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A comparative study of twill weave reinforced composites under tension–tension fatigue loading: Experiments and meso-modelling

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ABSTRACT

The tension–tension fatigue characteristics of two types of twill weave carbon/epoxy composite materials have been experimentally investigated. The fatigue strain vs load cycle number is calculated with the help of digital image correlation (DIC). The increase of displacement amplitude and the degradation of the fatigue moduli for these two materials are studied and compared. The fatigue strengths obtained from fatigue tests are used to compare with those predicted by the model and good agreements are obtained. The stress fields from meso-scale FE models are used to analyse the stress concentration that leads to the fibre rupture in the warp tows.

1. Introduction

Woven composites are gaining popularity in the industry. However, as it is known, the crimp of the tows decreases the in-plane mechanical properties. As concluded in Ref. [1] damage and strength of the textile composite under axial loads are strongly affected by the fibre crimp. On the one hand, high flexure introduces severe local stress concentration, especially at the tow cross-over locations. On the other hand, the shear-bending interaction between warp and weft tows leads to an early inter-fibre matrix cracking in the tows transverse to the loads.

Many factors affect the mechanical behaviour of the woven composites. These factors include: (1) the mechanical properties of the fibre and matrix material, (2) the fibre/matrix interface, (3) the fibre volume fraction (VF) of the reinforcement materials, (4) the processing techniques (resin transfer moulding vs autoclave) and the processing parameters (curing time, temperature, pressure...), and (5) the reinforcement's geometrical parameters such as tow width, tow thickness, unit cell size and crimp.

Detailed literature reviews on fatigue analysis of textile composites have been provided by Degrieck and Van Paepegem [2], Post [3], Passipoularidis and Brøndsted [4] and Xu [5], respectively. According to Xu [5], the existing fatigue models can be classified into three categories: Miner's-rule-like models, phenomenological models and progressive damage models. In the recent, intensive experimental investigations have been carried out on fatigue behaviour of woven composites [6,7], and comparative studies were conducted by Carvelli et al. [8,9]. In Ref. [8] the non-crimp stitched UD and non-stitched UD are experimentally studied and the stitching effects are analysed. The on-axis fatigue resistance is enhanced by the structural stitching but weakened in the orthogonal direction. In Ref. [9], the 3D non-crimp orthogonal woven composite and 2D plain weave laminate are comparatively investigated. The conclusion is that the former composite has a longer fatigue lifetime and later damage onset. Nishikawa et al. [10] compared newly developed plain weave spread tow (cross-section aspect ratio = 20 mm:0.05 mm = 400) carbon/epoxy to conventional plain woven composites through static and fatigue tests. The spread tow composite showed an increase of static strength about 14% and 15 times prolongation of the fatigue life. A more comprehensive collection of the studies on textile composites' fatigue behaviour has been recently published [11] that covers the experimental measurement, observation, numerical prediction and industrial application.

In this paper two types of twill weave carbon fibre epoxy composites are studied: (i) carbon/epoxy twill weave 3K tow laminates (CET3K) with (tow) width: thickness = 2 mm: 0.11 mm = 18, and (ii) carbon/epoxy twill weave 12K tow laminates (CET12K) with (tow) width: thickness = 5.45 mm: 0.16 mm = 34. The tow crimps of these two impregnated fabrics are 0.85% and 0.28%, respectively. These two selected materials have the same fibre/resin system and fibre volume fraction, and are processed using autoclave following the same curing cycle, in order to avoid influences of the aforementioned factors (1)–(4). In author's earlier work [1], these two materials were experimentally and numerically characterised

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under static loadings. With higher crimp the CET3K exhibits earlier damage initiation in weft tows and remarkably lower strength than that of CET12K.

In the current work, the materials' responses to fatigue loadings are investigated through tension–tension fatigue tests and the recently proposed fatigue model [12]. The goal of the experiments is to acquire the modulus-life curves and *S–N* plots. The test results of these two materials are compared and the different behaviour is analysed. Meantime, the meso-FE model (Fig. 8) is used to quantitatively demonstrate stress concentrations that lead to fibre breakage and final failure, and differences in stress–strain fields for the two materials.

The impregnated tows are represented in the model as unidirectional composite (UD). In order to produce the *S–N* curves to feed fatigue model, UD samples made from M10.1/T700S prepreg system, the same as in CET3K (VF = 55.2 ± 0.08%) and CET12K (VF = 53.6 ± 0.17%), are tested under tension–tension fatigue loadings, too. The M10.1 resin system that has high fatigue resistance is suitable for low pressure moulding processes allowing a range of processing temperature from 85 °C up to 150 °C.

