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Open hole quasi-static and fatigue characterisation of 3D woven composites

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ABSTRACT

This paper presents a comprehensive study on the open-hole quasi-static tensile and tension–tension fatigue behaviour of an orthogonal and an angle-interlock 3D woven carbon/epoxy composite. The full-field strain distribution during quasi-static tests was characterised using digital image correlation (DIC), and the fatigue damage behaviour was monitored using an infra-red camera. The notched tensile strength was less than 17% lower than the un-notched tensile strength and not very sensitive to the notch size. The fatigue specimens were loaded with maximum stress of about 60% of the ultimate failure stress and no complete fracture occurred after 5,000,000 cycles. The residual fatigue strength was also found to be similar to the quasi-static tensile strength in both weaves. The surface crack initiation and progression during fatigue loading was identified using thermoelastic stress analysis which revealed that the orthogonal weave had larger surface damage area than the angle-interlock weave.

1. Introduction

The aerospace and automotive industry have shown increasing interest in three-dimensional textile composites due to an excellent damage tolerance and the ability to produce near-net-shape components [1,2]. Developed from the traditional weaving technology, 3D woven composites provide better through-thickness properties and higher post-impact strength compared to the traditional 2D laminated composites [3,4]. However, the in-plane quasi-static properties of the 3D woven composites are generally lower than the 2D laminates due to fibre crimping induced by the interlacing movement during weaving process [1,5], and the fatigue properties of the 3D woven composites also seem to be lower than the comparable 2D composites [2,6–8]. The advantage of 3D woven composites is that they can be tailored to specific applications where certain mechanical properties (such as impact tolerance) are desired while other properties (such as in-plane tensile strength) are less critical.

Fatigue behaviour and notch sensitivities are two of the main concerns in composite materials since many aerospace applications require mechanical fastening and better fatigue properties. Much research has concentrated on the un-notched fatigue behaviour of 3D woven composites [7,6,8,9], with less research focused on the notched properties [10,11]. The tensile fatigue properties of 3D woven composites were found to be better than 2D woven laminates [7], but decrease with increasing content of through-thickness reinforcement [6,8,9]. The fatigue sensitivity and the quasi-static tensile strength of the investigated 3D interlock composites was found to be uninfluenced by the presence of a central hole [10–12].

Previous work on the fatigue damage progression characterisation for 3D woven composites was generally achieved by pausing the test and examining the specimen with X-ray computed micro-tomography [9] or optical microscopes [9,10]. Non-destructive testing equipment has been used to continuously monitor the fatigue damage in conventional laminated composites, such as acoustic emission [13–15], digital image correlation [14,16], and thermography [14,13,17,15]. However, these technologies have not been used to monitor the in situ open-hole fatigue damage progression of 3D woven composites to the author' s knowledge.

In our previous study [18], six 3D woven composites were tested under tension, compression, and flexure. One orthogonal weave and one angle-interlock weave showed higher tensile properties among all six weaves. Therefore, in this study, the open-hole quasi-static and tension–tension fatigue behaviour of these two weaves are investigated. The full-field strain distribution was obtained via digital image correlation during the quasi-static open-hole tensile tests, and the damage progression was characterised using thermal stress analysis during fatigue tests. The

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damaged samples were analysed using an optical microscope and post-fatigue tensile strength is also presented.

2. Materials and manufacture technique

The 3D woven fabrics were manufactured from a traditional narrow fabric weave loom (Muller-NC2-S) by M. Wright & Sons Ltd. A 1-by-1 orthogonal weave (W-1) and a through-thickness angle interlock weave (W-3) were produced and Fig. 1 shows the idealised weave geometries illustrated using TexGen [19]. Both weaves used 24 k IMS5131 yarns as warp tows, 2×6 k HTA40E13 yarns as weft tows. W-1 used 1 k Toray T300 as binder tows while W-3 used 3 k Tairyfil T33 as binder tows so that both weaves have similar amount of fibres in the through-thickness direction. The woven fabrics were 80 mm wide, 350 mm long, and 3 mm thick, and were placed in a closed mould tool for resin transfer moulding using a Hypaject MK-III RTM system. The resin (Gurit Prime 20LV with slow hardener) was degassed and heated up to 30 °C and then injected in the preheated and evacuated mould tool. The injection pressure was kept at 1 bar during infusion and was increased to 1.5 bar after the mould was fully filled with resin in order to reduce potential dry spots. The mould tool was then heated up to 50 °C for 16 h for curing. The produced composite parts had an overall fibre volume fraction of 49.86% for W-1 and 46.01% for W-3, and a warp fibre volume fraction of 27.72% for W-1 and 25.66% for W-3. The waviness of the warp tows (defined as tow wave amplitude/unit-cell-length) was also measured on the microscopic samples and was 1.37% for W-1 and 0.55% for W-3. Detailed microscopic analysis and mechanical characterisation of the manufactured composites have been reported previously [18].

