Assessment of Damage Progression in 3D Woven Carbon-Epoxy Composites Subjected to Out-Of-Plane Loading using Digital Image Correlation.

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Abstract

Three-dimensionally woven composites offer improved out-of-plane performance by including through-the-thickness mechanical reinforcement [1]. Recent work has demonstrated that this can be achieved without compromising the in-plane performance by producing weaves where the warp and weft tows are crimp-free [2]. This work, which included the testing and numerical analysis of several types of 3D woven architecture subjected to tensile, compressive and flexural loading, found that the angle-interlock configuration gave the best general performance. This was attributed to the better general load carrying capability of the binder tow. However it is generally accepted that the orthogonal weave can possess better crack arresting performance [3]. In order to investigate this further, both orthogonal and angle-interlock 3D woven carbon-epoxy composite specimens were subjected to out-of-plane loading and the damage initiation and progression was closely investigated. Both material weave architectures were subjected to shear failure by means of the five point bending test (FPBT) method [4-5] over several span-to-thickness ratios (s/t).

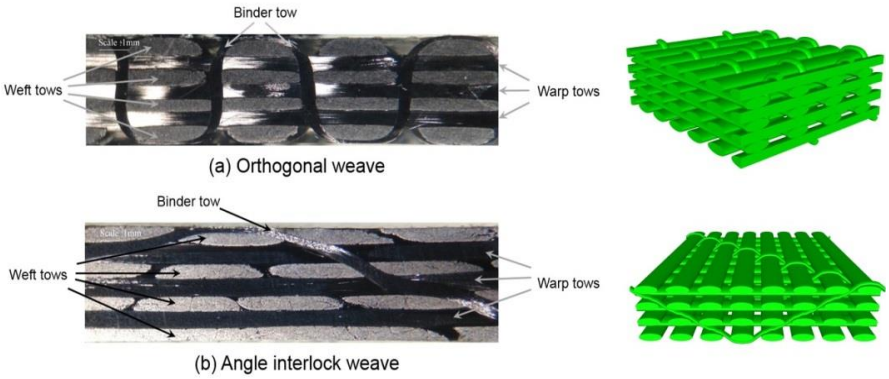

Figure 1. Actual and idealised 3D-weave architectures. (a) Orthogonal weave and (b) Angle interlock weave modelled using the TexGen

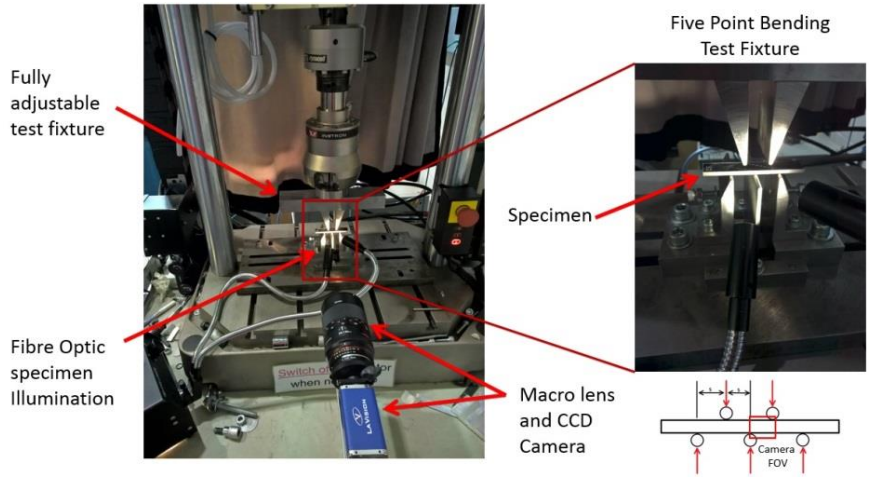

Figure 2. Test setup for Five Point Bending Test with 2D Digital Image Correlation Analysis

The experimental set up and test configuration can be seen in Fig. 2. The FPBT method induces a region of high shear force and zero bending moment between the centre-support and loading noses, useful for encouraging shear dominated failure.

Both weave architectures were manufactured using Resin Transfer Moulding and specimens with dimensions 75 x 15 x 3 mm were produced. The weave architecture consists of three warp layers which run the length of the specimen, four weft layers that run the width of the specimen and binder tows that also run the length of the specimens, interlocking the weft tows.

The failure event and damage progression was captured using the two-dimensional Digital Image Correlation (DIC) method, where crack initiation and damage progression is observed with full field strain visualisation through the thickness of the specimen. The DIC camera uses a field of view between the centre support and loading nose to focus on the region of high shear force and zero bending moment. Five test repeats were carried out for span/thickness ratios of 3, 4 and 5.

