Experimental Characterisation and Modelling of the Nonlinear, Pressure Sensitive Behaviour of UD Composites under Multiaxial Loading

T. Laux[1a], K.W. Gan[1,2], J.M. Dulieu-Barton[1] and O.T. Thomsen[1]

[1]Faculty of Engineering and the Environment, University of Southampton, Highfield, SO17 1BJ, Southampton, UK

[2]Faculty of Engineering and the Environment, University of Southampton Malaysia Campus (USMC), Kota Ilmu Educity @ Iskandar, 79200 Iskandar Puteri, Johor, Malaysia

[a]t.laux@soton.ac.uk

Background

Unidirectional (UD) fibre reinforced composites are widely used in lightweight structures due to their high specific stiffness and strength [1]. UD composites are anisotropic and exhibit nonlinear and pressure sensitive behaviour when subjected to multiaxial stress states especially in shear and transverse compression [2]. The significant nonlinearities are due to different physical effects that include plasticity, micro-cracking and geometric nonlinearity (*e.g.* fibre rotation) [3]. To accurately predict the stresses and strains and eventually failure in critical composite components it is therefore crucial to account for these effects [4-5].

Methodology

A simple non-associative plasticity model which accounts cumulatively for these nonlinear effects is developed and calibrated using a novel biaxial test fixture. The procedure is based on the Modified Arcan Fixture (MAF [6]) and Digital Image Correlation (DIC) as shown in Fig. 1 which allows the characterisation of materials in the full combined transverse tension/compression and shear stress domain using a single test fixture and a single specimen geometry. The compression/shear domain, which cannot be tested using the conventional Arcan rig [7], is crucial because this is where the nonlinear, pressure sensitive behavior is most significant [2]. The stress/strain state in the specimen's waisted gauge section (see Fig 1b) is defined by the loading angle α, which can be adjusted from pure tension over combined tension/shear, pure shear, combined compression/shear to pure compression as shown in Fig. 1a.

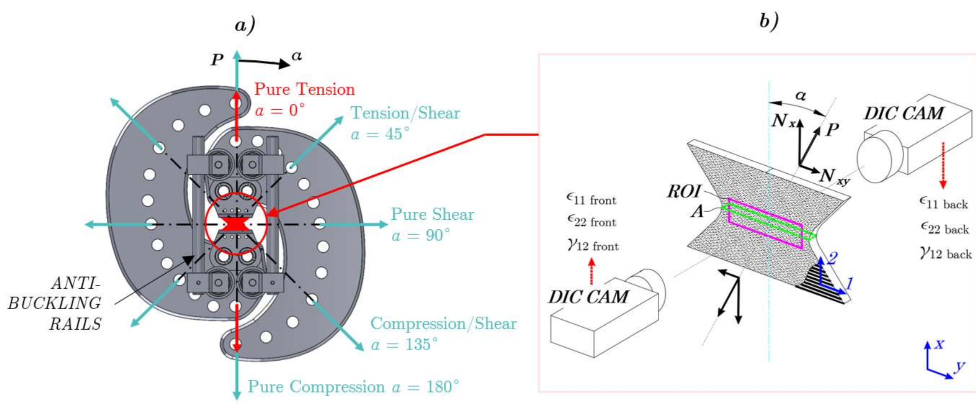

Fig. 1, (a) The Modified Arcan Fixture (MAF) and (b) the butterfly specimen and DIC set-up.

The proposed model was calibrated for RP-528 glass/epoxy [8] based on stress-strain curves derived from the MAF/DIC experimental data under various biaxial stress-states and was then implemented as a user material subroutine (VUMAT) for the FE software Abaqus [9].

