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THE EFFECT OF ORIENTATION ON THE SHOCK RESPONSE OF A CARBON
FIBRE - EPOXY COMPOSITE.

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The effect of fibre orientation on the shock response of a two-dimensional carbon fibre – epoxy composite has been studied using the technique of plate impact. In the through-thickness orientation, it appears that the material behaves as though it is a simple polymer. When one of the fibre directions is orientated parallel to the loading axis, very different behaviour is observed. The stress pulse has a pronounced ramp, before at sufficiently high stresses, a much faster rising shock occurs above it. Examination of the wave velocities suggests that the start of the ramp travels at a near constant velocity of *ca.* $7.0 \text{ mm } \mu\text{s}^{-1}$, whilst the shock velocity in this orientation converges with that of the shock velocity of the through-thickness orientation. Therefore we believe that the stress pulse is separated into a fast component that travels down the fibres, with the rest travelling at the shock velocity in the matrix between the 0° fibres (epoxy plus fibres normal to the loading axis). Finally, from the Hugoniot, we observed that at low shock intensities, the 0° orientation was significantly stiffer than the through-thickness orientation. As the severity of the shock increased, the Hugoniot of the two orientations converged. Therefore, it would appear that orientation only effects the shock equation of state at lower shock stresses.

Keywords: composite, shock, Hugoniot, orientation.

1. INTRODUCTION

The interest in the high-strain-rate response of composite materials comes from a number of sources. The explosives community has long considered particulate composite systems as many modern insensitive high explosive formulations consist of explosive crystals embedded in a polymeric binder [1-4]. Other applications include potting compounds for electronics (consisting of alumina particles in epoxy) have also been studied [5-7]. However, a major consideration is the requirement for light-weight materials for impact resistance, both from the military (armour materials) and aerospace (foreign object damage – FOD and bird strike) communities. Unfortunately, a high loading-rate event tends to be complicated. For example, the “target”, be it an airfoil or blade in an aeroengine, will have a complex geometry, whilst the projectile can be any material, impacting at an arbitrary angle and velocity. The resultant conditions of stress and strain at the impact site will therefore have compressive, tensile and shear components, rendering a meaningful analysis difficult or even impossible. By simplifying the loading geometry, the material response can be more readily understood, and quantitative mechanical and microstructural data can be extracted for use in constitutive models. At quasi-static strain rates, this includes loading in one-dimensional stress (both in tension and compression) or plane strain fracture toughness. At higher strain-rates (for example 10^3 s^{-1}), one-dimensional stress can be induced via devices such as the Hopkinson bar. At higher strain-rates still (*ca.* 10^6 s^{-1}) inertial effects come into play, rendering one-dimensional stress impossible, and one-dimensional strain conditions apply. This generally results in a shock wave forming within the specimen, and a number of techniques can be employed to investigate the materials response. This can be done explosively, or more commonly by plate impact. This

method impacts an accurately machined flyer plate (flat and parallel to better than $\pm 5 \mu\text{m}$) onto an equally accurately machined target plate that has been instrumented such that useful data can be obtained. The maximum allowable misalignment between the flyer and target plates is of the order 1 milli radian, and this results in the impact launching a planar shock wave into the target, behind which conditions of one-dimensional strain prevail. Under these conditions, all strain ($\boldsymbol{\epsilon}$) is accommodated along the impact (longitudinal) axis (x), whilst the orthogonal components (y and z) are zero due to inertial confinement. Correspondingly, whilst there is an impact stress (\boldsymbol{s}_x) there also have to be orthogonal components to maintain confinement, thus,

$$\boldsymbol{\epsilon}_x \neq \boldsymbol{\epsilon}_y = \boldsymbol{\epsilon}_z = 0 \text{ and } \boldsymbol{s}_x \neq \boldsymbol{s}_y = \boldsymbol{s}_z \neq 0. \quad (1)$$

A full description of one-dimensional shock loading is beyond the scope of this paper; however, the interested reader is directed to the review article of Davison and Graham [8] where a thorough discussion of the shock response of materials can be found.

Many structural composites consist of a mixture of stiff fibres (usually glass or carbon although sometimes Kevlar is used) in a polymeric binder (most often epoxy). These fibres can be unidirectional, or in two or three-dimensional weaves. Whilst a body of work has examined the response of these materials to shock loading, most of it has concentrated on the two-dimensionally woven materials, and is briefly reviewed here. In most cases, the loading axis has been normal to the plane of the fibres (*i.e.* the through thickness orientation). Dandekar *et al.* [9] investigated the equation of state of a glass fibre – epoxy composite, in terms of the shock stress, shock velocity (U_s) and particle velocity (u_p - *i.e.*

the velocity of material flow behind the shock front). Their results indicated that there was a linear relationship between shock and particle velocity of the form,

$$U_s = c_0 + Su_p, \quad (2)$$

where c_0 and S , the shock parameters were $2.96 \text{ mm } \mu\text{s}^{-1}$ and 1.11 respectively. This type of behaviour is typical of a wide range of materials, including metals [10] and some polymers [11], including epoxy resins [12, 13]. A linear U_s - u_p relationship was also observed by Zhuk *et al.* [4], thus it would appear that in the through thickness orientation, this class of composite displays fairly typical behaviour. Riedel *et al.* [14] also noted this behaviour for a carbon fibre – epoxy composite.

