The use of lateral gauges in the assessment of shear strength in a carbon fibre composite

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Abstract. Laterally orientated manganin stress gauges have been used to obtain strength measurements in multiple materials, most commonly polymers and metals. Composites such as carbon fibre provide an interesting challenge for lateral gauges, as any long range order within the composite will be broken up by the inclusion of the gauge. This study has investigated the shear strength of multiple orientations of a carbon fibre composite (TWCP) which has then been compared with the matrix material. The Hugoniot elastic limit of the 90\textdegree fibre weave TWCP composite was 2.27\textsuperscript{0.25} GPa, compared to 1.53\textsuperscript{0.20} GPa found for the fibre weave orientated at 0\textdegree with respect to the shock front. The lateral stress in both orientations however, was found to be the same, at a given particle velocity. This implies that either the matrix material dominates the lateral stress behaviour of this composite, or laterally orientated gauges are too intrusive and break up any long range order of the fibre weave. Further work utilising other strength assessment techniques will be employed to fully validate these experimental results.

1. Introduction

Due to their high strength to weight ratio, composites have become prevalent in their use as structural components in a wide range of industries. These components will experience a wide range of loading conditions during their lifetime, one of which is likely to be shock loading. An important aspect of shock loading in composites is orientation of the fibre weave with respect to the shock front; as composites are generally highly anisotropic by nature. In the literature however, there is a paucity of data regarding the strength behaviour of composites under shock loading conditions. A method for measuring strength in a variety of materials, such as metals and polymers, involve lateral gauges. Lateral gauges however are a highly intrusive technique requiring the sample to be sectioned for the gauges to be inserted, which would destroy any long range order of the fibres within the composite. Due to this, lateral gauges as a method of measuring strength in composites, need to be investigated to validate their use.

There are a few papers in the literature that deal with the mechanical strength of these materials under shock loading conditions. Dandekar \textit{et al.} [1] investigated the shock response of a glass fibre composite using a gas gun along with VISAR. Using shock reverberation experiments the Hugoniot elastic limit was found to be between 1.3 and 3.1 GPa, with the most likely value
being 1.3 GPa; however the authors concluded that more experiments were needed to narrow this value down.

Bordzilovsky et al. [2] investigated an aramid fibre composite over a wide range of orientations with manganin gauges used to study the shock profile. 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 no elastic precursor was seen with 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 the the orientation of the fibres.

The 0° TWCP has been previously investigated by Wood et al. [3]. As seen by other authors, investigating carbon fibre composites [4] the 0° orientated TWCP samples behaved monolithically. Convergence between the TWCP and the phenolic resin 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 1.39 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, as suggested by Bordzilovsky et al. [2].

A TWCP sample was investigated by Burrell et al. [personal communication]. The orientation of the weave was 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 for the $U_S-u_p$ plane the angle of the weave had an effect on the shock response when compared to a carbon fibre composite at 0°. It should be noted that this composite was of a vastly different composition. In the pressure-$u_p$ plane however, the difference between the compared composites was less pronounced.

2. Experimental Method
2.1. Material Properties

TWCP is a tape wrapped carbon fibre composite with a phenolic resin matrix material. This composite has a number of weave layers (with an approximate thickness of 300 μm) which are stacked upon each other, before being impregnated with the phenolic resin. The orientation of the fibre weave for these experiments are with respect to the shock front, such that 0° fibre weave is orientated parallel to the shock front, and the fibre weave orientated at 90° is perpendicular to the shock front.

The key elastic material properties of the 0° and 90° TWCP are shown in table 1 along with the elastic properties of the matrix material Durite SC-1008 obtained from reference [5]. 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 $v$.

$$c_B = \sqrt{c_L^2 - \frac{4}{3}c_S^2} \quad (1)$$

The density for the TWCP remained the same regardless of orientations as did the volume fraction of the fibres which was 54±4% [3].
Table 1. Elastic material properties.

| Sample   | $\rho_0$ (g cm$^{-3}$) | $c_L$ (mm $\mu$s$^{-1}$) | $c_S$ (mm $\mu$s$^{-1}$) | $c_B$ (mm $\mu$s$^{-1}$) | $v$ |
|----------|------------------------|--------------------------|--------------------------|--------------------------|-----|
| SC-1008  | 1.18                   | 2.67±0.02                | 1.38±0.02                | 2.14±0.03                | 0.36|
| TWCP 0°  | 1.46                   | 3.61±0.02                | 2.00±0.02                | 2.78±0.03                | 0.28|
| TWCP 90° | 1.46                   | 4.20±0.02                | 2.01±0.02                | 3.50±0.03                | 0.35|

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$^{-1}$. 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) and type J2M-SS-580SF-025 (lateral), manufactured by Vishay Micro-Measurements, allowed shock propagation/properties to be monitored. A simplified sample set up is shown in figure 1. Knowledge of flyer plate properties allowed calculation of key shock variables via the impedance matching technique [6], with gauge calibration following Rosenberg et al. [7] for longitudinal gauges and Rosenberg et al. [8, 9] and Millett et al. [10] for lateral gauges.

Figure 1. Simplified diagram of gauge position within experimental setup.

3. Results and Discussion
By taking the difference between longitudinal and lateral stress the shear strength can be calculated. By plotting this data against the elastic prediction the Hugoniot elastic limit can be ascertained. Figure 2 shows the data obtained for the 0° orientation using this technique. The data shows a clear deviation from the elastic prediction, despite some uncertainty in whether one of the data points is elastic in nature or at the elastic-plastic transition. This then results in a Hugoniot elastic limit of 1.53±0.20 GPa. This process is explained in greater detail in reference [3].
For the 90° TWCP material the same process was followed with the shear strength plot shown in figure 3. It can be seen with the lower longitudinal stress experimental data points (below 2 GPa) lie slightly above the elastic prediction. This is most likely due to an oversimplification of the elastic prediction, which does not take into account the different values of Poisson’s ratio caused by the materials anisotropy. The Hugoniot elastic limit for the 90° TWCP orientation was found to be $2.27 \pm 0.25$ GPa, with this error based on the data, and not any potential issue with the simplification of this composites Poisson’s ratio.

It was seen in reference [3] that the lateral stress exhibited in the TWCP orientation at 0° was comparable with the lateral stress measured in the matrix material. This data was compared to the 90° lateral stress data, with this shown in figure 4. It can be seen that the lateral stress values seen with both the phenolic resin and 0° TWCP material are comparable. There are potentially
multiple explanations for this behaviour. The first is that the matrix material (the phenolic resin) dominates the lateral stress of the material. Whether this is due to the matrix material being the weak portion of the composite or a transfer of the load from the fibre to the matrix is unknown. It is also possible that the break up of any long range order of the fibre weave has led to this matrix dominate response due to the very similar impedance match between the matrix and epoxy layer surrounding the gauges, with any fibre effect response diminished. If this is true then lateral gauges are indeed too intrusive of a technique to be successfully employed for this class of materials. To assess whether this is the case alternative strength measurement methods such as the self-consistent method would need to be employed [11], something the authors will pursue in the future.

4. Conclusion
By using manganin pressure gauges in both the longitudinal and lateral orientation with the plate impact technique the effect of orientation on strength has been investigated. The Hugoniot elastic limits for the 90° was found to be 2.27±0.25 GPa. When the lateral stress of the 90° was compared to the previously obtained 0° TWCP material and the matrix material response was found to be comparable. This could mean that the lateral stress is dependent on the matrix material or that lateral gauges are too intrusive of a technique due to the break up of long range order. More experiments will need to be conducted to confirm or disprove this conclusion.

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