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Failure analysis of triaxial braided composite

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ABSTRACT

This study focuses on the description of damage and failure behaviour of triaxial braided carbon/epoxy composites under tension. The tensile tests were instrumented with optical surface strain and acoustic emission measurements. Damage was observed using X-ray and microscopy. The damage develops in two stages: (1) intra-yarn cracking: increase of the crack density and crack length, (2) local inter-yarn delamination and conjunction of the intra-yarn cracks. Statistics of crack sizes at both stages were collected and the 3D geometry of cracks was reconstructed. A finite element model of the unit cell of the textile reinforcement is used to predict damage initiation and crack orientation using Puck's criterion. Progressive damage and stiffness deterioration is modelled using the degradation scheme of Murakami–Ohno and the damage evolution law of Ladeveze, applied to the average stress state of the yarns. Good agreement with experimental damage initiation threshold and non-linear tensile diagrams is found both for loading in fibre and off-axis directions.

1. Introduction

Braids in general and triaxial braids in particular are widely used reinforcements for textile composites [1]. The aim of the research reported here is to provide detailed information on geometrical features, mechanical properties, and damage initiation and accumulation processes in a braided composite. The correlation between the geometry of the textile reinforcement and damage is studied concurrently experimentally and numerically and goes through the following steps.

Experimental

(1) Characterisation of the 3D architecture of the composite; (2) tensile loading in different directions to explore anisotropy of damage accumulation; (3) identification of damage initiation and propagation by means of acoustic emission; (4) statistical characterisation of crack pattern and size on different stages.

Modelling

(1) Solid and finite element (FE) models of the composite (meso level); (2) study of the symmetry of the reinforcement; (3) calculation of homogenised stiffness; (4) prediction of damage initiation in the composite; (5) analysis of the stiffness degradation and the final failure.

This methodology was proposed in [2,3].

Damage accumulation in textile composites is a complicated multiscale process. Damage development starts at micro-scale (fibre inside the yarns) with fibre-matrix debonding, matrix cracking and fibre failure. At meso scale (unit cell of the reinforcement), damage develops by intra-yarn cracking and delaminations. Finally macro failure of a sample is characterised by dense cracking, crack conjunction and fibre rupture. The particular mechanism of damage accumulation (crack dimensions, stability, density, an overall response) strongly depends on the applied loading and architecture of the structure. The variability of textile structures brings a need for a generic approach, which should establish the intermediate (meso) scale bridging geometry, local stress-strain state and damage propagation.

Development of crack pattern in braided composites has been studied recently by cross-sectioning of preloaded specimens [4], and digital speckle photography [5]. Masters [4] observed the crack density increase when loaded in fibre direction and delamination when loaded in cross-fibre direction.

In modelling, the most popular approach for analysis of damage accumulation at the meso scale is local damage mechanics (e.g. for woven [7,8] and for triaxial braided composites [2,9]). In this approach a crack (or micro-cracked region) is replaced by a damaged zone of a finite size. The concept is attractive, because it uses well established failure criteria for UD composites and relatively simple tests on strength of unidirectional composites as input data. However, there are fundamental paradoxes of the approach [2,10]. It may predict widening of damage zone (instead of localised transversal cracking) and non-physical direction of propagation of the damage: across the fibre direction. The reason for it is the stress distribution in presence of local shear. The triaxial material in this

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study has yarns oriented at 45° to the loading direction, thus shear is always present.

Another approach to model damage accumulation is to assign the degradation to the entire ply or yarn. Pickett [11] used laminate representation of braided composite and damage mechanics approach developed for UD plies. In the current article, degradation of stiffness properties is assigned to the entire yarn according to the average stress in it. A combination of the damage evolution law of Ladeveze [12] and degradation scheme Murakami [13] is proposed. To predict the damage occurrence load level, crack location and orientation the Puck criterion for UD reinforced composite (benchmarked and verified by the World Wide Failure Exercise [14]) is used.

2. Experimental

2.1. Material

The geometry of the studied material is shown in Fig. 1 and Table 1. The reinforcement is a triaxial braid made of carbon rovings (linear density 1600 tex), with an areal density of 600 g/m^2. The four-layer braided composite has interlacing yarns in three directions: braiding yarns (organised in a so-called “diamond pattern”) and inlay yarns oriented at 45° to the braiding. The textile is impregnated in resin transfer moulding (RTM) with an epoxy matrix (the resin system is Epicote 828 LV/Epicure DX 6514 with the mixing ratio 100/17).

The internal architecture of the composite presents quite a complex configuration. Five yarns (two in each biaxial direction and one inlay yarn) are interlaced at a relatively small distance, which leads to a complex shape of the yarn mid-lines and cross sections. On the other hand the yarns are organised in an “open” structure. The unit cell has a large open inner space, which is not occupied by the reinforcement (Fig. 1) and which causes nesting of the layers. Fig. 2a and b presents the series of cross-sections demonstrating this nesting. The cuts in the figure, normal to the plane of the composite plate, were done orthogonal to the machine direction.