By their very nature, two dimensional fibre composites are highly anisotropic. Most of the work discussing the response of composites to shock loading has examined the material with the fibre plane normal to the loading axis. Overall, when shocked in this orientation, fibre based composites appear to behave in a manner similar to monolithic polymers, indeed Zaretsky *et al.* [15] have made this point. However, it would be expected that when the fibre direction is orientated along the impact axis, the response would be quite different. Work by Holmes and Tsou [16] on an aluminium fibre epoxy composite, shocking along the fibre axis showed no evidence of an elastic precursor wave (*i.e.* the one-dimensional strain yield stress – the Hugoniot Elastic Limit; HEL). Comparison of the shock velocities between thicknesses of 9.5 and 25.4 mm showed that it was constant, suggesting that the shock itself was steady. However, they did observe a slight waviness to the shock front, with a periodicity that corresponded to the fibre spacing. Eden *et al.* [17]

used high speed photography to investigate a quartz – phenolic resin composite. Their results clearly differentiated between the response of the fibres and the matrix, indicating that the individual fibres were acting as wave-guides. However, as the previous authors demonstrated, the interval between the leading edges of the shock in the fibres and the matrix reached a constant value, where the overall shock front became stable. More recently, Bordzilovsky *et al.* [18] examined the effects of orientation to the shock axis of a unidirectional aramid fibre – epoxy composite, with the orientation of the fibres ranging from 5 to 90° to the shock axis. Where the mis-orientation between fibres and the loading axis was small, a distinct low amplitude precursor wave was observed before arrival of the main shock. As the angle increased, the duration of this precursor decreased until it disappeared at 90°. This was interpreted as an elastic wave. Hereil *et al.* [19] observed similar behaviour in a three dimensional carbon – carbon composite, with a low amplitude ramp preceding a much more quickly rising shock front. However, their interpretation suggested that this precursor was due to a high velocity wave transmitted along the fibres orientated in the shock axis, whilst the main shock was transmitted through the “matrix”, in this case the fibres and binder orientated orthogonally, in agreement with previous studies [16, 17].

In this paper, we examine the shock response of a two-dimensional carbon fibre – epoxy composite in two orientations; through thickness (fibres normal to the impact axis) and fibre 0° (fibres parallel to the impact axis). The effects of specimen thickness on shock velocity and shock stress are also investigated.

2. EXPERIMENTAL.

Samples of a two-dimensional carbon fibre epoxy composite of dimension 60 mm x 60 mm were cut from larger sheets received from the manufacturer. These were lapped flat and parallel to a maximum of $\pm 5 \mu\text{m}$, to thicknesses of 2.3, 3.8 and 5.7 mm. For through thickness measurements, a manganin stress gauge (MicroMeasurements LM-SS-025CH-048) were supported on the back of the target with a 12 mm block of polymethylmethacrylate (PMMA). To provide further protection for the gauge, it was backed into the PMMA by *ca.* 1.5 mm. This gauge is referred hence forth as the back surface (or BS) gauge. A second gauge was supported on the front of the target assembly with a 1 mm cover plate of either dural (aluminium alloy 6082-T6) or copper, matched to the material of the flyer plate. It was insulated with 200 μm of mylar from the flyer plate and the specimen, and is referred to as the 0 mm gauge. Shock stresses were induced by the impact of dural and copper flyer plates in the velocity range 225 to 1125 m s^{-1} , using a 50 mm bore, 5 m long single stage gas gun [20]. Gauge calibrations were according to Rosenberg *et al.* [21] Fibre 0° specimens were made by taking lapped 5.7 mm plates of the composite and, after cleaning the surfaces, glued together using a low viscosity epoxy adhesive and holding under pressure for a minimum of 12 hours. These were then sectioned and lapped to thicknesses of 6 and 10 mm. Target assemblies were made using the same techniques discussed above, and the impact velocities were in the range 200 to 920 m s^{-1} . Specimen geometries and gauge placements are shown in Fig. 1.

FIGURE 1 NEAR HERE

3. MATERIALS DATA.

Specimen material was provided by Short Brothers PLC of Belfast. The fibres were Hexcel 5HS in a satin lay up of orientation 0/90, ± 45 , 0/90, ± 45 ... The areal weight was 370 g m^{-2} . The resin was an epoxy, Hexcel RTM6. The composite was cured at 180°C under a pressure of 670 kPa. The longitudinal sound speed in the through-thickness orientation was $3.02 \pm 0.03 \text{ mm } \mu\text{s}^{-1}$ and the ambient density was $1.50 \pm 0.01 \text{ g cm}^{-3}$. The microstructure is presented in Fig. 2.

FIGURE 2 NEAR HERE

4. RESULTS.

In Fig. 3, we present typical gauge traces from a specimen shocked in the through thickness orientation. The shock stress was generated by the impact of a 5 mm dural flyer at a velocity of 504 m s^{-1} .

