An Image-Based Inertial Impact Test for High Strain Rate Interlaminar Shear Properties of Fibre-Reinforced Polymer Matrix Composites

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Abstract. This work focusses on the numerical design of a novel image-based inertial impact test to measure the interlaminar shear modulus of fibre-reinforced polymer composite materials at high strain rates. The principle is to combine ultra-high-speed imaging and full-field measurements to capture the dynamic kinematic fields, exploiting the inertial effects generated under high strain rate loading. The kinematic fields are processed using the virtual fields method to reconstruct shear stress-shear strain curves to identify the shear modulus. Simulations demonstrate the potential for the proposed method to identify the shear modulus at strain rates where current test methods become unreliable (500 s^{-1} on average, and on the order of 2,000 s^{-1} locally).

Introduction

The mechanical response of fibre-reinforced polymer (FRP) composite materials subjected to high rates of deformation (crash, blast, *etc.*), is dependent on the interlaminar properties. As the interlaminar properties are matrix-dominated, literature suggests that strain rate has a significant effect on stiffness and strength [1]. Testing FRP composites in shear is commonly done using thin-walled tubular specimens or lap-shear specimens, loaded in torsion or compression, respectively with a split-Hopkinson pressure bar (SHPB) system [1]. The effect of strain rate on the interlaminar shear modulus and shear strength has not been well characterised, with unacceptably high scatter shown across available studies [1]. The uncertainty can be primarily attributed to limitations of the SHPB system. Under high strain rate loading, inertial effects induce heterogeneous kinematic fields. This violates the assumption of quasi-static equilibrium required to infer the response of the material in SHPB test. The prolonged time required for inertial effects to dissipate in low wave speed materials, has resulted in a consensus that the SHPB system provides unreliable measurements of the material stiffness [2]. Recently, the image-based inertial impact (IBII) test has emerged as a viable alternative to obtain in-plane properties [3]. The virtual fields method (VFM) is used to process the dynamic, kinematic fields captured using ultra-high-speed imaging and the grid method [4] to identify stiffness and strength. Using the specimen as a dynamic load cell alleviates many of the assumptions associated with the SHPB. This work describes the extension of the IBII test to attempt to measure the interlaminar shear modulus at strain rates where existing tests are unreliable.

Test Concept

A preliminary configuration for the proposed IBII interlaminar shear test is shown in Fig. 1. The specimen is subjected to high strain rate loading using a stress pulse from an impact with a projectile. The projectile is embedded in a nylon sabot, with a diameter matching that of the gas gun that will be used for later experimental validation (see [4] for further detail about the experimental implementation of the IBII test). Shear is generated in the region of the specimen overhanging the waveguide. The dynamic response of this region is measured using ultra-high-speed imaging, coupled with the grid method. The idea of the tapered waveguide is to minimise the shear stress concentration at the interface with the specimen. From equilibrium, the average shear stress, $\overline{\sigma_{xy}}^{x}$, at any horizontal plane, y, and time, t, can be expressed as a function of the measured surface accelerations (`stress-gauge approach' Eq. (1)).

$$\overline{\sigma_{xy}(\mathrm{y},t)}^{x} = \rho y \overline{a_x(\mathrm{y},t)}^{S} \tag{1}$$

In Eq. (1), ρ is the material density, a_x denotes x-acceleration, the superscripts x and s, coupled with the overline, respectively denote the horizontal line average at a slice located at y, and the average surface acceleration between the bottom free edge and y. Using reconstructed stress averages, shear stress-shear strain curves can be generated at any horizontal slice in the specimen and used to identify the shear modulus.

Numerical Modelling

The material used in this study is a unidirectional carbon/epoxy pre-preg (AS4-145/MTM45-1). The plate has a nominal thickness of 18 mm, which sets the width of the specimen. The specimen overhang of 27 mm is selected to closely match the specimen aspect ratio with the camera spatial resolution (Shimadzu HPV-X, 400 x 250 pixels). The 2-3 interlaminar plane is considered (E_{33} = E_{22} = 7.6 GPa, ν_{23} = 0.225, G_{xy} = 3.65 GPa, ρ = 1,605 $kg \cdot m^{-3}$), but the same method can be easily applied for testing in the 1-3 interlaminar plane.

