BIAXIAL TESTING OF GLASS/EPOXY COMPOSITE LAMINATES USING A MODIFIED ARCAN'S FIXTURE (MAF)

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Keywords: Polymer-matrix composites (PMCs), biaxial strength, biaxial mechanical testing

ABSTRACT

A series of biaxial loading tests have been conducted on composite laminates made from a unidirectional E-glass/epoxy prepreg system. The tests were conducted using a Modified Arcan Fixture (MAF) to test matrix-dominated unidirectional $[90]_{12}$ and $[+60/-60]_{3}$ laminate configurations, as well as a $[-30/+30]_{3s}$ laminate with a fibre-dominated response. In addition to combined tension-shear loading, which can be conducted using a conventional Arcan test fixture, the MAF enables the application of pure compression or high compression to shear bidirectional load conditions. The two matrix dominated $[90]_{12}$ and $[+60/-60]_{3s}$ laminates were tested successfully to failure. The work has demonstrated the potential of the MAF for the characterisation of the strength of multidirectional composite laminates over the entire combined tension/compression-shear stress domain using a single test fixture. However, for the testing of the fibre dominated $[-30/+30]_{3s}$ laminate configuration, it was found that the failure occurred due to premature shear-out or bearing failure at the pin holes instead of at the gauge section. Thus, the tests have shown that the MAF rig grip design requires modification to enable testing of fibre-dominated laminate configurations.

1 INTRODUCTION

Multiaxial stress analysis of multidirectional composites has gained attention through efforts such as the Worldwide Failure Exercises (WWFE-1, 2 and 3) [1-3]. However there is still 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, no generally agreed consensus has been reached in the composites community on the appropriate definition and design of multiaxial testing methodologies for composites. Following on from the approach of combined tension and shear loading of polymer foam materials using a novel modified Arcan fixture (MAF) rig concept [4], the present paper focuses on the further development and validation of the MAF setup which has been modified to study laminated polymer composite materials as shown in Figure 1. The rig has the potential to allow full characterisation of the composite strength in the combined tension/compression and shear stress domain using a single test fixture, which is not possible with the conventional Arcan rig. The combinations of tension/compression and shear loading can be achieved by using the appropriate pairs of loading holes. Figure 1 also shows the butterfly shaped test specimen geometry that was designed for this study. The in-plane biaxial mechanical response and failure behaviour of 3 different E-glass/epoxy laminate configurations is investigated. This includes two laminates with a matrix dominated load response and failure behaviour with stacking sequences of $[90]_{12}$ and $[+60/-60]_{3s}$, and one laminate that has distinctly fibre dominated response characteristics with a stacking sequence of $[-30/+30]_{3s}$. The main goal is to study the applicability of the MAF set-up for testing a broad range of multidirectional laminates subjected to multiaxial stress states.

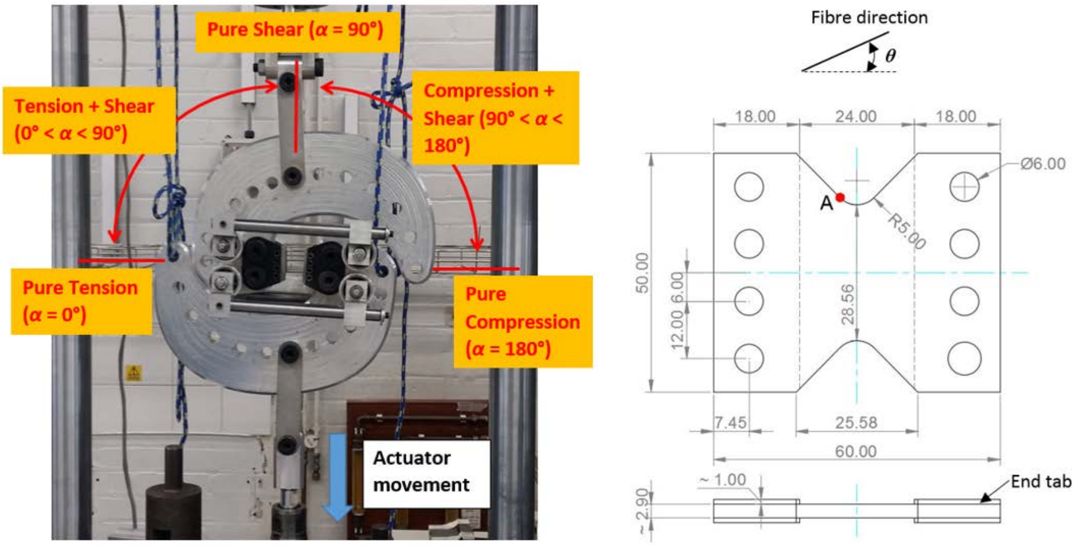

Figure 1: The modified Arcan fixture (MAF) and the dimension of the butterfly specimen.

