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DOI:
10.1063/1.4971684

Document Version
Final published version

Link to publication record in Manchester Research Explorer

Citation for published version (APA):

Published in:
SHOCK COMPRESSION OF CONDENSED MATTER - 2015

Citing this paper
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Impact and Damage of an Armour Composite

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Abstract. The current study assesses the application of the Taylor Test to validate hydrocode modelling of composite materials. 0° in-plane and through-thickness rods were cut from a 25 mm thick composite panel, made from autoclave cured 0°, 90° uni-directional carbon/epoxy prepreg. The rods were fired against a semi-infinite steel anvil and high-speed video imaging was used to capture the difference in rod shape and damage patterns during the experiments. Results of simulation with a rate sensitive, transversely isotropic composite material model implemented in the CTH hydrocode were compared with the present experiments. The model showed good correlation with global deformation of the rods, and was used to qualitatively assess some of the asymmetric deformation features in the material. As the present model implementation did not account for damage at this stage, it did not predict inter-ply delamination normal to the impact face for the in-plane 0° rods and that parallel to the impact face in the through-thickness samples.

1. INTRODUCTION

Defence and aerospace industries are increasingly incorporating composite materials for armour and structural engineering design applications. Hydrocode models have been used to predict the external damage profiles of homogeneous materials [1], however many of those currently available lack the ability to account for the rate sensitivity of constituents and changes in the material symmetry axis associated with deformation of composite materials. In the current study, rods used in Taylor tests were cut in the in-plane 0° and through-thickness orientations from a carbon epoxy composite plate and fired into a semi-infinite steel anvil using the Taylor Test geometry [2], which traditionally has been reserved for homogeneous materials. The experiments were compared to hydrocode simulations with a non-linear rate sensitive model accounting for evolution of the composite isotropy axis during loading.

2. EXPERIMENTAL

The composite panel was constructed from autoclave cured, prepreg sheets, made from unidirectional intermediate modulus carbon fibers encased in toughened epoxy. These prepreg sheets were layered in the 0° and 90° orientations to a final panel thickness of approximately 25 mm.

![Figure 1](image_url)

**FIGURE 1.** Carbon fibre composite rods (units in mm): (a) in-plane 0° and (b) through-thickness samples
Right angle cylinders (Taylor test rods) were machined from the in-plane 0° and through-thickness orientations of the panel as shown in Fig. 1. The rods had a diameter of 7.6 mm and a length of 22.5 mm giving an approximate length to diameter ratio of 3:1. The rods were fired from a single stage gas gun, into a solid steel anvil. For analysis of the ratio effect, an additional 7.6 mm-diameter rod which has the length to diameter ratio of 5:1 ratio was made with the in-plane 0° orientation. Molybdenum disulphide (MoS₂) grease was used on the surface of the anvil to prevent friction at the impact face. A digital high-speed camera, operating at approximately 120,000 frames per second and with a 1 microsecond frame exposure time, was used to record the events.

![High speed video image sequences: (a) 5:1 ratio 0° in-plane, (b) 3:1 ratio 0° in-plane and (c) through-thickness](image)

**FIGURE 2.** High speed video image sequences: (a) 5:1 ratio 0° in-plane, (b) 3:1 ratio 0° in-plane and (c) through-thickness

High-speed sequences were recorded from experiments involving the in-plane and through-thickness Taylor test rods. For each test, the impact velocity was 150 m/s. Figure 2(a) shows progressive still images for the 5:1 ratio 0° in-plane rod. During the impact, material at the front end of the rod begins to deform laterally along the impact face, shaping some material at the rear of the rod to appear as a convex aspect. Figure 2(b) shows progressive still images for the 3:1 ratio 0° in-plane rod. Again material at the front end of the rod begins to deform laterally along the impact face. Additionally, the vertical carbon fiber plies and smaller clusters of carbon fibers within deformed laterally along the impact face as the rod undergoes inter-ply shear failure. Some material was present at the rear surface of the cylinder, but to a lesser extent than that observed in tests on the 5:1 rods undergoing the same mode of failure at a later time but it had a bigger part of the rod (almost a half of the initial length) recovered after the test. The result for the through-thickness rod shown in Fig. 2(c) was clearly different. The images show the rod initially compressing at 9 μs, rebounding at 17 μs and later the rod undergoes elongation and eventually tensile failure occurs between the plies.
3. MODELLING AND DISCUSSION