FIGURE 3 NEAR HERE

These traces show a number of features. The amplitude of 0 mm trace is defined by the impact conditions, that is the flyer material and the impact velocity. From this, and the known shock response of the flyer material [10], the particle velocity can also be determined using impedance matching (*i.e.* momentum transfer) techniques. There is small oscillation superimposed upon the top of the trace. We believe that this may be due to wave

interactions between the fibre and matrix reflecting back to the gauge location. However, their amplitude is so low that they do not have a significant effect. Very little more can be gained from this trace, since at this point the shock has only travelled through 1 mm of dural. Further information however, can be determined from the back surface trace. The temporal spacing (Δt) between the traces in combination with the specimen thickness (w) can be used to obtain the shock velocity ($U_s = w/\Delta t$), taking into account both the offset distance of the gauge within the PMMA, and the known shock response of PMMA [11, 22]. The shape of the gauge trace in the back surface location will also have been modified by the passage of the shock through the composite, and hence its mechanical response. It can be seen that there is a very sharp rise with a slight rounding as the stress approaches its peak amplitude. This is not dissimilar to the response of a monolithic epoxy resin [13].

The situation is somewhat different when shock axis is parallel to a fibre direction. Representative gauge traces are shown in Fig. 4.

FIGURE 4 NEAR HERE

To aid clarity, we have split this figure in two, to show the response at low and high shock amplitudes. In Fig. 4a, the impact conditions were a 6 mm composite plate impacted with a 5 mm dural flyer at 200 m s^{-1} . The 0 mm trace, in contrast to the equivalent trace in figure 3, has a longer rise time, with a break in slope at *ca.* 0.6 GPa. This is due to the thick insulation around the gauge (*ca.* 200 μm of mylar). This was present as previous shots had shown that the gauge would often fail at this position in the fibre 0° orientation, unless the insulation was very thick. Therefore, it would take longer for the stress to equilibrate within

the gauge layer, as reflected in the longer rise time. As a consequence, we have indicated the arrival of the stress pulse at the 0 mm gauge with a vertical line, which we have used as a fiducial for subsequent wave velocity measurements. The back surface gauge trace will show the shape of the shock wave, as modified by its passage through the sample. In this case, the trace clearly has a ramped nature, in common with the observations of Eden *et al.* [17] when using quartz stress gauges to measure the shape of the stress pulse in a similar orientation. As such, we have measured two temporal spacings between the gauges, these being t_{toe} at the beginning of the rises of the stress pulses and t_{head} at the maximum stress amplitude. The situation under higher stress conditions (10 mm specimen impacted with a 5 mm copper flyer at 936 m s^{-1}) is different again, as shown in Fig. 4b. It can be seen that the 0 mm trace did not survive for long, although it did so for long enough to obtain a stress measurement. This would be due to the more extreme loading conditions. The major difference however is in the back surface trace. Now it can be seen instead of the simple ramped trace seen in Fig. 4a, there is an initial ramp, up to a stress level of *ca.* 1.0 GPa, followed by a much steeper rise to the final stress amplitude. This is qualitatively similar to the traces observed by Bordzilovsky *et al.* [18] and Hereil *et al.* [19] who proposed either an elastic precursor or a high velocity wave front transmitted along the fibres respectively. However, we should also point out that back surface traces of near identical form have been measured in an unfilled borosilicate glass [23]. In that work, this was explained in terms of collapse of the open structure in the glass to a denser form. Whilst we would not suggest that this mechanism is operating in this material, it does show that vastly different deformation mechanisms can produce similar results.

In the following figures, we examine the equation of state in terms of the shock and particle velocities, and stress and particle velocities. Fig. 5 presents the relationship between shock velocity and particle velocity for the through thickness orientation, both as a function of specimen thickness (Fig. 5a) and against the data of others (Fig. 5b) [14, 24].

FIGURE 5 NEAR HERE

From Fig. 5a, it would appear that there is no significant effect of specimen thickness on the shock velocity. However, we do acknowledge that at the very lowest particle velocity, it seems that the shock velocity is highest in the lowest specimen thickness. However, when errors are taken into account, it can be seen that they overlap, hence it is difficult to make a definite statement concerning specimen thickness, especially when at higher particle velocities, there is no obvious thickness effect. As such, we have chosen to assume that the shock velocity is steady by our minimum specimen thickness of 2.32 mm, and thus we have assumed that the material behaves according to equation 2, yielding values of c_0 and S of $3.23 \text{ mm } \mu\text{s}^{-1}$ and 0.92 respectively. We have also compared our results to those within the literature (figure 5b). Riedel *et al.* [14] quote values of $c_0 = 2.54 \text{ mm } \mu\text{s}^{-1}$ and $S = 1.41$. However, we feel unable to comment further on this data set due to the high degree of scatter, and that no value of the ambient density was quoted. The data of Bushman *et al.* [24] is perhaps more illuminating. They quote values of c_0 and S of $2.86 \text{ mm } \mu\text{s}^{-1}$ and 1.22, with an ambient density of 1.46 g cm^{-3} . Therefore, their value of c_0 is lower whilst their value of S is greater than ours. Although these shock parameters are simple empirical constants, Davison and Graham [8] have equated c_0 with the ambient bulk sound speed,

and S to depend upon the first pressure derivative of bulk modulus. Therefore, these results would indicate that our material has a lower compressibility than that of Bushman *et al.*

