The effect of fibre orientation on a TWCP composite

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Abstract. Multiple authors have shown that orientation can greatly affect the shock profiles seen in composites. Carbon fibre composites are employed in multiple sectors, with their use in the aerospace industry becoming more prevalent. An angle of 20° between the outer surface and the weave direction has been shown to provide a good compromise between strength and ablation, making orientation an important property. Using a single stage gas gun with manganin pressure gauges the shock response of both a 90° and 45° layup TWCP composite was investigated up to a particle velocity of approximately 1 mm s⁻¹, in both the US-u_p and pressure-volume planes. Comparisons in terms of shock propagation were also made with a previously investigated TWCP orientation of 0°. This allowed a detailed interrogation of the effects of weave orientation in this important TWCP composite to be made. It was found that the shock response was not greatly altered by orientation of the carbon fibre weave above a certain particle velocity. This was due to the 90° behaving elastically until a particle velocity of 0.6 mm s⁻¹. Above this value the experimental data had very little deviation regardless of the angle.

1. Introduction

The use of carbon fibre composites has become more widespread in recent years, especially in the aerospace industry. Consequently, knowledge of how such materials behave while under shock loading is of increasing importance, especially because such aerospace vehicles will likely encounter significant loading within their lifetime. Investigated here is a tape wrapped carbon fibre composite with phenolic resin known by the acronym TWCP, with the angle of the weave altered to investigate shock behaviour. The orientations of TWCP investigated were 0° (fibre weave parallel to shock front), 25° and 90° (fibre weave perpendicular to the shock front).

Multiple authors have investigated the effect that orientation has on the shock response of carbon fibre composites. One such study was conducted by Millett et al. [1], where the fibre weave was orientated at 0° and 90°. In the U_S-u_p plane the Hugoniot for the 0° orientated composite behaved as a monolithic material. For the 90° fibre weave orientation a precursor wave was seen in the shock traces. This was explained as either a separation of elastic and inelastic components of the shock wave or as the shock front travelling through the fibres first. In the pressure-u_p plane a deviation is seen between the 0° and 90° orientations before convergence occurs at the higher pressure (approximately 6 GPa).
Bordzilovsky et al. [2] investigated an aramid fibre composite over a wide range of orientations with the diagnostic employed being manganin gauges. The orientations investigated (with respect to the direction of shock) were 5°, 15°, 45° and 90°. At the lower orientations (5° and 15°) a distinct elastic precursor was seen, which disappeared as the angle increased, until none was seen at the 90° orientation. By comparing the dynamic response to the static behaviour it was determined that the yield strength was dominated by either the yield strength of the matrix material, or the interlaminar strength depending on the orientation of the fibres.

Willows et al. investigated the shock response of a carbon fibre composite using the plate impact technique [personal communication]. Using VISAR and manganin stress gauges the shock profile of both ring up and ring down experiments were found. They also concluded, with the help of a computational model that fibre orientation is unimportant above a $u_p$ value of 1000 m s$^{-1}$, backing the results seen by Millett et al. [1] for their carbon fibre composite.

The 0° TWCP has been previously investigated by Wood et al. [3]. As seen by Millett et al. [1] the 0° orientated TWCP samples behaved monolithically. Convergence between the TWCP and the phenolic resin matrix material was seen at the higher particle velocity range. In the pressure-volume plane deviation was seen between the hydrostat and the experimental data above 5 GPa. A Hugoniot elastic limit for the TWCP was found to be 1.53 GPa with the lateral stress being comparable to the phenolic resin implying that the lateral stress in the TWCP material is dominated by the matrix material.

A TWCP sample was investigated by Burrell et al. [personal communication]. With the weave angled at 20° to the impact surface, due to this angle being the best compromise between strength and ablation. They found that in the Hugoniot in the $U_S-u_p$ plane the angle of a weave had an effect on the shock response when compared to a carbon fibre composite at 0°, though it should be noted this composite was of a vastly different composition. In the pressure-$u_p$ plane however, the difference was less pronounced.

2. Experimental Method

2.1. Material Properties

The key elastic material properties of the 0° TWCP are shown in table 1. The values of longitudinal sound speed ($c_L$) and shear sound speed ($c_S$) were calculated from ultrasonic measurements using a Panametrics 5077PR pulse receiver in the pulse-echo configuration employing 1 MHz transducers. The bulk sound speed ($c_B$) was calculated using equation (1). Also included is Poisson’s ratio, denoted by $v$.

$$c_B = \sqrt{c_L^2 - \frac{4}{3}c_S^2}$$

The material constituents remained the same with the only difference being the orientation of the carbon fibre weave with respect to the impact surface. The volume fraction of the fibres within the composite were obtained via optical micrographs and calculated to be 54±4% [3] for all of the orientations investigated here.

