Off-Axis Testing of Fibre Composites at High Strain Rates using an Image-Based Inertial Impact Test

L. Fletcher[1a], J. Van-Blitterswyk[1] and F. Pierron[1]

[1]University of Southampton, Southampton, SO17 1BJ, Hampshire, United Kingdom

[a]L.C.Fletcher@soton.ac.uk

Abstract. Off-axis testing of composites at high strain rates is challenging using current split-Hopkinson bar methods due to inertial effects. Therefore, this study presents a new Image-Based Inertial Impact (IBII) test method for testing composite materials off-axis at high strain rates. This test method uses full-field displacement measurements of strain and acceleration coupled with the Virtual Fields Method to identify high strain rate material properties. In this study the IBII test is used to identify the transverse and shear modulus of a 45° off-axis specimen at strain rates on the order of 1000 s^{-1}.

Introduction

Composite materials are used in a variety of applications that subject them to high strain rate dynamics loads. Strain rate dependence of composites materials is particularly important for applications in the automotive and aerospace industries where composites can be subjected to a variety of dynamic loads (*e.g.* car crash and hail/bird strikes on aircraft). For carbon fibre composites it is generally accepted that the fibre dependent properties are not strain rate dependent whereas the matrix dependent properties are strain rate dependent [1, 2]. Current data for strain rate dependence of composite material has been mainly obtained using the split-Hopkinson pressure bar (SHPB) technique. A key assumption of the SHPB analysis is that the specimen is in a state of quasi-static equilibrium such that inertial effects can be neglected. This limits the effective strain rates that can be tested with the SHPB problematic to below than 1000 s^{-1}.

The Image-based Inertial Impact (IBII) test is a newly developed high strain rate test method that does not rely on the assumption of quasi-static equilibrium. The IBII test uses ultra-high speed imaging and full-field displacement measurements to obtain strain and accelerations fields in an impacted test specimen [3]. The acceleration fields are then used with the Virtual Fields Method to calculate stress averages which can be used for stiffness and strength identification. This technique has already been successfully applied to the transverse tensile properties of carbon fibre composites [4]. The purpose of this study is to explore the applications of the IBII test to off-axis composite specimens with the aim of identifying multiple stiffness parameters in a single test.

Theory and Test Concept

The off-axis composite specimen shown in Fig. 1 is subjected to a dynamic load F(t). In a similar manner to [4], it can be shown that rigid body virtual fields in the material co-ordinate system lead to the following equations for the transverse $\overline{\sigma_{22}}^l$ and shear stress averages $\overline{\sigma_{12}}^l$ over the angled slice l:

$$\overline{\sigma_{22}}^l = \rho \frac{S}{l} \overline{a_2}^S \ , \ \overline{\sigma_{12}}^l = \rho \frac{S}{l} \overline{a_1}^S \quad (1)$$

where ρ is the density of the material and S is the shaded trapezoidal area in Fig. 1. The overline notation indicates spatial averaging, where $\overline{\sigma_{22}}^l$ indicates the average of the transverse stress over the angled slice l and $\overline{a_2}^S$ indicates the spatial average of acceleration over the shaded trapezoidal area in Fig. 1. Using similar assumptions to [4] the transverse modulus E_{22} can be directly identified by linearly fitting $\overline{\sigma_{22}}^l$ against $\overline{\varepsilon_{22}}^l$. The shear modulus G_{12} can be identified in a similar manner by plotting $\overline{\sigma_{12}}^l$ against $\overline{\varepsilon_{12}}^l$.

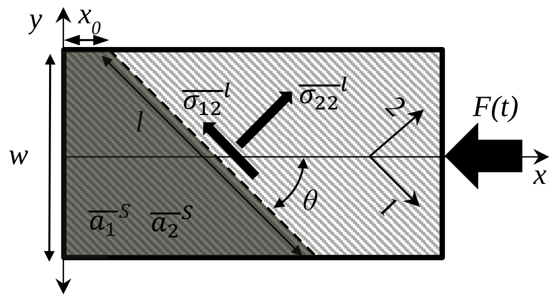

Figure 1: Schematic representation of the image-based impact test on an off-axis composites specimen