Both architectures failed consistently in shear, and both show considerable damage tolerance with sustained load carrying capacity ranging from 50 – 80% of the maximum. Some load recovery was observed prior to successive load drops indicating crack bridging as a mechanical means of through the thickness reinforcement. The orthogonal weave architecture shows distinct localised strain concentrations at the warp/weft tow interfaces where shear failure occurs and these are bridged successfully by the binder tow. This mechanism is observed in the load-displacement plots as a characteristic “saw-tooth” pattern post initial failure,

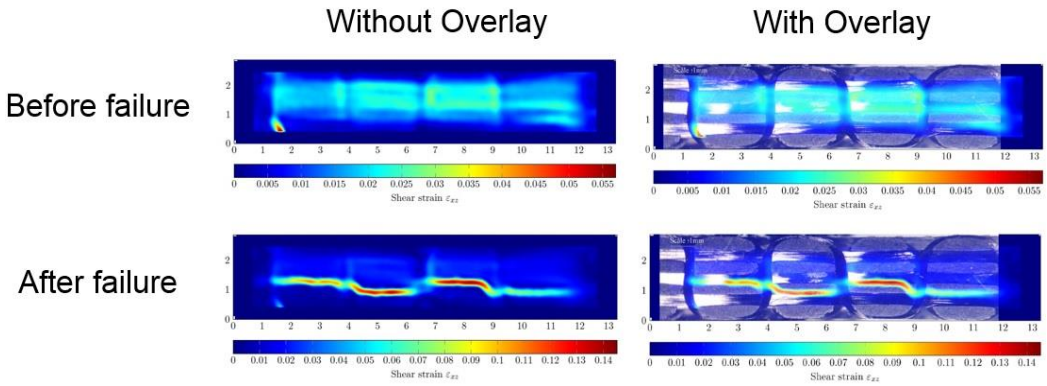

Figure 3. DIC Strain analysis results of orthogonal weave architecture before

caused by successive load drops. An example of the Digital Image Correlation strain analysis prior to and post shear failure can be seen in Fig. 3. Stress-displacement plots from the two weave architectures under identical specimen size and test conditions can be seen in Fig. 4. These show how the angle interlock weave architecture has, in general, a greater failure stress coupled with a more gradual failure compared to the several distinct and sharp load drops that take place within the orthogonal weave architecture. The DIC strain analysis proved to be an effective method in understanding strain distribution through the thickness of the material and identifying the mechanisms by which the binder tow within each architecture acts to inhibit and affect crack propagation, or deflect it resulting in higher work required for failure. The assumption that the crack is planar cannot be made as the mechanical reinforcement through the width of the specimens takes place in discrete locations through the width of the specimen and may affect the propagation of the crack front. The angle-interlock weave architecture offered higher failure loads (and therefore shear stresses) compared to the orthogonal weave architecture for identical test conditions and specimen size, indicating a higher resistance to shear failure and greater damage tolerance, along with a much more gradual failure. Failure within the orthogonal weave architecture is observed as distinct load drops indicating successive crack propagation and arresting, whereas failure and damage progression within the angle interlock architecture acts within an energy

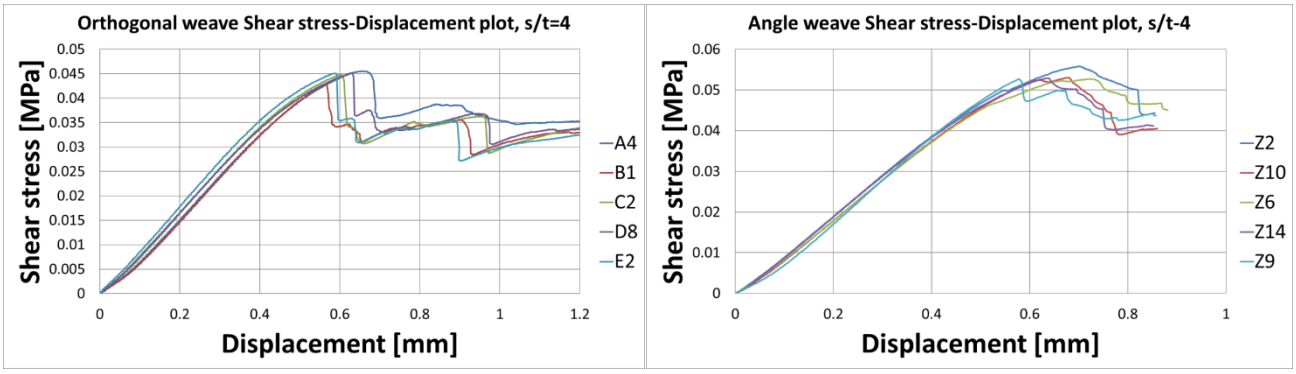

Figure 4. Comparison of shear stress-displacement plots for orthogonal and angle interlock weave.

absorbing mechanism by deflecting the crack path along the binder tow.

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