2 METHODOLOGY

The composite material considered is an E-glass/RP528 UT300 E00 M32 prepreg system with a nominal ply thickness of 0.25 mm. 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 Figure 1. End tab strips were attached to the laminates using thin film adhesive (epoxy adhesive film SA80 from Gurit). They were then waterjet-cut to the final butterfly shape shown in Figure 1.

The tests were performed using an Instron 100 kN universal test machine. The specimens were mounted in the mechanical grips of the fixture and were then loaded at a rate of 1 mm/min until significant damage occurred. Nine bidirectional load configurations were tested for the $[90]_{12}$ laminates, namely pure tension (α = 0°), combined tension-shear (α = 30° and 45°), pure shear (α = 90°), combined compression-shear (α = 120°, 135°, 150° and 165°) and pure compression (α = 180°). The angle α refers to the angle between the loaded hole and the first hole of the loading arm (α = 0°) as shown in Figure 1. Six load configurations were tested for the $[+60/-60]_{3s}$ laminates, i.e. pure tension (α = 0°), combined tension-shear (α = 45°), pure shear (α = 90°), combined compression-shear (α = 120° and 150°) and pure compression (α = 180°). Four load configurations were tested for the $[-30/+30]_{3s}$ laminates, i.e. combined tension-shear (α = 45°), pure shear (α = 90°) and combined compression-shear (α = 120° and 150°). Between two and four specimens were tested for each load configuration.

3 EXPERIMENTAL RESULTS

3.1 $[90]_{12}$ unidirectional specimens

All the $[90]_{12}$ butterfly specimens failed catastrophically by inter-fibre matrix failure around the waist of the butterfly specimen along a perpendicular, straight and flat fracture plane, except for some of the combined compression-shear (α = 135°, 150° and 165°) and pure compression (180°) load cases where the fracture planes inclined at an oblique angle θ_{fp}. The failure modes for selected load cases are shown in Figure 2. To define the failure envelope, the material-axis in-plane stresses (σ_{22} and τ_{12}) for all specimens are plotted in the σ-τ stress domain in Figure 3.

