Design of a photomechanical test to measure the high strain rate through-thickness tensile strength of composites

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

[1]University of Southampton, Southampton SO17 1BJ, UK [a]J.Van-Blitterswyk@soton.ac.uk

Abstract. This work presents the design of a photomechanical inertial test to determine the through-thickness tensile strength of composites at high strain rates. The idea is to couple the virtual fields method with high-speed (inter-frame time of 0.2μs), full-field acceleration maps so that the specimen acts as a load cell. Dynamic tensile stresses are introduced indirectly through the reflection of a compressive pulse generated by the impact from a projectile. The higher compressive strength of the composite enables test parameters to be tailored such that the reflected tensile pulse causes failure without inducing damage in compression. Explicit dynamic simulations are used to optimise the projectile and waveguide length, and projectile speed, such that these conditions are achieved. Preliminary experiments on carbon/epoxy laminated specimens will also be performed for validation of the proposed test.

Introduction

The expansion of composite materials in naval, ground vehicle and industrial applications has led to the design of thick composite sections to withstand complex three-dimensional stress states. Such structures are often subjected to high rates of deformation and therefore, the strain rate sensitivity of through-thickness properties must be understood. Through-thickness testing is challenging under quasi-static conditions due to gripping and alignment issues. An additional challenge for high strain rate testing is the management of inertial effects, which create heterogeneous stress states and difficulties in measuring impact forces. In the case of the popular Split Hopkinson Pressure Bar (SHPB), this typically limits the achievable strain rates to less than 10^3 s^{-1} [1] due to the low wave speed in relatively soft materials (i.e. the through-thickness direction of a composite laminate). Recent studies have shown that the virtual fields method (VFM), coupled with high speed measurements of surface accelerations, can exploit the inertial effects and eliminate many of the issues with existing tests [2,3]. The surface acceleration maps are processed using the VFM to reconstruct stress and identify material properties without need for external force measurement. This principle will be extended here to develop a test for identifying the through-thickness tensile strength of composite materials.

Application of the Virtual Fields Method to Dynamic Tests

The proposed test configuration (Fig. 1) is designed to indirectly load the specimen in tension through the application of a compressive pulse from a projectile traveling at speed, $\boldsymbol{V_P}$. The specimen is bonded to the end of a `waveguide', which reduces non-uniformities in the kinematic fields measured on the specimen due to slight misalignments at impact. The pulse imparted by the projectile travels through the waveguide and is transferred into the specimen. Once in the specimen the pulse travels to the free edge, where it then reflects as a tensile wave travelling back towards the waveguide. For materials with higher compressive strength, the parameters of the projectile and waveguide can be tailored to ensure maximum reflected tensile stresses are induced with the minimum required compressive pulse.

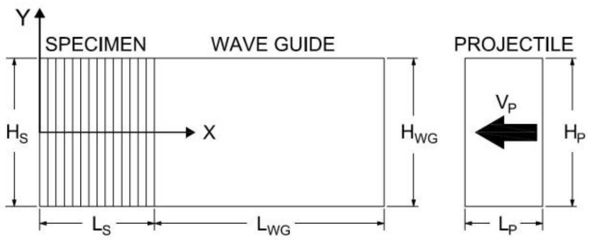

Figure 1: Schematic of simulated impact experiment. Fibres are oriented parallel to the Y axis.

High speed imaging is used in conjunction with a full-field measurement technique, such as the grid method [4], to capture the surface displacements and strains. These maps are processed using the VFM to identify the failure strength of the material. In this case, a simple rigid body virtual field is selected, which allows the average axial stress, $\overline{\sigma_{xx}}$, at any position, x, and time, t, to be expressed as a function of the measured surface accelerations (Eq. (1)):

$$\overline{\sigma_{xx}(x,t)} = \rho x \overline{a_{xx}(x,t)} \tag{1}$$

where $\boldsymbol{\rho}$ is the material density, and $\overline{\boldsymbol{a_{xx}(x,t)}}$ denotes the average acceleration over the specimen surface between the free edge and point $\boldsymbol{x}$.

