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A novel fixture for determining the tension/compression-shear failure envelope of multidirectional composite laminates

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ABSTRACT

A new approach for biaxial loading of fibre reinforced composites is presented, based on the use of a Modified Arcan Fixture (MAF). In addition to combined tension-shear loading which can be achieved using a conventional Arcan fixture, the MAF allows the application of pure compression and compression-shear loading. Digital Image Correlation is used to obtain the full-field deformations of the specimens to establish the load response and failure behaviour for a range of multiaxial stress-strain states. The approach is demonstrated on glass/epoxy prepreg laminates. For unidirectional matrix dominated laminate it is shown that the failure envelope is described accurately by Puck's inter-fibre failure theory. For the multidirectional matrix-dominated laminate it is shown that the in-situ strength is much greater than that predicted using the unidirectional properties. The potential of the MAF for characterisation over the entire combined tension-shear and compression-shear domains using a single fixture is demonstrated.

1. Introduction

There is an increasing requirement to understand better the behaviour of composite materials subject to complex multi-axial loading conditions as to enable efficient deployment in a range of load carrying applications in the aerospace, marine and other industries. The analysis of multidirectional composites subjected to multiaxial loading has progressed through initiatives such as the World Wide Failure Exercises (WWFE-1, 2 and 3) [1–3]. In order to replace costly and time-consuming physical materials and structures tests with model-based virtual testing, robust material and failure models must be established, validated by experimental data. Currently there is a scarcity of reliable experimental data for multiaxial load cases due to the complexity of multiaxial testing and design of the test specimens. In fact, a generally agreed consensus has not been reached in the composites community on the appropriate definition and design of multiaxial testing methodologies for composites.

Most biaxial or multiaxial tests reported in the WWFEs [1–3] were performed on filament-wound small diameter tubular specimens subjected to combined tension/compression, internal pressure and/or torsional loading. However, tubular specimens are not representative of typical laminated composite materials coupon specimens or structures which are flat/planar or display a large curvature radius compared with the laminate thickness, and where the arrangement of reinforcement fibres is ply-wise discretely discontinuous. For that reason, cruciform specimens often have been chosen [4–9] to characterise the biaxial mechanical performance of composite laminates for biaxial tension-tension, tension-compression and compression-compression loading. Successful testing of cruciform specimens requires extensive and careful machining of the specimens to create a reduced gauge section thickness and a corner fillet to prevent premature failure outside the gauge section. In addition, a sophisticated biaxial test machine with four independent actuators is often required. For the tension-shear load regime, the Arcan test rig [10–13], originally developed for shear testing of polymers and composites, can be modified by adding a sequence of loading holes in the arms of the fixture to achieve combinations of shear and tensile stress states. In particular, Tan et al. [13] examined the subcritical damage mode of quasi-isotropic central-notched and open-holed CFRP laminate subjected to combined tension and shear, and pure compression using a modified Arcan rig. However, the conventional Arcan rig is restricted to pure tension or combined tension-shear load cases and cannot be utilised for testing specimens loaded in the combined compression-shear load regime or in pure compression. Moreover, the stress state in a biaxially-loaded multidirectional

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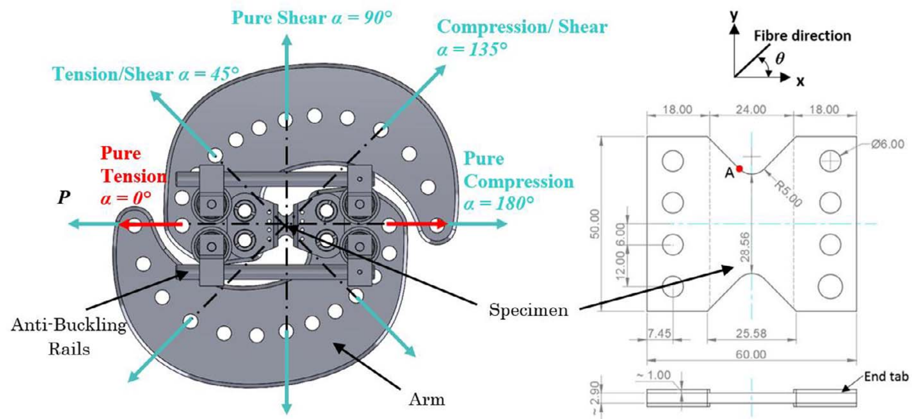

Fig. 1. The Modified Arcan Fixture (MAF) and the dimensions of the butterfly specimen.

laminated specimen is complex, and due to its irregular geometry and anisotropic nature can only be modelled realistically using e.g. non-linear finite element analysis or other advanced numerical tools. Thus, to advance the understanding of the biaxial load response and failure behaviour of composite materials, a combined experimental and numerical approach is required. A prerequisite for enabling this is the development of a test rig or a standardised test, which can generate high fidelity multiaxial experimental data for validation of numerical models and failure theories.