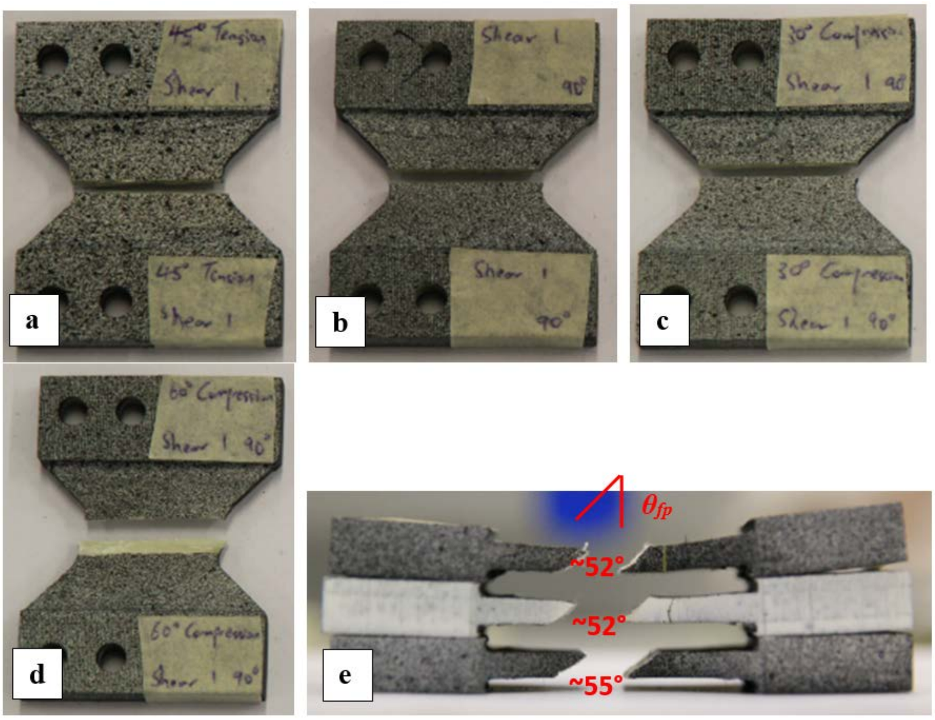

Figure 2: Failure of the $[90]_{12}$ specimens under (a) combined tension-shear (α = 45°), (b) pure shear (α = 90°), (c) combined compression-shear (α = 120°) and (d) combined compression-shear (α = 150°) loading configurations. (e) Side view of specimens in (d) showing the fracture plane generally inclines at an angle about 53°.

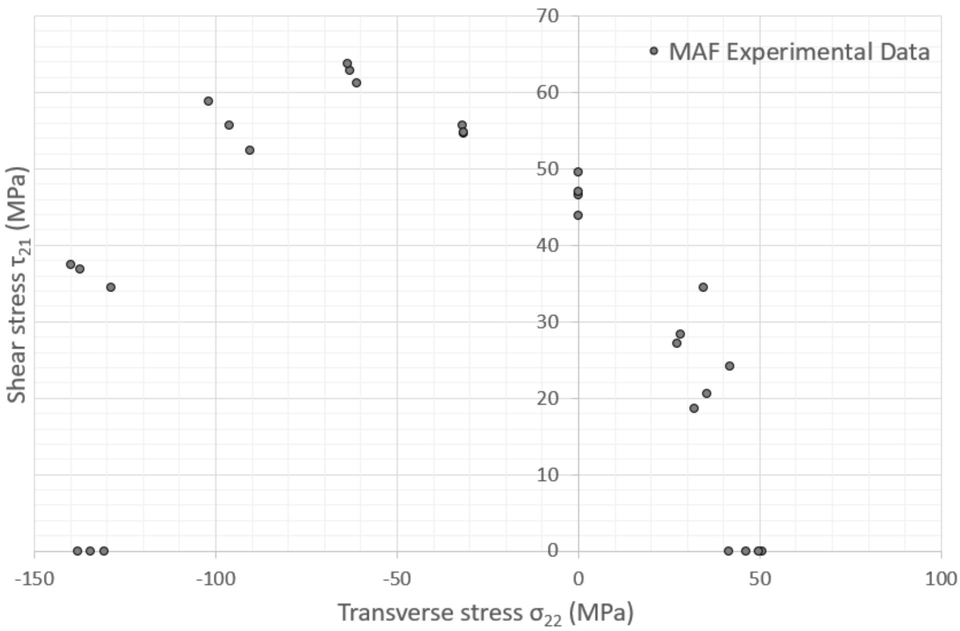

Figure 3: In-plane failure stresses of the $[90]_{12}$ laminates in the σ_{22} - τ_{12} domain.

3.2 $[+60/-60]_{3s}$ angle-ply specimens

The failed $[+60/-60]_{3s}$ specimens tested under the various load configurations are shown in Figure 4. Catastrophic failure was mostly observed in all cases, indicated by a sharp load drop in the load-displacement curves, with some loading configurations showing stiffness reduction kinks before the final load drop associated with ultimate failure. In general, all specimens failed at the gauge area, but did not give a well-defined clean and flat fracture surface, which makes the definition of the fracture stresses on the fracture path/plane less straightforward than for the $[90]_{12}$ specimens. So the average stresses (σ_{xx} and τ_{xy}) at the failure initiation across the waist are used as the representative stresses in plotting the failure envelope in Figure 5. The global x-axis is in the direction perpendicular to the waistline of the butterfly specimens.