The high non-homogeneity of the meso structure creates a large variation of fibre volume fraction along the mid-lines and across the sections of the yarns. The sectioning shows, that the fibre volume fraction (averaged over the cross-section of one yarn) changes in a wide range of 50–80% along the yarn path. Apparently, the high local fibre volume fraction in the inlay yarns is caused by their compaction by the interlaced braiding yarns and yarns of other layers. There is also a variation of fibre volume fraction across the yarns. At the edges the fibre volume fraction is 15% lower than in the middle zone (Fig. 2c).

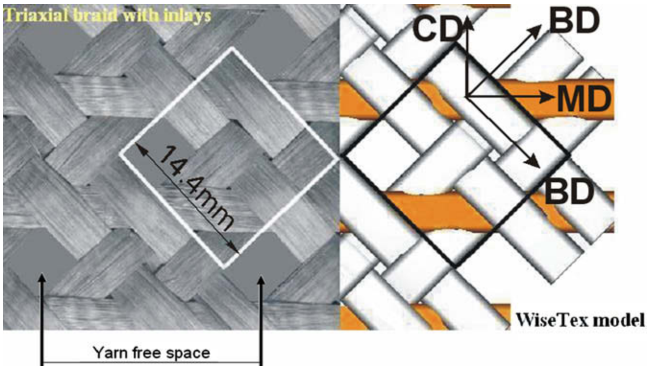

Fig. 1. In plane geometry of the fabric and correspondent geometrical model (created using [17]). MD – machine (inlay), CD – cross-, BD – braiding directions.

2.2. Tensile test

Quasi-static tensile tests were performed using the methodology of textile composite testing presented in [3,6,15]. Experimental analysis, apart from stiffness and strength characterisation, aims at the identification of two levels of damage development: damage initiation (indicated as strain ε_1) and advanced stage of damage (ε_2). Three basic material directions were selected for testing (Fig. 1): two axes of orthotropy: inlay (MD –machine) and normal to inlay directions (CD – cross), and direction of the braiding yarns (BD). The tensile specimen width covers at least two unit cells.

The tensile tests on Instron 4505 were displacement controlled, with cross-head speed of 1 mm/min, and accompanied by acoustic emission (AE) registration – Table 2. Two AE sensors were placed on the same side of the specimen. Based on the predetermined wave velocity in the sample (by the pencil test), signals from the sensors were analysed and those signals coming from the grips were filtered out. The actual strain in the sample was measured by a digital image correlation system (Aramis 4.7) – Table 2 [16]. The studied square field of observation, in the centre of the specimen, covered the full width of the specimen. The actual strain was measured by averaging of the local strain over the entire observation field.

The measured Young's moduli and Poisson's ratios of the material are given in Table 3. The stiffness degradation was characterised by the normalised tangent stiffness $\bar{E} = E/E_0$ (the ratio of the instantaneous tangent stiffness to the initial stiffness) (Fig. 3). In all the cases the slight stiffness degradation starts from about 0.2–0.3% of the applied deformation, close to the on-set of acoustic events. In the MD specimens the degradation has a constant rate and does not exceed 15% even at the advanced stages of deformation. The CD and BD samples exhibit a fast drop of the Young modulus after deformation of 0.4–0.5%.

2.3. Acoustic emission registration

AE was recorded and processed using the software Wave Explorer 1.02 from DigitalWave. The cumulative event energy was used for the study of the damage development, as it was found to be less sensitive to noise and experimental settings, than an event number count [3,15]. A first set of specimens was loaded up to final failure. The second and the third sets of specimens were loaded up to predefined levels, determined by analysis of the tensile and AE diagrams.

Typical diagrams of cumulative energy of events are shown in Fig. 3. These diagrams are used to determine the strain corresponding to onset of damage ε_1 – Table 4. The damage before ε_1 is negligible. At later stages, a more rapid increase of energy takes place. For CD and BD samples, it is possible to identify a second stage of the damage accumulation (called ε_2) as a “knee” on AE curves, which is close to a slope change in the tensile (stiffness degradation) diagrams. It refers to a state of well-developed damage. The cumulative energy of AE at this stage is an order of magnitude higher than at the damage initiation level. This circumstance was used to define ε_2 for the MD samples: it was chosen so that the acoustic emission energy at ε_2 would be 10 times higher than at ε_1.

2.4. X-ray investigation

Specimens loaded up to ε_1 and ε_2 were inspected by X-ray in a Philips HOMX 161 Microfocus System). Low voltage (i.e. low energy) radiation has been used in order to keep a good contrast. The specimens were immersed in an X-ray opaque solution of diiodomethane for a distinct absorption of radiation of cracks (Fig. 4). Cracks are organised in an interconnected network and