Following the previous success of biaxial testing on polymer foam materials [14], the focus of the present paper is on the development and validation of a novel Modified Arcan fixture (MAF) setup (Fig. 1) for the investigation of the in-plane biaxial mechanical response and failure behaviour of multidirectional composite laminates. Three different E-glass/epoxy laminate configurations are investigated; two that display matrix dominated load response and failure behaviour with stacking sequences $[90]_{12}$ and $[+60/-60]_{3s}$, and another that displays distinctly fibre dominated response characteristics with stacking sequence $[-30/+30]_{3s}$. Fig. 1 also shows the butterfly-shaped test specimen geometry used for this study; more details of the specimen design is given in Section 2.1. The MAF enables the application of combined tension/compression and shear loading states (i.e. pure tension, pure compression, pure shear, biaxial tension-shear and biaxial compression-shear) to the specimen through a series of loading holes every 15° spanning an arc of 180° on the loading arms (Fig. 1); more details of the MAF geometry and design are provided in Section 2.1. In contrast to the standard Arcan rig, compression and compression-shear testing is facilitated by the introduction of a pair of anti-buckling guide rails fixed to the MAF arms on both sides, which serve to eliminate out-of-plane displacement of the rig. The desired normal to shear stress ratio is selected by using appropriate pairs of loading holes.

The mechanical response and failure of unidirectional $[90]_{12}$ specimens is investigated and exploited to validate inter-fibre failure criteria, that are used as the basis for predicting failure in angle-ply laminates. The purpose of the work is to demonstrate the feasibility of the MAF approach and that accurate material properties can be obtained from complex loading in the shear-compression domain by using such a fixture. To enable a detailed evaluation of the effectiveness of the MAF approach, the specimens were imaged on both sides so that 2D Digital Image Correlation (DIC) could be used to obtain full-field measurement of in-plane strain, thereby identifying damage during loading, and also enabling the strains on both sides of the specimen to be obtained to assess if any out-of-plane bending was being induced. It is demonstrated that the rig has the potential to allow full characterisation of the composite laminate strength in the combined tension/compression-shear stress domain using a single test fixture and hence obtaining the corresponding failure envelope, which is not possible with the conventional Arcan rig.

2. Methodology

2.1. Modified Arcan Fixture (MAF) and specimen fabrication

The MAF consists of a pair of boomerang-shaped arms (with diameter about 0.47 m and thickness 40 mm) made from high strength aluminium alloy Alumec 89. The specimen is secured in the centre of the fixture at both ends of the specimen by mechanical grips made from Uddeholm Impax Supreme steel via four M5 bolts tightened to 5 Nm of torque (the recommended maximum value). The bolts served to align the specimen in the grips and to provide mechanical clamping forces such that the specimen could be primarily loaded by friction between the grips, which have knurled surfaces to enhance the friction. The MAF is designed so that it can be attached to a standard universal test machine via two double-sided fork-lugs, where all combinations of tension/compression and shear loading are achieved with a positive applied displacement.

The butterfly configuration was chosen to encourage failure at a known position. The radius of the waisted part of the specimen clearly has the potential to act as a notch and encourage premature or unexpected failure. To examine this, specimens were initially machined with three different notch radii 10 mm, 5 mm and a sharp notch (~0.7 mm i.e. the smallest feasible radius that can be produced with the waterjet cutter used for the specimen manufacture). Similar to the results from the polymer foam material testing [14], preliminary tests showed that failure for most specimens tends to initiate at the site of stress concentration where the curvature of the notch meets the straight edge (Point 'A' in Fig. 1). The largest notch radius, i.e. 10 mm, gave the crack initiation location farthest away from the specimen waist and near to the tabs. However, it was decided not to use the sharp notch specimens as the diameter of the waterjet could not be controlled accurately during machining the sharpest radius, thus making it impossible to achieve a consistent notch radius. The butterfly specimen geometry with a notch radius of 5 mm gave the best compromise and was therefore selected for the tests, as this was deemed a sufficient compromise to demonstrate the MAF feasibility.

The specimen material considered was E-glass/RP528 UT300 E00 M32 prepreg system with a nominal ply thickness of 0.25 mm. Identical panels with three different stacking sequences: $[90]_{12}$, $[+60/-60]_{3s}$ and $[-30/+30]_{3s}$, were fabricated. The corresponding fibre direction θ with respect to the reference horizontal axis of the specimen is illustrated in Fig. 1. The three stacking sequences are representative of unidirectional, matrix-dominated angle-ply and fibre-dominated angle-ply laminates, respectively, with the main goal being to study the applicability of the MAF set-up for testing a broad range of multidirectional laminates. The laminates were cured at 120 °C and 6.2 bar for an hour, as specified by the supplier, which resulted in a cured thickness of nominally 2.9 mm. Cross-plied end tab strips made from