[24]

The Hugoniot of this carbon fibre composite in stress – particle velocity space is shown in Fig. 6, along with the pressure data of Bushman *et al.* [24]

FIGURE 6 NEAR HERE

The curve fitted to the data is the hydrodynamic pressure (P_{HD}), calculated via,

$$P_{HD} = \mathbf{r}_0 U_s u_p, \quad (3)$$

using the measured values of c_0 and S for our material, as shown in equation 2 and Fig. 5. It can be seen that as particle velocity increases, our measured stresses become noticeably higher than the calculated pressure. However, we also note with interest that the pressure measurements of Bushman *et al.* [24] agree well with our own pressure calculations, even though their data extends to much higher particle velocities.

In Fig. 7, we present data where we examine shock wave velocity data as a function of orientation of the fibre direction to the shock axis.

FIGURE 7 NEAR HERE

As we showed in Fig. 4, when one of the fibre directions is parallel to the shock axis, the ramped nature of the back surface gauge traces led us to determine two wave velocities, a velocity at the initial rise of the pulse (as indicated by t_{toe}) and a velocity either at the maximum stress amplitude (Fig. 4a) or at the top of the ramped part of the signal (Fig. 4b) as indicated by t_{head} . We can thus see that the velocity measured at the initial rise (c_{toe}) is significantly greater than the shock velocity in the through thickness direction. There is quite a high degree of scatter in this data set, but we would suggest that it near constant with particle velocity, at a value of *ca.* $7.0 \text{ mm } \mu\text{s}^{-1}$, further suggesting that if this wave has been transmitted along the fibres, it is largely elastic in nature. In contrast, the second wave velocity in the fibre 0° orientation, whilst initially greater than the shock velocity in the through thickness orientation, eventually converges with that data set.

Finally in Fig. 8, we examine the effects of orientation on the Hugoniot in stress – particle velocity space.

FIGURE 8 NEAR HERE

As with Fig. 6, the curve fit is according to equation 3, using the shock – particle velocity relationship determined for the through-thickness orientation. It can be seen that at lower stresses, the fibre 0° is stiffer, but as stress increases, the Hugoniot of both orientations converge. This is in agreement with the behaviour of the shock velocities shown in Fig. 7.

5. DISCUSSION

One of the main objects of this programme was to determine the effect of orientation of the fibres to the shock-loading axis. As such we have shot samples in the through-thickness orientation (fibres normal to the loading axis) and in the 0° orientation such that one of the fibre directions in the 0/90 ply lay parallel to the loading axis. From Figs 3 and 4, we can see qualitatively that orientation has a strong effect. In the through thickness orientation (Fig. 3), the back surface trace, whose shape will be influenced by the mechanical properties shows a steep rise, with a slight rounding as the stress reaches its peak amplitude. No break in slope in the rise was noted that would indicate the presence of an elastic precursor. In this respect, the material appears to behave as a monolithic polymer such as epoxy [13]. In contrast, the 0° orientation (Fig. 4) shows a very different response. At low shock amplitudes (Fig. 4a) the back surface trace shows a clear ramped nature, whilst at high amplitudes (Fig. 4b), it showed a ramp up to a stress of *ca.* 1.0 GPa, before the signal rises more rapidly. This latter behaviour has been observed in a number of other materials, including a unidirectional composite [18], and a three dimensional carbon – carbon composite, where by definition, one of the fibre directions lay along the loading axis [19]. A number of mechanisms have been proposed to explain this behaviour.

Bordzilovsky *et al.* [18] suggested that this simply be due to the separation of the elastic and inelastic components of the shock front, in essence an HEL. In contrast, Hereil *et al.* [19] suggested that the first part of the wave be transmitted along the fibres, with the rest transmitted through the matrix, which they defined as a mixture of fibres orientated normally to the loading axis, and the binder. We also observed that the form of these traces was near identical to similar traces taken from the open structured borosilicate glass [23].

This was explained in terms of the collapse of the open structure to a denser state, in effect

densification of a porous material. We note with interest that Hereil *et al.* [19] observed that their material contained a quantity of cracks and voids after the final manufacturing step in their material. Ahrens and Johnson [25] have also quoted the density for monolithic graphite and carbon fibres as 2.21 and 1.52 g cm⁻³ respectively, suggesting that the carbon fibres themselves contain significant porosity. Therefore, it could be argued that porosity, be it within the composite microstructure as a whole, or simply in one of the components such as the fibres should have a significant effect upon the shock response. However, if this were true, it would be expected to appear regardless of orientation. From Fig. 3, it can be seen that the through thickness orientation does not behave as if porosity has a significant role.