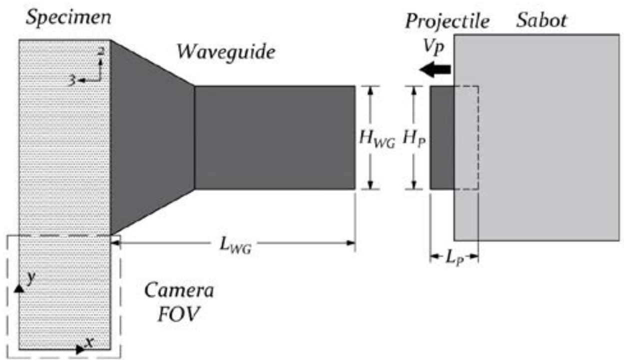
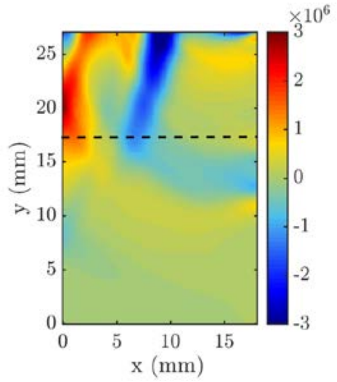


Figure 1: Schematic of the simulated IBII interlaminar shear experiment

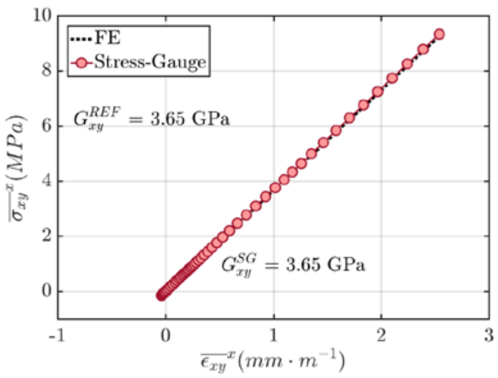
Explicit dynamics simulations in ABAQUS were used to explore the feasibility of the proposed test. Plane stress CPS4R elements (2D, 4 node, reduced integration) were used with a mesh size of 0.1 mm. For all materials, β damping (7 $x10^6$ ms) was applied to eliminate numerical 'ringing' in the acceleration fields. The time step was allowed to float; however, field outputs were fixed to 0.2 μs intervals to match the frame rate of the HPV-X camera. The projectile and waveguide are modelled as 6061-T6 aluminium (E = 70 GPa, ν = 0.3, ρ = 2,700 kg·m^{-3}), and the sabot is modelled as Nylon 6-6 (E = 3.45 GPa, ν = 0.4, ρ = 1,140 kg·m^{-3}), The test configuration has a total waveguide length, L_{WG}, of 75 mm, projectile length, L_P, of 10 mm, and impact speed, V_P, of 50 m·s^{-1}. The tapered waveguide section is 25 mm long with a 45° angle to allow for lateral wave expansion.

Results and Discussion

A snap shot of a_x shows that the impact pulse creates highly heterogeneous fields, with accelerations exceeding 3 $x10^5$ *g*. Reconstructed stress averages, from the acceleration fields, and average shear strain along a horizontal slice at y = 17 mm, are used to generate the shear stress-shear strain curve shown in Figure 2b. This validates the use of the stress-gauge approach for identifying the reference shear modulus. Defining a strain rate for the measured properties is challenging since the inertial effects create highly heterogeneous strain and strain rate maps. For the given configuration, strain rates reach 500 s^{-1} on average, and on the order of 2,000 s^{-1} locally.



(a)



(b)

Figure 2: (a) Map of a_x (m·s^{-2}) at 14 μs, and (b) shear stress- shear strain curve at y = 17 mm

Conclusions and Future Work

This paper demonstrates how full-field measurements, coupled with the virtual fields method, can be used to exploit inertial effects under high strain rate loading to identify the interlaminar shear modulus. Having access to the full-field, dynamic response of the material removes many of the limitations associated with existing test methods. Future work will focus on further design work to increase the amount of shear strain generated within the specimen, followed by experimental validation of the test. Reconstructed stress averages can be used in the future to estimate shear strength, with the objective to begin populating a tension-shear failure envelope.

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