2. Tension–tension fatigue test

2.1. Experimental setup

The fatigue tests are conducted using MTS® 810 servo hydraulic testing machine equipped with a fatigue load cell of 100 KN and MTS® 647 Side-Loading hydraulic wedge grips. The operation system is TestStar-790.00 digital controller. A sinusoidal-wave constant-amplitude tension–tension fatigue load with stress ratio $R = 0.1$ is applied to the samples. The tests are carried out in a conditioned room with a temperature of 18 °C. 3 Hz load frequency is uniformly applied to all tests. Two factors have to be considered when defining the load frequency:

(A) **The consistency of frequency for all samples:** The frequencies of the fatigue loading applied to UD samples (*S–N* curves to feed the model [12]) and textile composites are identical. In an ideal case the frequency has little effect on fatigue life of the composites when the temperature is strictly controlled [13].

(B) **High level fatigue loadings:** As high level fatigue loadings (75–85% of the static strengths – Table 1) will be applied, the load frequency should be less or equal than 3 Hz in order to prevent the failure near to the end-tabs. De Baere et al. [13] often observed in-tab failures under fatigue loadings 75% of the strength at 5 Hz frequency. He assumed higher frequency leads to higher heat generation between tab and sample surface due to friction which decays the adhesive and hence induces the in-tab failure. Lower than 3 Hz frequency would not be affordable in fatigue since the total test campaign would be extended to more than one year [5].

2.2. Acquisition of the fatigue strain

All the fatigue tests in this work are load-controlled. However, the recorded grip displacement by the machine is not the true elongation of the sample but the summation of the sample elongation and the compliance of the test machine. Use of a dynamic extensometer was not possible because it tended to be detached from the specimen in the very early test stage. Hence a relation between the grip displacement and the true strain in the middle of the sample was measured using optical extensometer (digital image correlation or DIC – Vic2D®) and then this relation applied in fatigue testing to estimate the sample strain. The DIC averaging area (80 mm × 25 mm) was set to the centre of the sample. The full configuration was explained in Ref. [1].

In the first cycle a very low frequency (0.01 Hz) tensile load is applied to sample, stretching the sample up to the maximum fatigue load. The longitudinal strain, ε_{sample}, and hence the sample's elongation, $D_{sample}(F)$ can be obtained by Eq. (1):

$$D_{sample}(F) = \epsilon_{sample} \cdot L_{sample} \quad (1)$$

where L_{sample} is the sample free length. The total elongation, $D_{total}(F)$, of the sample and machine is known from the MTS data file. Hence the machine compliance, $D_{machine}(F)$ vs load F can be obtained as:

$$D_{machine}(F) = D_{total}(F) - D_{sample}(F), \quad (2)$$

as sketched in Fig. 1.

After removing the DIC, in the rest of the load cycles, the sample's elongation can be calibrated by Eq. (3):

$$D_{sample}(F) = D_{total}(F) - D_{machine}(F) \quad (3)$$

where $D_{machine}(F)$ is the machine tension–deformation curve obtained from Eq. (2). The assumption is taken that the dynamic effect (from 0.01 Hz to 3 Hz) will not give a relevant influence. Sample-grip slippage has to be strictly prohibited during all tests. Therefore a red mark was drawn on the grips aligning to the end-tabs to indicate any slippage.

2.3. Experimental data of carbon/epoxy UD

The M10.1/T700S prepreg system is processed into UD composite plates by using autoclave as explained in detail in Ref. [5]. The test coupons are prepared following the description in Ref. [1]. The width of the samples is 15 mm according to ASTM D3039 for UD composites. The mechanical properties are acquired through tensile tests using Instron® 4505 at a cross-head speed of 1 mm/min combined with extensometer. The mechanical properties in the fibre direction are listed in Table 2.

The fatigue tests have been performed in the fibre direction. Four loading levels are predefined: 70%, 75%, 80% and 85% of the static strength. For each loading level, at least three valid test results are necessary. Fig. 2(a) exhibits the normalised fatigue life

Table 1
Stress levels (%) and corresponding fatigue loadings (MPa).

	CET3K	CET12K
Static strength [1]	960	1132
75%	720	849
80%	768	906
85%	816	965

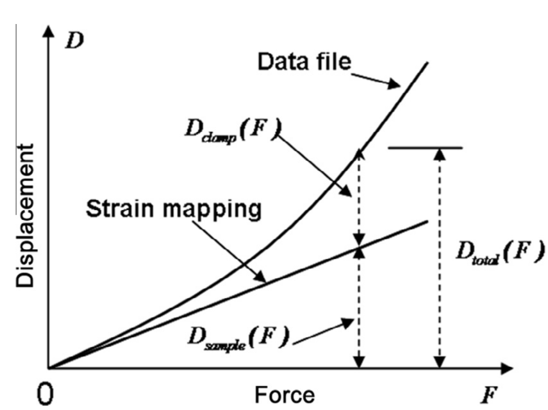

Fig. 1. Sketch showing how to calculate the machine compliance $D_{machine}(F)$ vs tensile loading by using DIC: the quasi-straight curve is obtained using DIC and the non-linear one is based on the force–displacement data recorded by MTS®810.