Further insights can be gained from examination of the material's equation of state in terms of shock stress, shock velocity and particle velocity. In Fig. 5, we showed that the U_s-u_p relationship of the through thickness orientation was linear, with no effects of specimen thickness. Our value of c_0 was determined to be 3.23 mm μs^{-1} . As we have already mentioned, Davison and Graham [8], in metals at least, equate this empirically derived value with the bulk sound speed. However, when compared to the measured longitudinal sound speed of 3.02 mm μs^{-1} , it can be seen that it is significantly greater. This is a behaviour that has been observed in many polymers, including epoxy resins, both by Carter and Marsh [11] and ourselves [13]. This would certainly explain why no evidence of an elastic precursor was seen in Fig. 3, as the shock front would always be supersonic with respect to the longitudinal sound speed. It is possible that the shock speed becomes non-linear with particle velocity at low shock intensities, as has been shown in some polymers such as PMMA [22], but unfortunately our own data did not extend to these low

particle velocities, nor did those of other researchers on carbon fibre based composites [14, 18, 19].

In Fig. 6, we presented our own stress – particle velocity data, compared to the pressure – particle velocity data of Bushman *et al.* [24] and our own calculated hydrodynamic pressures from equation 3. It can be seen our data lies somewhat above both our calculated pressures and the data of Bushman *et al.*, although we would point out that the two sets of pressure data agree extremely well, even beyond the particle velocity range of our own measurements. We believe that this lies in the nature of the measurements. We have used manganin stress gauges to measure the longitudinal stress. This has a hydrostatic pressure component (P) and a shear strength component (t), thus,

$$s_x = P + \frac{4}{3} t. \quad (4)$$

Bushman *et al.* [24] measured a surface velocity, and therefore used equation 3 to determine a hydrodynamic pressure. Our own measurements took into account the *strength* of the material, and hence they are somewhat higher. This suggests that the shear strength also has a positive dependence upon the applied shock stress. Such behaviour has been seen in a number of other materials, including metals such as titanium aluminides [26] and polymers such as polyether ether ketone [27], epoxy [28] and polycarbonate [29]. Further, independent measurements of the shear strength in these materials [26, 27, 29, 30] confirmed that the shear strength did indeed increase with shock stress. Therefore, it would

appear that in the through thickness orientation, the response to shock loading is controlled in large part by the epoxy binder phase.

The situation is somewhat different when shock loading down a fibre direction. From Fig. 7, we extracted two wave velocities. The first from the base of the stress traces we showed had a near constant velocity of *ca.* $7.0 \text{ mm } \mu\text{s}^{-1}$ with increasing particle velocity. We believe that this portion of the stress pulse was transmitted down the fibres, and suggests that the response of the fibres themselves remains elastic under all impact conditions studied. The second portion of the stress pulse has a velocity that converges with the shock velocity in the through thickness direction. Therefore we propose this was transmitted through the “matrix” between the 0° fibres, by which we mean a mixture of epoxy binder and fibres orientated normal to the loading axis. We see a similar situation in the Hugoniot data, presented in Fig. 8. Here, we can see initially that the 0° orientation is stiffer than the through-thickness direction. However, at higher stresses, as with the shock velocity data, there is a convergence between the two data sets. Therefore, it would appear that when shocked down a direction parallel to a fibre direction, a small part of the total stress pulse is transmitted along the fibres themselves elastically. The greater portion is transmitted through a mixture of the epoxy binder and fibres orientated normally to the loading axis. Therefore, it can be seen why we get the convergence in the shock velocity and shock stress particle velocity data as the severity of the impact conditions increase. Ultimately, at sufficiently high stresses, there will be no effect of orientation on the equation of state.

6. CONCLUSIONS

A series of plate impact experiments have been performed on a two-dimensional carbon fibre – epoxy composite to determine the effect on orientation on its equation of state. When shocked along the through thickness direction (fibres normal to the loading axis), the material appears to behave in a manner similar to a monolithic polymer such as epoxy. Measurements of the shock pulse after it has travelled through the composite show a fast rising shock front with a slight rounding as the stress reaches its maximum amplitude. No evidence of an elastic precursor was observed. Examination of the shock – particle velocity curve showed a linear relationship, with little or no evidence of sensitivity of specimen thickness. The value of c_0 (the zero particle velocity intercept of the shock velocity) was actually greater than the measured longitudinal sound speed. This behaviour has been observed by a number of authors (including ourselves) in a wide range of polymers, including epoxy resins. This tells us that the shock velocity will always be greater than the longitudinal sound speed, and hence explains why no evidence of an elastic precursor was observed in the back surface gauge traces. Comparison of the measured stresses with the calculated hydrodynamic pressure shows an increasing divergence between the two as stress increases, with the stress being the greater. This is typical of many polymeric materials (including epoxy), and thus suggests that in the through thickness orientation, this carbon fibre epoxy composite behaviour is dominated by the epoxy binder.