2.2. Plate impact technique

Plate impact experiments employed a 50 mm diameter, 5 m long barrel single stage gas gun to accelerate flyer plates to velocities between 200 and 1000 m s$^{-1}$. The simplified experimental set up is shown in figure 1. Surfaces perpendicular to the impact axis were machined flat and parallel to tolerances of < 10 $\mu$m. Samples were held in place using a sacrificial barrel extension, ensuring alignment. Impact velocity was obtained via a series of sequential conducting pins. Manganin stress gauges of type LM-SS-125CH-048 (longitudinal) manufactured by Vishay Micro-Measurements, allowed shock propagation to be monitored. Knowledge of flyer plate properties allowed calculation of key shock variables via the impedance matching technique [4],
with gauge calibration following Rosenberg et al. [5] for the experimentally employed manganin gauges.

3. Results and Discussion
Figure 2 shows the experimental data gathered for the 45° and 90° orientations of TWCP along with the ascertained Hugoniots. Also included is the experimental data and Hugoniot for the 0° TWCP gathered by Wood et al. [3]. At the lower particle velocities a greater deviation between the experimental data, of the different fibre orientations is seen. This is due to an elastic wave dominating the behaviour of the composite at particle velocities of less than 0.6 mm \( \mu \text{s}^{-1} \), with the main shock wave becoming the dominant behaviour above this value. Beyond this value all of the experimental data points converge and show little to no difference regardless of the orientation. A difference can be seen with the Hugoniots, caused by a divergence of the low \( u_p \) experimental data. By examining the experimental data convergence can be seen between the experimental data at an approximate value of 0.6 mm \( \mu \text{s}^{-1} \), close to the suggested value of 1 mm \( \mu \text{s}^{-1} \), discussed by Willows et al. [personal communication].

Figure 3 shows the experimental data as well as the Hugoniots for the 0°, 45° and 90°, again with the 0° results gathered from reference [3] in the pressure-\( u_p \) plane. As it can be seen there is a low amount of deviation between the experimental data, regardless of the orientation. There is also little difference between the respective Hugoniots with deviation seen at the higher particle velocities. The only outlier is from the 0° orientation, which was noted as deviation from the

| Sample                  | \( \rho_0 \) g cm\(^{-3} \) | \( c_L \) mm \( \mu \text{s}^{-1} \) | \( c_S \) mm \( \mu \text{s}^{-1} \) | \( c_B \) mm \( \mu \text{s}^{-1} \) | \( v \) |
|------------------------|-----------------------------|--------------------------------|--------------------------------|-----------------------------|-----|
| TWCP at 0° [3]         | 1.46                        | 3.61                          | 2.00                          | 2.78                        | 0.28|
| TWCP at 45°            | 1.46                        | 3.47                          | 1.04                          | 3.26                        | 0.45|
| TWCP at 90°            | 1.46                        | 4.20                          | 2.01                          | 3.50                        | 0.35|

Figure 1. Simplified diagram of experimental setup.
Figure 2. Experimental data for the Hugoniot in the pressure-particle velocity plane. This shows that with regard to the pressure-$u_p$ Hugoniot plane, orientation is unimportant below a $\sigma_x = 5$ GPa.

4. Conclusion

By using the plate impact technique with manganin pressure gauges in the longitudinal orientation, the effect of fibre weave orientation on the shock response has been investigated. It has been found that above a $u_p$ value of 0.6 mm $\mu$s$^{-1}$ orientation has little effect on the shock properties, regardless of the orientation. Below this value elastic waves dominate the behaviour of the $90^\circ$ orientation leading to a greater difference between this experimental data, and the experimental data of the other fibre weave orientations ($0^\circ$ and $45^\circ$). Examining the behaviour of just the $0^\circ$ and $45^\circ$ orientations, little difference was seen between the experimental data points in the $U_S-u_p$ plane. This behaviour was also seen in the pressure-particle velocity Hugoniot plane, where only a small deviation was seen between the experimental data regardless of the angle.

Figure 3. Experimental data for the pressure-$u_p$ plane for the different TWCP orientations.
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