The mathematical description used in this study is a non-linear two-component model, with rate sensitivity and evolving isotropy axis. The model [3] includes the conservation laws of mass, momentum and energy completed with the following constitutive equations:

\[
\frac{dA}{dt} + AW = -A\Psi, \quad \frac{dB}{dt} = F(A, \Psi)B, \quad \frac{d\Delta}{dt} = -\Lambda.
\]

Here \( A \) is the deformation gradient tensor, \( \Delta \) is the residual microstrain tensor, \( W \) is the strain rate tensor, \( \Psi \) is the strain rate relaxation governing the rate sensitivity, \( \Lambda \) is the microstrain relaxation tensor and \( B \) is the orthogonal rotation matrix governing the material symmetry axis. The system is completed by the ‘equations of state’ as a form of thermo-elastic Hooke’s law for transversely isotropic material employing the homogenization procedure [4].

A version of this model has been implemented in the Sandia shock physics hydrocode CTH [5] and earlier (see paper [6]) in VecDyna-3D [7]. Within the model, the composite material is constructed as a block of a two-component material with prepreg plies. Normal vector to the plies is the symmetry axis of the material. The simulated Carbon Fibre Reinforced Plastic (CFRP) has a volume fraction of carbon (first constituents of the two-component material) and epoxy (the second component) with the following typical mechanical characteristics: \( \rho_1 = 1.8 \) g/cm\(^3\), \( K_1 = 65.6 \) GPa, \( G_1 = 55.5 \) GPa, \( K_2 = 5.4 \) GPa, \( G_2 = 2.5 \) GPa, and the composite density \( \rho_0 = 1.49 \) g/cm\(^3\), corresponding to 50% volume concentration of each constituent [8, 9]. Here, \( K \) and \( G \) are bulk and shear modulus, the heat capacities are selected in agreement with the tabulated data for carbon and epoxy resin. The yield limit at the strain rate of quasi-static \( 10^{-2} \) (\( Y_s \)) and dynamic \( 10^3 \) (\( Y_d \)) inverse seconds is selected as \( Y_s = 0.8 \) GPa and \( Y_d = 1.6 \) GPa for fibres and \( Y_s = 0.1 \) GPa and \( Y_d = 0.2 \) for the matrix.

In order to analyse the resulting wave structure within the model, a standard plate test was simulated using a 10 mm thickness steel flyer plate, with an impact velocity of 250 m/s impacting a stationary 15 mm thickness CFRP target. The wave profiles generated from the plate impact simulation are shown in Figure 3, with the initial ply orientation in the CFRP being \( 0^\circ \) in-plane, through-thickness and \( \phi^\circ \) off-axis shown in Fig. 3(a), (b) and (c), respectively.
respectively. The pressure profiles within the flyer plate-target set resulting from the impact of CFRP with 0º in-plane, through thickness and 45º off-axis initial ply orientations were plotted at time intervals between each of the four curves of 1.0, 0.5 and 0.9 μs, respectively. This was done to visualise the different wave profiles resulting from the different ply orientations. In order to distinctly identify the wave splitting in the present one-dimensional calculation, the quasi-static and dynamic yield limits for the epoxy resin were selected to be 0.01 GPa and 0.02 GPa, and an elevated flyer plate velocity was chosen that exceeds the rod velocity in the present tests.