The behaviour when shocked along a fibre direction is different. At low impact velocities, the stress pulse is distinctly ramped, whilst at higher stresses, the ramp is followed by a much faster rising shock front. We believe that this is evidence of the stress pulse being separated into a fast moving component in the fibres, followed by a slower

moving shock in the matrix (a combination of the epoxy binder and fibres orientated normally to the loading axis). The velocity of this slower moving shock is coincident with the shock velocity in the through thickness direction, further evidence about how the stress pulse separates in this particular orientation. Finally, we have shown that the 0° orientation has a stiffer Hugoniot, but as particle velocities increase, it converges with that of the through thickness orientation. Therefore we propose that in this composite, the orientation of the fibres to the loading axis only effects the shock-induced equation of state at lower stresses. As stress increases, it becomes decreasingly influential, until under significantly severe loading conditions, it has no effect at all.

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FIGURES.

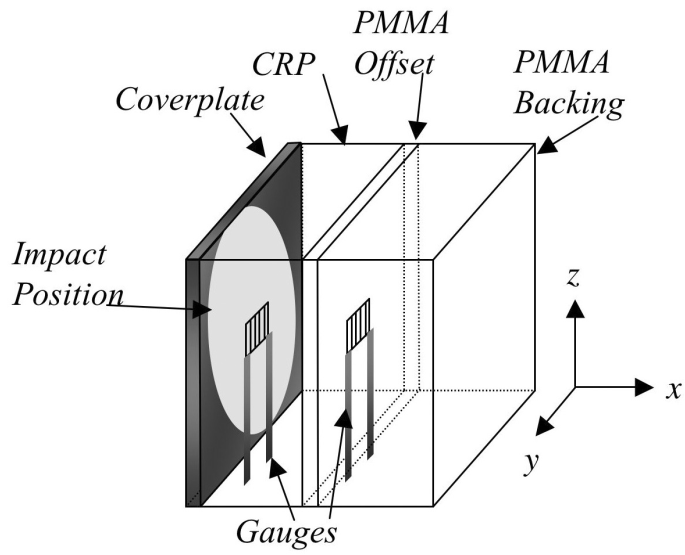


Figure 1.

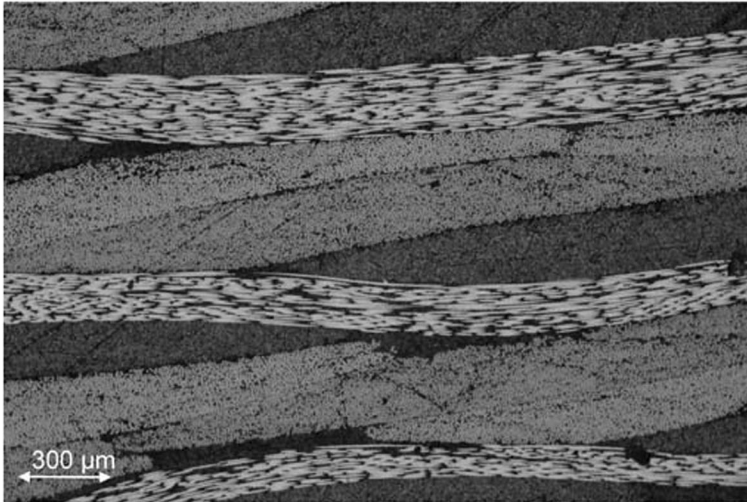


Figure 2.