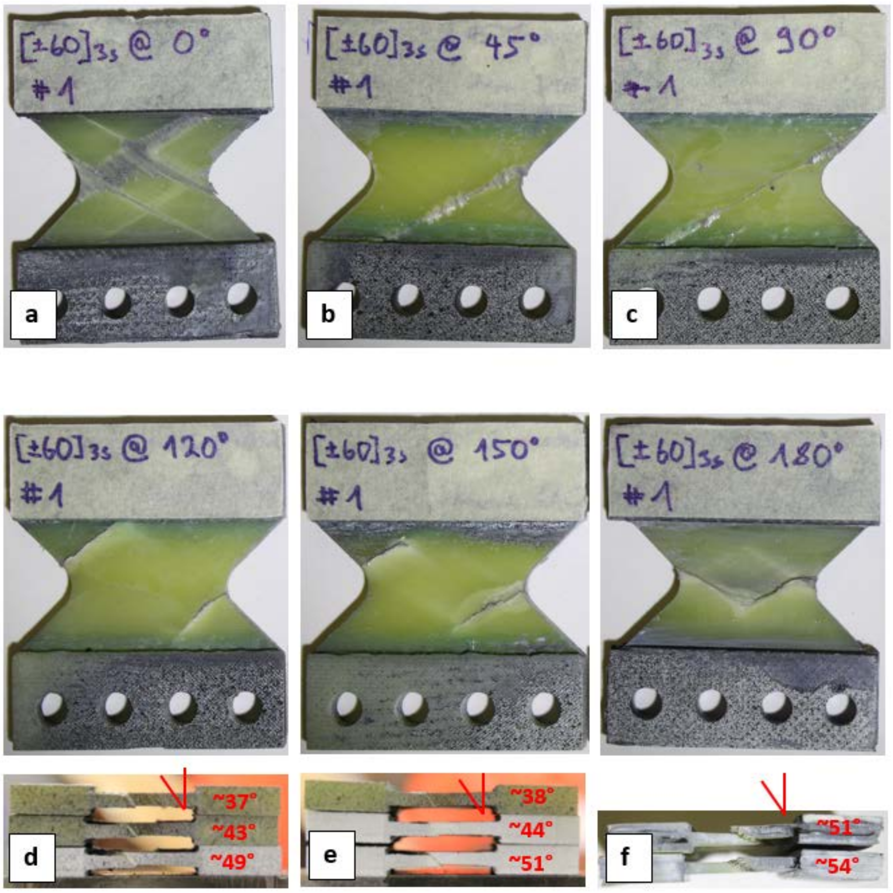

Figure 4: Failure of the $[+60/-60]_{3s}$ specimens under (a) pure tension (α = 0°); (b) combined tension-shear (α = 45°); (c) pure shear (α = 90°); (d) combined compression-shear (α = 120°); (e) combined compression-shear (α = 150°); (f) pure compression (α = 180°) loading configurations. In cases (d) to (f) the specimens fractured at an angle between 37°-54°.

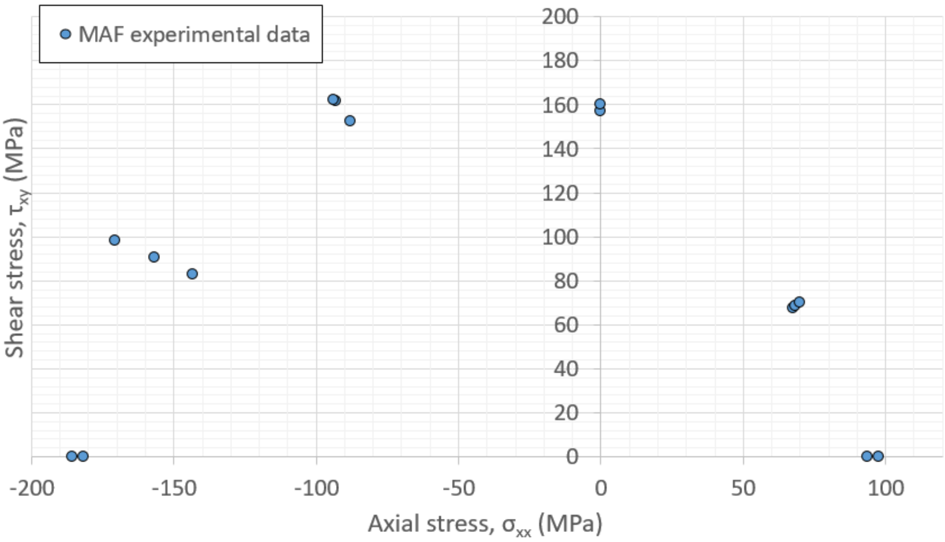

Figure 5: In-plane failure stresses of the [+60/-60]$_{3s}$ laminates in the $\sigma_{xx} - \tau_{xy}$ domain.