Previous simulations of an off-axis oriented transversely isotropic Aluminium/Lexan composite calculated within the assumption of small elastic deformations have demonstrated a possible three-wave pressure pulse profile, caused by the shockwave changing the initial axial ply orientation [10]. The mechanical properties of the constituents of the present material are essentially more contrasted, and whilst acknowledging the difference in impact velocity, the three-wave splitting caused by the same mechanism results. For the present case of moderate impact velocity corresponding to the Taylor tests, it is interesting to observe a multi-wave structure in the loading of the in-plane oriented samples, due to wave splitting along the components accompanied by elastic precursors in the constituents. In the through-thickness orientation, the composite strength is close to the strength of the epoxy resin, having the greatest impedance mismatch with the steel flyer and thus inducing a lower peak pressure in the target of configuration Fig. 3(a). In contrast, the in-plane configuration provides a better impedance match and corresponding maximum stress transfer, as shown in the higher peak pressure values in Fig. 3(b). For the angled in-plane ply orientation case (an off-axis oriented sample) in Fig 3(c), the fibres change orientation and the rotation matrix updates with the change in the Euler angle, relative to the material symmetry axis (the drop in the angle value below π/4 follows the plastic wave). Therefore the rotation angles change follows the plastic wave as shown in Fig. 3(c).

Numerical set-up of the in-plane Taylor tests conducted in the present experiment is essentially three-dimensional. Executing an accurate three-dimensional calculation was beyond the computer processing power and execution time capabilities available for the present study, so a coarse CTH simulation was conducted and analysed to demonstrate the asymmetry of the wave transmission affecting the mechanical response of the CFRP rod during the Taylor test. The results of the coarse study are presented in Fig. 4 and represent one quarter of the full set-up, which is sufficient due to the symmetry of the set-up against x = 0 and y = 0 planes. These planes and z = 0 plane are under the symmetry boundary conditions in the present CTH calculations with the remaining boundaries to be under absorbing boundary conditions. The in-plane material structure and coordinate reference is outlined schematically in Fig. 4(b). Following the one-dimensional calculations in Fig. 3, it is seen that the waves propagate fastest from the contact interface z = 0 in z- and x-directions along the material plies as in Fig. 3(b) and slowest in y-direction across the plies as in Fig. 3(a). Therefore, during the wave propagation, pressure equilibrates relatively fast in the x-direction, while pressure disequilibrium between bulk and surface response in the yz-plane lasts longer, exhibiting an asymmetric response seen in the pressure plot in Fig. 4(a). This response results in a faster expansion of the rod in the yz-plane than in xz-plane as seen in Fig. 4(c). A larger difference in the response of the central part of the rod in the yz-plane is then observed, with an initial slow spreading over the rod cross-section during pressure equilibration in x-direction, as seen in Fig. 4(d).
As a result of the asymmetric deformation, a convexity is formed at the free end of the rod, as shown in Fig. 4(e).

This feature was more prominent when simulating the experiment with a VecDyna implementation, because a higher resolution three dimensional version was able to be executed (due to the Lagrangian nature of the VecDyna-3D code). Size of this convexity varies with time due to wave circulations along the rod. Therefore, this feature is larger and it is seen for a longer time for the 5:1 ratio rod in Fig. 2(a) than for a shorter 1:3 ratio rods in Fig. 2(b).

![Figure 5](image1)

**FIGURE 5.** Two-dimensional CTH calculation of initial rod-anvil interaction for plane (upper plots) and axial symmetry (lower plots) cases. Material symmetry directions are along y-axis (a), x-axis (b), and z-axis (c).

The material structure of the CFRP does not fit into the two-dimensional set-up. The coarse three-dimensional calculation does not give confidence of the physical reasons for the features occurring in the calculation and in the experiments. In order to understand the wave patterns resulting in the features, a detailed wave analysis is needed, at least in the vicinity of the impact interface. Therefore, a thorough CTH analysis of the wave interference in the rods was conducted in a detailed two-dimensional set-up at initial stage of the rod-anvil interaction.