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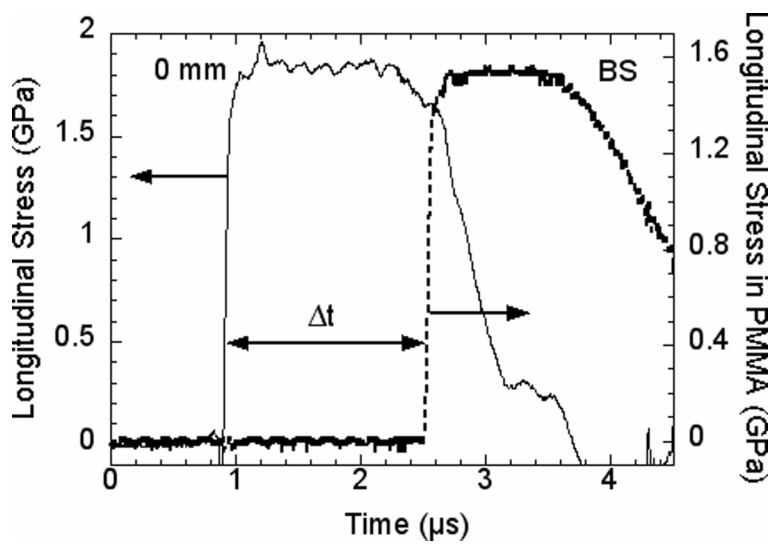
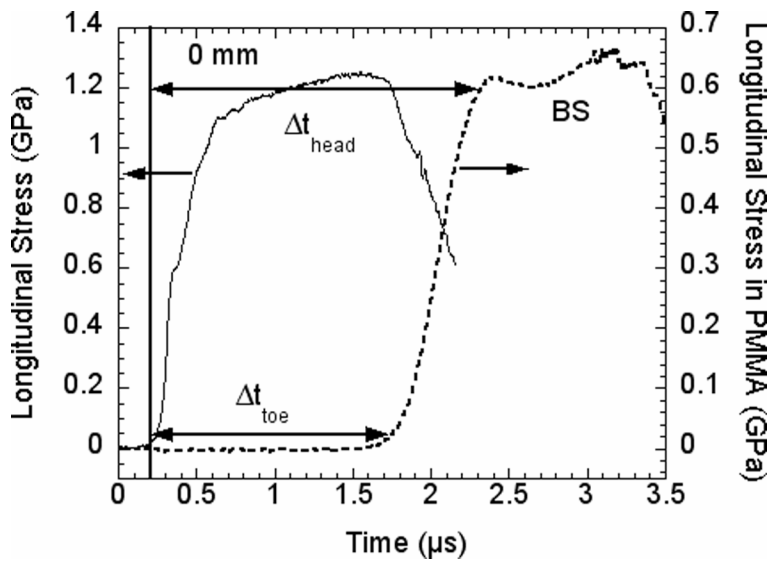
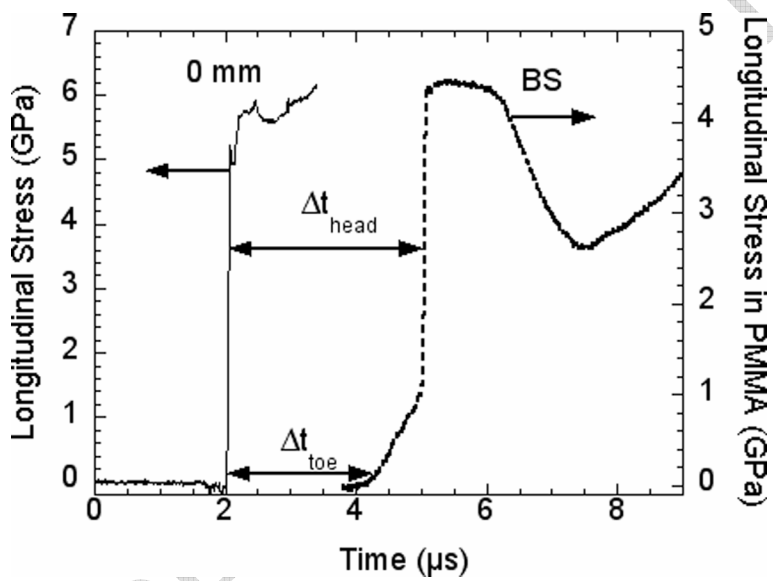


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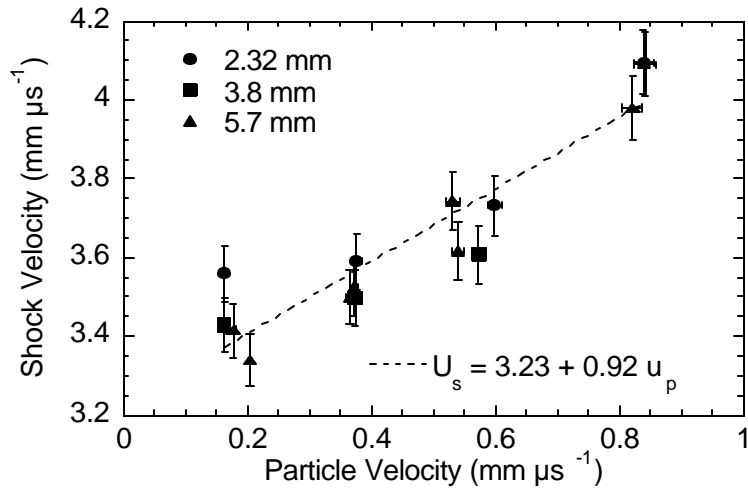


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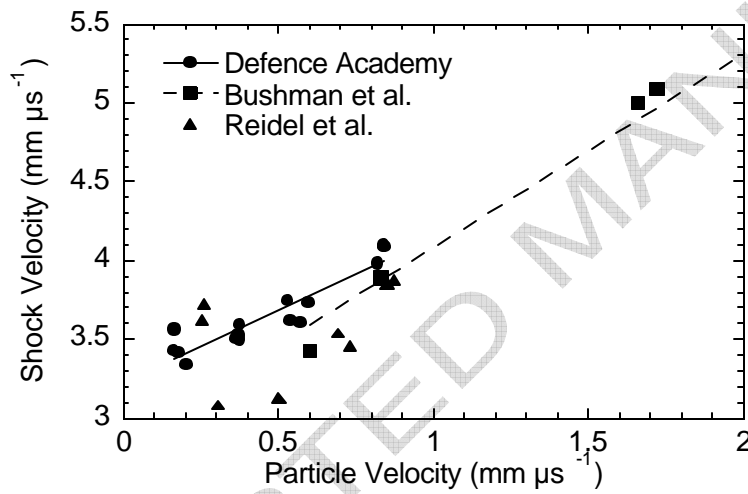


b.

Figure 4.



a.



b.

Figure 5.

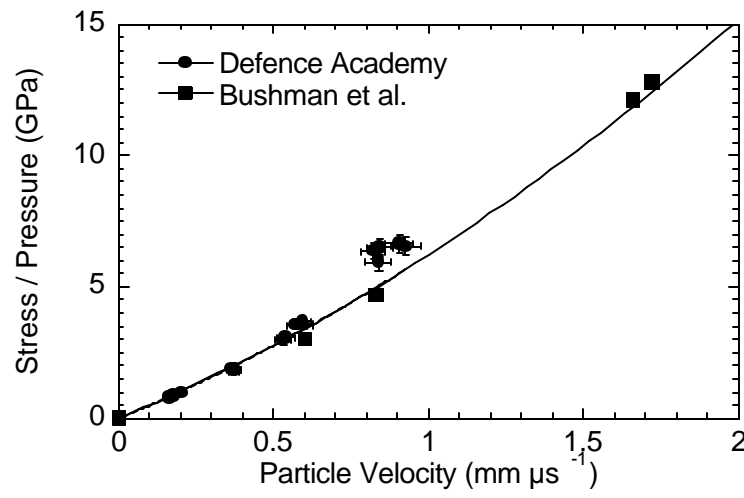


Figure 6.

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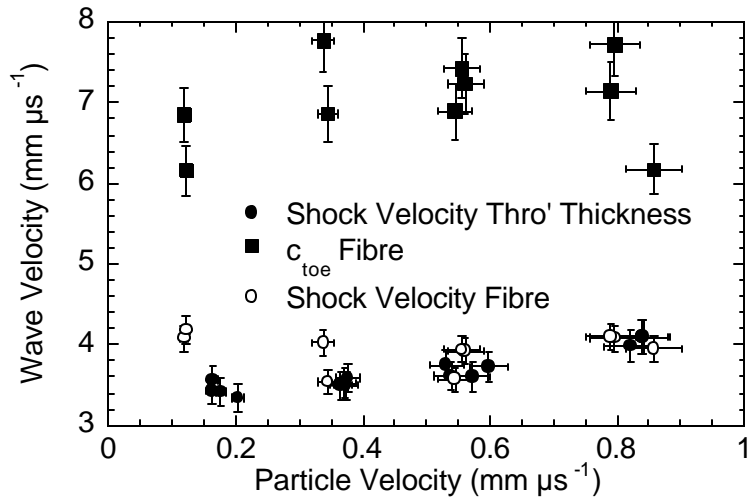


Figure 7.

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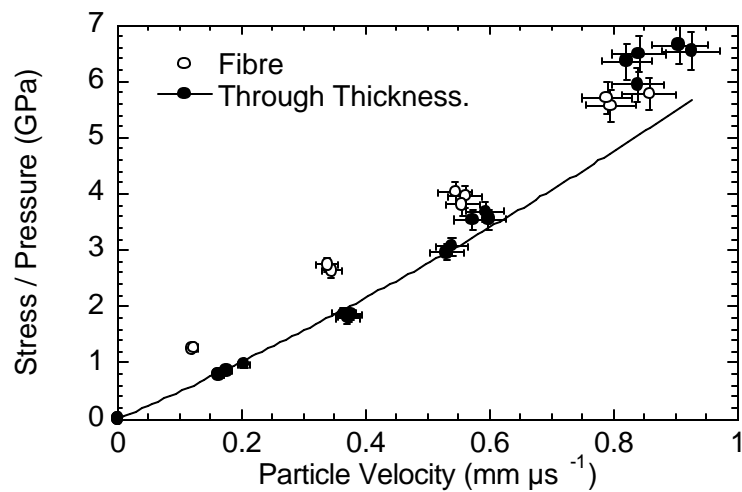


Figure 8.

FIGURE CAPTIONS

Figure 1. Schematic of target geometry and gauge placement.

Figure 2. Microstructure of carbon fibre epoxy composite.

Figure 3. Typical gauge traces from the through thickness orientation. The specimen was 3.8 mm thick. The impact conditions were a 5 mm dural flyer at 504 m s^{-1} .

Figure 4. Gauge traces from the fibre 0° orientation.

- a. 6 mm specimen plate, 5 mm dural flyer at 200 m s^{-1} .
- b. 10 mm specimen plate, 5 mm copper flyer at 936 m s^{-1} .

Figure 5. Shock velocity versus particle velocity for carbon fibre – epoxy composite.

- a. Variation according to specimen thickness.
- b. Comparison with data within the literature; Riedel *et al.* [14] and Bushman *et al.* [24]

Figure 6. Shock Hugoniot of carbon fibre epoxy composite in stress – particle velocity space. We have included the pressure – particle velocity data of Bushman *et al.* [24] The curve fit is the hydrodynamic pressure, calculated according to equation 3, using the experimentally derived U_s - u_p relationship from figure 5a.

Figure 7. Wave velocity versus particle for carbon fibre epoxy composite as a function of orientation of the fibres to the loading axis.

Figure 8. Shock Hugoniot of carbon fibre – epoxy composite in through thickness and fibre 0° orientations.

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