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Effect of strain rate and fibre rotation on the in-plane shear response of ±45° laminates in tension and compression tests

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A B S T R A C T

This work focuses on the effect of strain rate and fibre rotation on the in-plane shear properties of composite laminates. The effect of fibre rotation on the measured shear properties, was for the first time experimentally quantified with the comparison between compression and tension tests of the ±45° laminate samples. Significant increase of shear strength and decrease of final failure strain was observed with the increase in strain rate from 5e-4 1/s to 1300 1/s. The nonlinear shear model was developed to simulate the large deformation process, in which the fibre orientation was updated as a function of the in-plane shear strain. The results of this investigation should motivate the updating of procedures for experimental characterization as well as analytical and numerical modelling of in-plane shear response of laminates.

1. Introduction

Carbon fibre composite laminates feature high stiffness and strength in fibre orientation, while their elastic moduli as well as strength in transverse direction are relatively weak. Inter-fibre failure is one of the dominating failure modes for composite laminates, and significant nonlinearities may occur prior to fracture in composite structures. Considerable nonlinearity of in-plane behaviour has been observed in off-axis compression tests of unidirectional laminates, and it has been found to be dependent on the strain rate [1,2]. The shear properties of laminated composites are very important for predicting permanent deformation and damage, and several models have been developed [3–6]. In this study, the rate dependent in-plane shear properties were characterized using ±45° laminates, in order to gain deeper understanding of their nonlinear deformation behaviour, and to support the development of constitutive models for simulation of composites subjected to impact loading.

The in-plane shear response can be obtained from off-axis compression/tension tests. Achieving large deformations poses several challenges, as the deformation process becomes unstable once damage has initiated [1,2]. The ±45° laminates yield quite uniform shear stress distribution over the whole gauge area [7], and provide stable damage evolution for large deformation. However, the tension test of ±45° exhibit significant fibre rotation [8]. The reinforcement fibres get more aligned with the loading axis as the shear strain increases during tests, resulting in the overestimation of the shear stress, as confirmed with analytical and numerical work [9,10]. The opposite trend may be observed when the compression loading is applied, and this can be used in comparison with tension tests to evaluate the influence of fibre rotation on measured shear response.

This paper aims to study the rate-dependence in in-plane shear, and to reveal the effect of fibre rotation on the laminate response in both experiments and modelling. The experimental setups and related data processing methods are introduced in Section 2. The corresponding numerical models of the specimens and the developed constitutive model used to simulate the conducted experiments are outlined in Section 3. All results and discussions are presented in Section 4, followed by concluding remarks in Section 5.

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2. Experimentation

2.1. Material and specimen

A 2 mm-thick laminate ($[0^{\circ}/90^{\circ}]_{4s}$) was made of HexPly® IM7/8552 carbon-epoxy prepreg, a material extensively used in both industry and academic research. The laminate has been inspected using ultra-sound scan to ensure that no large defects or voids were present. The specimens for tension and compression tests were all manufactured by cutting this laminate at 45° with a water-cooled diamond saw. The gauge section of the dog-bone tension samples was shaped and surface finished using a surface-grinding machine. The geometry of these samples is shown in Fig. 1, with the same gauge section of 5 mm by 8 mm in both tension and compression tests. The tension samples were bonded using 3M Scotch-Weld DP490 adhesive into impedance matched, metallic, threaded end-sleeves for gripping into the loading rigs.

The matrix material of the laminates, 8552 epoxy, was tested in compression at different strain rates in this study. The cylindrical samples were cut from the epoxy cast with diameter of 4 mm, and their thickness was 2 mm.

2.2. Test setup

The Zwick/Roell Z250 screw driven testing machine with 20 KN loading cell was used in quasi-static tests. The displacement controlled loading rate was 0.01 mm/s. An in-house built Split-Hopkinson-Tension and Compression Bar systems [11] were used for dynamic tests (Fig. 2). The striker velocity was approximately 5 m/s in compression tests, and 11 m/s in tension tests. Strain gauges were used to acquire the strain history on the split Hopkinson bars, from which the force histories applied upon all samples were calculated. These dynamic experiments are considered valid for the purpose of classical characterisation of mechanical performance on condition that the dynamic equilibrium and strain homogeneity along the sample gauge section are both established during the tests [12,13]. A 0.5 mm-thick cardboard was used to shape the loading pulse in the dynamic compression test thus filtering out undesirable high frequency response of the loading system to the impact loading imposed by the striker. The relatively long tension samples required a considerably longer time than the compression samples to reach dynamic equilibrium conditions. For that reason, a 3 mm-thick rubber sheet was used as pulse shaper to more gradually ramp up the force applied on samples.