Test Design and Optimisation Through Finite Element Simulations

Explicit dynamics simulations in ABAQUS were used for the initial test design. Plane stress CPS4R elements (2D, 4 node, reduced integration) were used in all simulations. The mesh size, stiffness-proportional damping coefficient, $\boldsymbol{\beta}$, and time step were selected using a parametric sweep such that the error between the reconstructed stress (Eq. (1)) and simulated stress were minimized over an entire wave reflection. This resulted in a mesh size of 0.1 mm, $\boldsymbol{\beta}$ coefficient of 7x10^{-6}, and time step of 5x10^{-8} ms. The specimen thickness, $\boldsymbol{L_S}$ (Fig. 1), is held constant at 20 mm (representative of a thick laminate). The specimen dimensions are then fixed such that spatial resolution of the high speed camera (Shimadzu HPV-X) is maximized (400x250 pixels), which sets the specimen height, $\boldsymbol{H_S}$, at 12.5 mm. The height of the waveguide, $\boldsymbol{H_{WG}}$, and projectile, $\boldsymbol{H_P}$, were also fixed at 12.5 mm. The material properties of the specimen are representative of a typical unidirectional carbon/epoxy pre-preg laminate: $\boldsymbol{E_x}$ = 10 GPa, $\boldsymbol{E_y}$ = 135 GPa, $\boldsymbol{G_{xy}}$ = 4.5 GPa, $\boldsymbol{\nu}$ = 0.022, $\boldsymbol{\rho}$ = 1,600 kg/m^3. The strengths assumed for design are 75 MPa and 300 MPa in tension and compression, respectively. The projectile and waveguide are aluminium ($\boldsymbol{\rho}$ = 2,200 kg/m^3, $\boldsymbol{E}$ = 70 GPa, $\boldsymbol{\nu}$ = 0.3).

A parametric sweep of values for the waveguide length, $\boldsymbol{L_{WG}}$, projectile length, $\boldsymbol{L_P}$, and projectile speed, $\boldsymbol{V_P}$, (Fig. 1) was then performed to select the combination of parameters such that the target tensile stress is obtained with minimal loading in compression. Full-field displacements were extracted at 0.2 μs increments (HPV-X frame rate at full resolution). The maximum line average of stress through the width of the specimen, as a function of projectile length, $\boldsymbol{L_P}$, are shown for tension and compression in Fig. 2a and Fig. 2b, respectively.

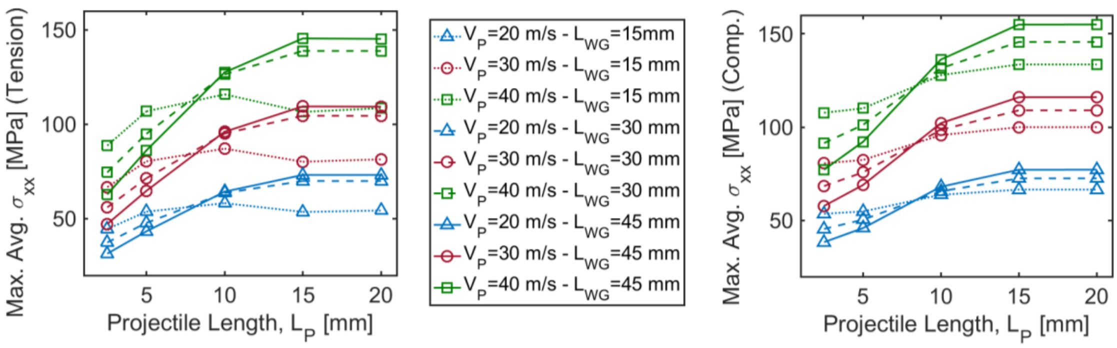

Figure 2: Simulated maximum average tensile stress (a), and compressive stress (b) as a function of varying projectile length, projectile speed and wave guide length.

Figure 2a generally shows that maximum tensile stress in the specimen increases with increasing projectile length and velocity. In some cases (i.e.: L_{WG} = 15 mm and $L_P \geq$ 10 mm), the waveguide has the effect of truncating the input pulse and therefore, the maximum tensile and compressive stress (Fig. 2b) within the specimen. To avoid this, the waveguide length must be selected such that the full reflected pulse in the projectile is captured (in this case, at least twice the projectile length). Based on the results in Fig. 2, the optimal test configuration consists of a projectile length of 10 mm, an impact speed of 30 m/s and waveguide length of 30 mm. Results from experimental validation tests will be presented. Experiments will be performed using an in-house gas gun rig, and a Shimadzu HPV-X camera used to acquire images at a frame rate of 2 Mfps.

Conclusions and Future Work

This work presents the design of a new inertial test to determine the through-thickness tensile strength of composites at high strain rates. The specimen is loaded in tension through the reflection of a compressive pulse imparted by a projectile. The full-field displacements maps are processed using the virtual fields method to reconstruct stress within the specimen. The results of a preliminary optimisation suggest that an impact speed of 30 m/s, projectile length of 10 mm, and a waveguide length of at least 30 mm is required to fail the specimen in tension. Future work will focus on the validation of this design with experimental measurements.

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