3.3 [-30/+30]$_{3s}$ angle-ply specimens

The response of the [-30/+30]$_{3s}$ specimens is fibre-dominated with respect to the loading direction. For loading angles α = 45°, 90° and 120°, shear-out and bearing failure initiated prematurely at the pin holes of the specimens well before any failure at the gauge section occurred. This was followed by debonding of the end tabs (Figure 6a). The tests were stopped as it was not possible to load the specimens any further. However, three specimens were successfully tested for the combined compression-shear (α = 150°) load case, which showed a complex crack pattern with inter-fibre failure (IFF), fibre kinking and fibre fracture, and ultimately failed catastrophically due to out-of-plane buckling instability at the gauge section (Figure 6b).

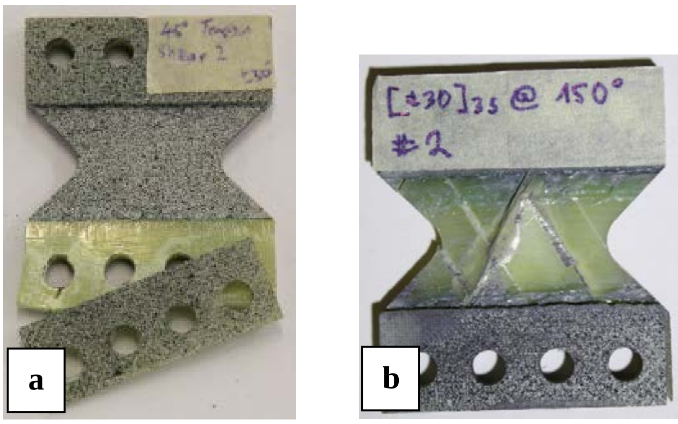

Figure 6: (a) Shear –out failure at the pin hole of the [-30/+30]$_{3s}$ specimen. (b) Failure of the [-30/+30]$_{3s}$ specimen under combined compression-shear (150°) showing complex crack pattern.

Failure occurred due to edge effects in 3 out of 4 loading angles, and not in the gauge section as desired, for the [-30/+30]$_{3s}$ specimens. This suggests that the current configuration of the MAF rig along with the use of butterfly-shaped specimens is not suitable for the testing of laminate configurations that display fibre-dominated behaviour, as well as for testing of stronger and stiffer carbon fibre reinforced laminates. To obtain failure in the gauge section, it will be necessary to achieve sufficiently high stresses to break the fibres in the gauge section. The butterfly specimen used for this study was designed to be loaded primarily by friction between the grips. The pin holes were intended for assisting alignment of the specimens during mounting in the test rig. However, the observed failure at the pin holes indicates that the frictional forces generated by the clamps were insufficient to ensure that slippage of the specimens did not occur. Thus, to enable testing of laminate configurations with fibre dominated response characteristics, a re-design of the rig and specimen geometry is required, especially with respect to the gripping mechanism. This is being pursued in further research.

4 CONCLUSION

A modified Arcan fixture (MAF) has been employed to investigate the biaxial strength of multidirectional E-glass/epoxy laminates, which makes material evaluations more straightforward. Successful testing of butterfly specimens of stacking sequences $[90]_{12}$ and $[+60/-60]_{3s,}$ which exhibit a matrix dominated response, has been demonstrated. It was shown, that it is possible to establish an approach for composite testing where a complete biaxial failure envelope can be generated using a single test fixture and one single specimen geometry. Complete failure envelopes for the $[90]_{12}$ and $[+60/-60]_{3s}$ matrix dominated laminate configurations have been generated using the MAF in the σ-τ stress space, which shows that the approach has the potential to be used to obtain valuable biaxial experimental data for development and validation of numerical models. However, for the tests conducted on fibre-dominated specimens of stacking sequence $[-30/+30]_{3s}$ it was found that premature failure occurred due to shear-out failure at the pin holes. The cause of the problem lies in the design of the specimen grips used for the MAF, and further research is ongoing to resolve this issue so that both fibre and matrix dominated laminate configurations can be tested throughout the tension-shear and compression-shear loading envelopes.

ACKNOWLEDGEMENTS

The work was supported by Fundamental Research Grant Scheme (FRGS) (FRGS/1/2015/TK09/USMC/03/1) of the Ministry of Higher Education (MoHE) of Malaysia.

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