The results are shown in Fig. 5. The plane geometry and axi-symmetric geometry aspects have been considered. The coordinate system for the plane set-up is seen in Fig. 5 with the Cartesian z-coordinate directed normal to the xy-plane. In the axi-symmetric set-up, x is the polar radial coordinate, y – axial coordinate, and z – angular coordinate. It is seen from the plot of pressure fringes in Fig. 5(a) that in the case approximating the through-thickness Taylor test of the rod shown in Fig. 1(b), the shock speed in the x-direction is larger than in the axial direction forming similar patterns in the plane and axi-symmetric cases. The noticeable difference is a pressure concentration in the vicinity of the rod axis in the axi-symmetric case. In both cases the shock speed in the axial direction is minimal corresponding to the calculation in Fig. 2(a).

![Figure 6](image2)

**FIGURE 6.** Two-dimensional axi-symmetrical CTH calculation of wave propagation in rod during Taylor impact. Material symmetry directions are along y-axis (a), x-axis (b), and z-axis (c).

In contrast, the cases (b) and (c) in Fig. 5, approximating the Taylor test with in-plane material orientation of the rod corresponding to Fig. 1(a), differ by position of observer to the rod side looking at the rod either along the x-
coordinate for the case (b) as shown in the three-dimensional schematic in Fig. 4(b) or along the y-coordinate for the case (c).

The velocity fringes in Fig. 5(b) shows patterns similar to Fig. 5(a) with, however, opposite ratio of axial shock speed to radial (horizontal in the plane case) one because in this case the rod axis is parallel to the material layers (the material layers are cylindrical surfaces successively enveloping the rod axis) and the axial shock speed is maximal. The wave interference at the axis is the feature similar to the previous case.

In the case of Fig. 5(c) the axial shock speed is the same as in Fig. 5(b) but the observer sees the whole material ply surface for the plane case in contrast to the previous case, when facing the material layer cross-sections. It is interesting to note that in the case of the axial symmetry, the rod axis is accumulating the response due to the material symmetry axis directed along the angular coordinate (the rod is composed from vertically oriented layer sections of the material radiating from the rod axis), whereas for the plane case the material axis is directed towards the observer.

This analysis can be used for discussion of results of CTH calculation on a coarser grid but containing the whole rod. The results are shown in Fig. 6 for the case of axial symmetry only with the same material orientation choice corresponding to cases (a), (b), and (c) as in the case of Fig. 5.

It is seen that in the case of the through-thickness rod shown in Fig. 6(a) the velocity pattern is similar to the pattern in Fig. 5(a) and the velocity direction (V is vertical velocity in the legend of Fig. 6) changes from the negative directed towards the anvil \((x < 0)\) at \(t = 6 \mu s\) to positive at \(t = 15 \mu s\) with only small change in the rod shape and nearly flat rod ends, while impact energy mostly transferring in the axial direction.

In the case of in-plane orientations (b) and (c) the velocity pattern for the case of material layers enveloping the rod axis (b) is similar to the case (b) in Fig. 5 and some shear is noticeable affecting shape of the free end of the rod. This change is even more noticeable for the material layers radiating from the rod axis with the velocity higher at the rod axis due to the cumulative effect and exhibiting the rod bulge at the axis noticeable both in the three-dimensional simulation for the in-plane oriented rods and corresponding experiments.

5. CONCLUSIONS

The Taylor test, most commonly used on homogeneous materials, may be a valuable tool for verifying hydrocode models of composite materials. Taylor cylinders cut from different orientations within a composite panel show different dominant failure mechanisms occurring due to different tensile loads. In application of a phenomenological model, global deformation of the cylinder could be predicted reasonably well. The inclusion of damage in a model implementation should see the model better predict interply shear and tensile failure of composite rods for later parts of the loading history.

ACKNOWLEDGMENTS

Acknowledgment is given to staff in the University of Manchester's North West Composite Centre and the CMEC technical assistant Ryan Delve for his work in fielding the experimental equipment.

REFERENCES