3. Testing procedure

3.1. Open-hole quasi-static tests

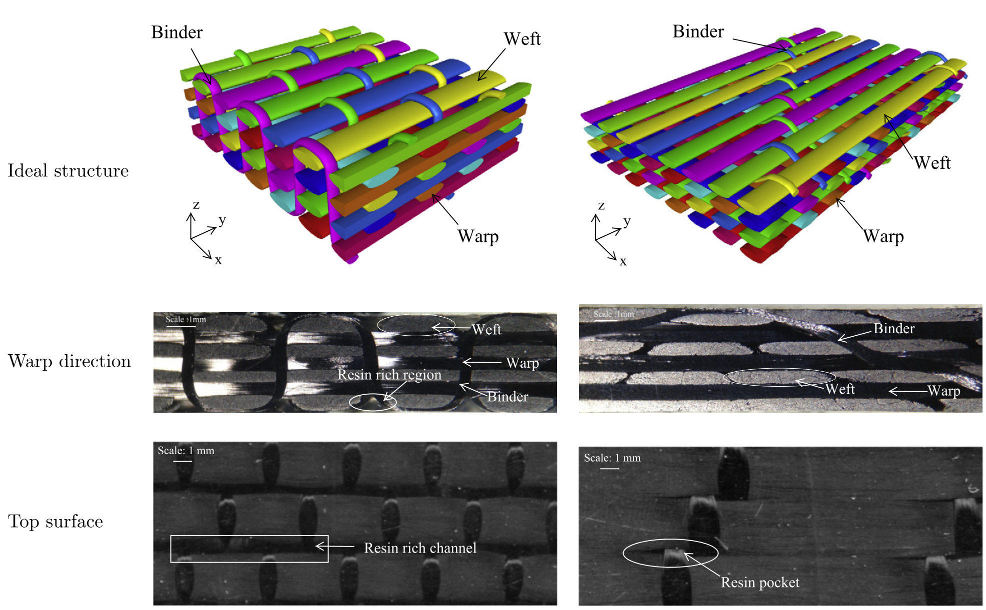
The open-hole tensile tests were carried out using an Instron 6025 testing machine with a 100 kN load cell and a LaVision DIC system to record full-field strain distribution on the surface of the specimens. All of the specimens were loaded at 2 mm/min until failure, the load and displacement data were recorded at 2 Hz, and the DIC images were recorded at 4 Hz. According to ASTM D5766 [20], a suggested geometry of the sample is 36 mm wide by 300 mm long with a 6 mm (1/6 of the width) diameter hole in the centre. However, based on the un-notched tensile strength of these two weaves [18], using a standard sized specimen is likely to result in a failure load (120 kN) higher than the load capacity of the testing machine (100 kN). Therefore the width of the samples was reduced to 25 mm. Previous literature has shown that the 3D woven composites were insensitive to the size of the notch [11], therefore five samples with 4.1 mm diameter notch (refereed to as "standard" samples) and seven samples with 12.5 mm notch (refereed to as "enlarged" samples) were tested. The larger notch was used to promote failure in fatigue tests as the available fatigue machine has a load capacity of 25 kN. In the absence of standard tests, it is only possible to qualitative comparison with other research findings. The samples were cut from the moulded panel using a diamond saw and the holes were drilled using a silicon carbide drill to minimise damage. Five specimens of each configuration were painted with random white speckle pattern on matt black base and two extra enlarged samples were also tested without the DIC speckle pattern to monitor surface damage evolution.

3.2. Open-hole fatigue tests

According to thermoelastic theory, the temperature of a material changes when the material changes volume due to mechanical work, and the temperature change can be related to the stress change in an adiabatic environment using Eq. (1) [21]. Generally if the fatigue loading frequency is higher than 5 Hz, the loading process can be treated as adiabatic. Therefore the temperature difference between the peak and valley of the cyclic load can be related to the stress change, and the development of the stresses during the fatigue loading can be treated as an indicator of damage development.

$$\Delta T = -\frac{T}{\rho C_p}(\alpha_{11}\Delta\sigma_1 + \alpha_{22}\Delta\sigma_2) \tag{1}$$

where ΔT (K) is the temperature oscillation during a fatigue cycle on the surface of the specimen, T (K) is the absolute temperature on the surface of the specimen, ρ (kg/m^3) is the density, C_p (J/kg K) is the specific heat capacity at constant pressure, α_{11} and α_{22} (K^{-1}) are the surface coefficients of thermal expansion



(a) W-1 (b) W-3

Fig. 1. Weave architectures of W-1 and W-3.