The samples were coated with a black speckle pattern on a white background, which enabled displacement and strain measurement across the whole sample surface using digital image correlation (DIC) methodology (in-house [14] and commercial software GOM Aramis were used). Quasi-static tests were recorded with a camera at frame rate of 2 FPS. The ultra-high speed camera SI-Kirana was used in dynamic tests.

The quasi-static compression tests of 8552 epoxy was done with the Zwick/Roell Z250 machine at two different loading rate: 0.001 mm/s and 0.1 mm/s. Dynamic tests were carried out on the split Hopkinson compression bar with striker velocity of 3–8 m/s.

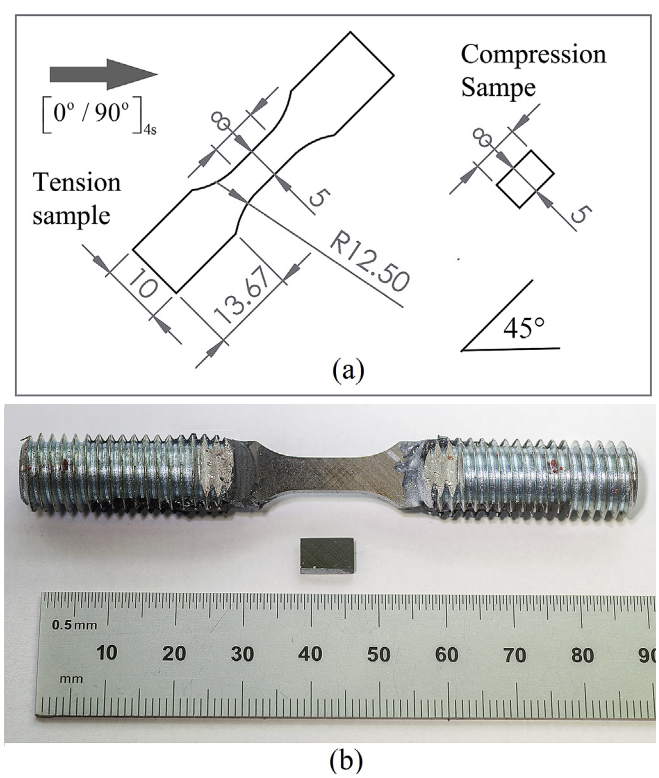

Fig. 1. (a) the geometry and (b) the samples for experiments.

2.3. In-plane shear data processing

The displacement (extension and contraction) across the laminate specimens gauge section and the corresponding strain can be evaluated from the images taken during tests by means of the DIC method. The strain distribution within gauge area is reasonably uniform over the gauge section. The average normal strains in both x and y directions were calculated from the changing of edge length of the gauge area as:

$$\begin{aligned} \varepsilon_{xx} &= \Delta l_x / l_x \\ \varepsilon_{yy} &= \Delta l_y / l_y \end{aligned} \tag{1}$$

where Δl_x and Δl_y are the elongations, while l_x and l_y are the length and width of the gauge area in the direction of parallel and perpendicular to the loading direction. The shear strain is then calculated as:

$$\gamma_{12} = \varepsilon_{xx} - \varepsilon_{yy} \tag{2}$$

This equation is strictly valid only for fibre angles of ±45°, and increasing error is involved with the rotation of fibres in shear deformation.

The shear stress was calculated considering the change in cross-section:

$$\tau_{12} = \frac{F}{2A}(1 + \varepsilon_{xx}) \tag{3}$$

2.4. Correction for fibre rotation

The calculation of the shear stress with Eq (3) is accurate for small strain conditions, while the fibre rotation gets pronounced when the strains get large. There is an analytical solution for linear-elastic materials to estimate the ratio between the shear stress τ_{xy} at small strains calculated with Eq (3) and the true shear stress $\overline{\tau}_{xy}$ [10]: