitted waves. Wave speed data are shown in Figure 3. Typical attenuation data will be shown later, but in general, the pulses were found to attenuate exponentially with propagation distance. Numerical least-squares values for attenuation and wavespeed are listed in Table 3 below for the three composite types alongside literature values for Plexiglas flyer material.

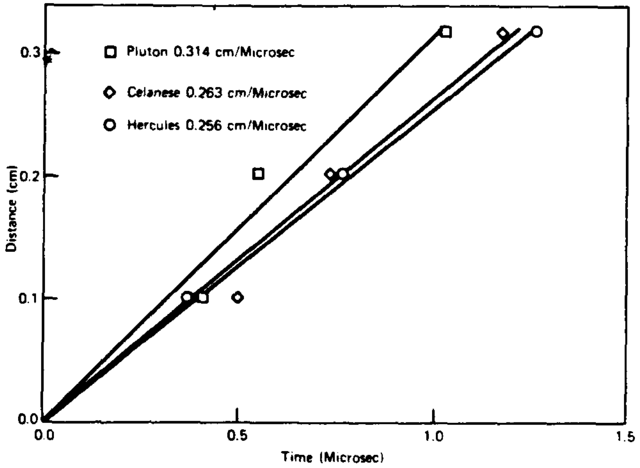

Figure 3. Distance-time data for wavespeed determination in study materials.

Table 3. Wave Propagation Parameters.

	Pluton	Hercules	Celanese	Plexiglas
Attenuation, db/m	508	251	394	---
Wavespeed, m/sec	3140	2560	2630	2830
Ultrasonic speed, m/sec	3070	2510	2630	---
Impedance, Gg/sec.m^2	3.47	3.99	4.21	3.40

Also included in Table 3 is a comparison with the ultrasonic sound speed as measured in through transmission by a pair of 5 MHz barium titanate piezoelectric crystals. The acoustic impedance (density times wavespeed) is calculated from the measured wavespeed and the density given in Table 2.

The attenuation tabulated above is due to hydrodynamic catchup and void crushing; the fibers are so small (approximately five microns) relative to the Fourier wavelengths in the stress wave that appreciable geometric dispersion does not occur. The higher wavespeed in the Pluton material is due to this fiber having a higher transverse modulus than the more anisotropic Hercules and Celanese fibers.

The compression-only shock loading described above was used to measure wave propagation characteristics, while avoiding tensile damage by means of rear-surface momentum traps which separate from the surface rather than allow a reflected tensile wave to enter the specimen. Other specimens were then shock loaded with unsupported rear surfaces in order to measure the ability of the material to withstand tensile spallation. Specimens were loaded at various intensities until that intensity was found which just produces incipient damage in the specimen – the "spall threshold". Specimens were sectioned and examined micrographically as seen in Figure 4 to determine the onset of microcracking. This threshold was determined for three different waveforms, two rectangular of different durations and one triangular.

A simple but reasonably valid equation relating the incident stress σ in the wave propagation direction to the impact velocity V and the impedances Z_f and Z_s of the flyer and sample is:

$$\sigma = VZ_fZ_s/\,(Z_f + Z_s) \qquad (1)$$

This equation assumes linear response of both the flyer and specimen, which is approximately correct at the relatively low pressures reported here. The wave duration t_d is the time taken for the compressive wave to transverse the flyer, reflect from its rear surface, then traverse the flyer again as a reflected tensile wave and unload the compression at the speci- front surface:

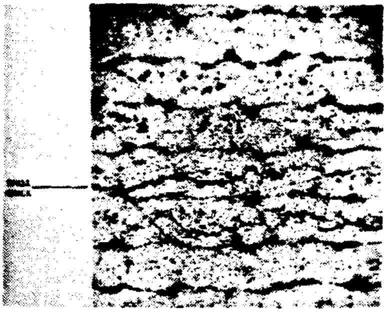

Figure 4. Pluton composite after shock loading, section perpendicular to fiber direction.

$$t_d = 2t_f/c_f \qquad (2)$$

where t_f is the flyer thickness and c_f is the wavespeed in the flyer. The impulse imparted is then the product of σ and t_d. These formulae were used to calculate incident pressures and durations for the flyer plate tests, but are not applicable for the direct contact triangular wave tests. For these, gage records were used to measure the waveform directly and the impulse was determined by numerical integration of the stress-time history.

A principal result of the spall threshold testing is that all three composite types spalled at essentially the same pulse intensity, so that the fiber modulus had no effect on the shock hardness. Micrographic analysis of the spall cracks showed them to pass through the weaker matrix phase only. Since all three composites exhibited the same order of wave attenuation, the shock hardness is therefore controlled primarily by the dynamic tensile strength of the epoxy matrix. The measured or calculated wave parameters of the three different waveforms at the intensity necessary to cause incipient spallation are listed in Table 4 below:

Table 4. Spall Threshold Parameters.

Waveform	Intensity σ,MPa	Duration t_d,μsec	Impulse Pa·sec
rectangular	90.0	1.08	95.0
rectangular	125	0.67	84.0
triangular	143	1.42	103

The data of Table 4 indicate that total impulse provides a reasonable failure criterion for the composites studied here, as all waveforms capable of inducing damage contained an impulse near 100 Pa · sec. Other criteria might also be used to rationalize these data; for instance, the temperature-dependent thermofluctuation model of Zhurkov [7] was found to provide a reasonable fit to the data as well. However, use of these higher-order models is likely not justified until additional data over a wider range of waveshapes and temperatures is obtained. In addition, the maximum-impulse criterion is very convenient in computational analysis of impact.

CONCLUSIONS

The attenuation and spall threshold measurements given above provide guidance as to the resistance of graphite/epoxy laminates to intense impacts. The shock hardnesses of the graphite/epoxy composites are appreciably less in terms of spallation impulse than woven-fabric reinforced composites [8] and much less than three-dimensionally reinforced composites [9]. One naturally inquires whether this is due to inferior wave attenuation, inferior dynamic strength, or both.

Figure 5 compares the attenuation in the Celanese composite (the curves for the Pluton and Hercules are similar when plotted on this scale) with published attenuation data for cloth laminate quartz/phenolic [10] and three-dimensional graphite/phenolic. The 3D material clearly owes part of its shock hardness to its superior attenuative properties. The attenuation of the 1D Celanese and the cloth laminate are similar, however, so that the higher spall threshold of the quartz/phenolic must be ascribed to dynamic strength. Since the resins have similar strengths, this must

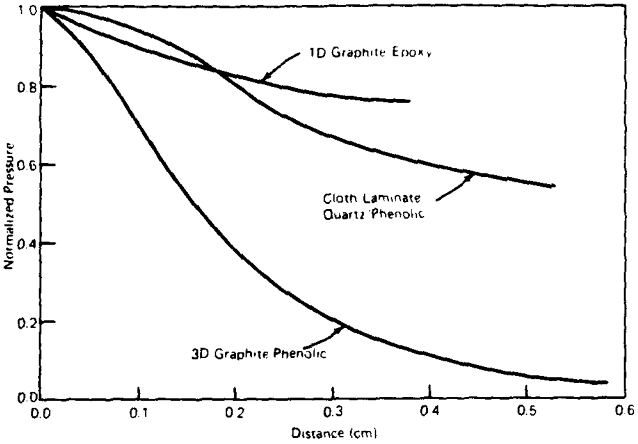

Figure 5.* *Comparison of stress wave attenuation in various composite materials.

be due to an ability of the woven fibers to provide strengthening in the wave propagation direction by having some fibers oriented partially in the through-thickness direction.

The hardness of the graphite/epoxy material could be improved if desired by increasing the attenuation and the through-thickness strength, especially the latter. Some possible means of achieving this would be to group fibers into more heterogeneous bundles to induce geometric dispersion, covering plies of very high porosity could be used to yield crushup attenuation, and viscous attenuation could be increased by the addition of rubber particles to the epoxy matrix. These particles may also increase the dynamic toughness of the matrix. Use of some woven rather than unidirectional reinforcement would increase strength as in the quartz/phenolic described above.

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