Experimental Method

A 45° off-axis composite specimen was cut from a unidirectional plate of Gurit SE70 carbon fibre with a diamond saw. The specimen had in-plane dimensions of 70 x 45 mm, the layup of the plate was $[0]_{12}$ with a cured thickness of 3.7 mm. The specimen was impact tested using a purpose-built gas gun coupled with a Shimadzu HPV-X ultra-high speed camera imaging at 2 Mfps. The specimen was bonded to a cylindrical aluminium waveguide (diameter 45mm and length 50mm) which was placed on a wedge shaped foam stand aligned with the gas gun barrel. The waveguide was impacted with a cylindrical aluminium projectile at 50 $m.s^{-1}$ (diameter 45mm and length 25mm). The camera was triggered using a copper foil contact trigger on the waveguide and the flash light was triggered using the infrared light gates on the front of the gas gun barrel. The grid method was used to obtain full-field displacement measurements. A series of white squares where printed on the surface of the specimen using a Canon UV flatbed printer forming a black on white grid pattern. The raw full-field displacements where spatially smoothed using a Gaussian filter (over a 41 pixel diameter) before calculating the strain fields with a centred finite difference method. Similarly, the raw displacement fields were temporally smoothed with a Savitsky-Golay filter (3^{rd} order over 15 frames) before numerical differentiation to obtain the acceleration fields.

Results and Discussion

The stress-strain curves for the transverse and shear directions are shown in Fig. 1 and Fig. 2 respectively. These curves are reasonably linear and consistent between sections. For both cases the stress-strain curves can be fitted to obtain the associated modulus, giving a modulus for each angled slice along the specimen length. An average identified modulus can be obtained by taking the average over the middle 50% of the specimen to avoid edge effects from the smoothing filters. For the transverse modulus the average identified value is E_{22} = 7.8 GPa. For the shear modulus the average identified value is G_{12} = 3.4 GPa. The peak average strain rate in the transverse direction was 820 s^{-1} and for the shear direction it was 1300 s^{-1}. The identified transverse modulus compares extremely well to a previous study using the IBII test on the same material (7.9±0.3 GPa at 2000 s^{-1} [4]). The identified shear modulus seems low, however it is not possible to make comparisons to a quasi-static reference modulus as this data was not available for this particular material.

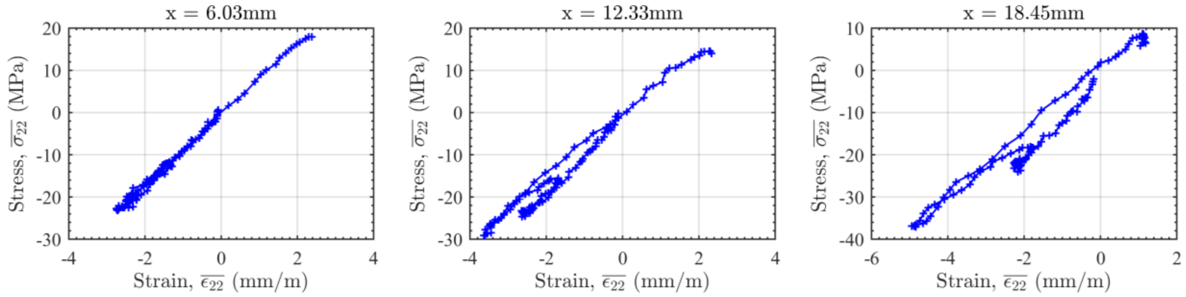

Figure 2: Stress-strain curves for the transverse stress and strain components

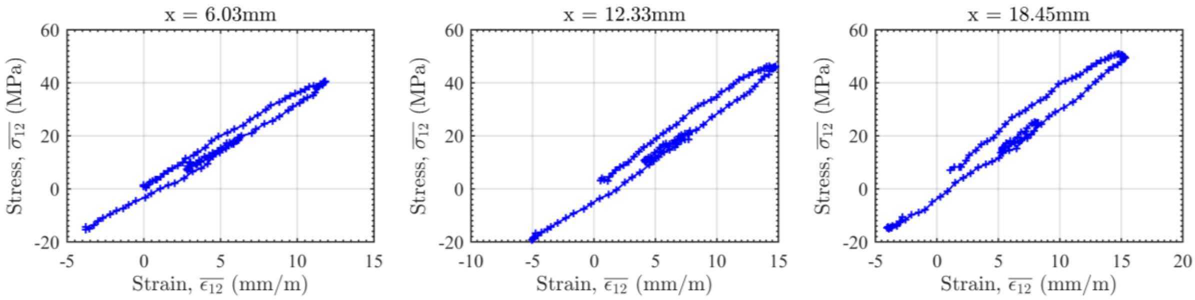

Figure 3: Stress-strain curves for the shear stress and strain components

Summary and Conclusion

This study has demonstrated that the IBII test can successfully identify the transverse and shear modulus of an off-axis composites specimen at high strain rates. The transverse modulus was identified as E_{22} = 7.8 GPa at a peak strain rate of 820 s^{-1}. The shear modulus was identified as G_{12} = 3.4 GPa at a peak strain rate of 1300 s-1. Future work will include extending the IBII method to identify the shear/tension failure envelope from a series of off-axis tests at different angles.

References

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