Preliminary Results

FE model predictions of the shear (γ_{12}) and transverse (ε_{22}) strains using the nonlinear user material subroutine (VUMAT) and a linear elastic model were compared against DIC strain maps. An example result is shown in Fig. 2 for a combined compression/shear load case (α=120°, $\sigma_{22\,AVG}$= -26 MPa, $\tau_{12\,AVG}$ = 47 MPa). The nonlinear model predicts strain maps in Fig. 2c - d that are in excellent agreement with the DIC results in Fig. 2a - b. The high shear strains in the gauge sections as well as the high transverse strain concentrations at the notches, which are largely 'plastic' strains, are well accounted for. This is not the case for the linear FE model (Fig. 2e - f) where both predictions show poor correspondence with the experimental results. The improvement of the proposed nonlinear model over the linear model is significant.

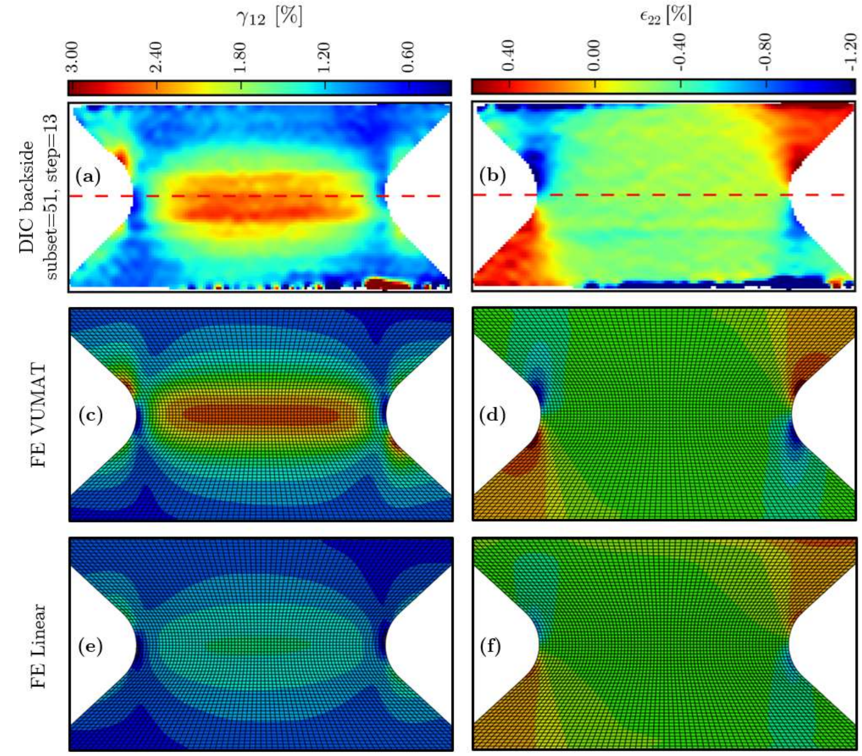

Fig. 2, DIC shear (a) and transverse (b) strain maps; predicted shear (c) and transverse (d) strain maps using the proposed nonlinear user material (VUMAT); predicted shear (e) and transverse (f) strain maps using a linear elastic FE model.

Conclusions

A simple nonlinear constitutive model based on non-associative plasticity has been developed for UD composites subjected to multiaxial loading. It is demonstrated that the model can be calibrated using biaxial experimental data obtained from the MAF/DIC procedure. Comparison of model predictions to the DIC strain maps have shown that the model can predict the nonlinear pressure dependent constitutive behaviour of UD composites with good accuracy. The model can therefore potentially be used as a tool to investigate multiaxial stress/strain states and failure in critical composite components and structures.

Acknowledgements

The research is supported by the EPSRC Doctoral Training Grant. The secondment of the first author to the University of Southampton Malaysia Campus, Malaysia, where a part of this research was conducted, is supported by the Fundamental Research Grant Scheme (FRGS/1/2015/TK09/USMC/03/1) of the Ministry of Higher Education of Malaysia. The first author acknowledges the support received through a Stanley Gray Fellowship granted by the Institute of Marine Engineering, Science and Technology (IMarEST).

References

[1] I. M. Daniel: *Engineering mechanics of composite materials*, edited by Oxford University Press, Oxford, 2005.

[2] E. S. Shin and K. D. Pae: *Effects of hydrostatic-pressure on the torsional shear behavior of graphite epoxy composites*, *J. Compos. Mater.*, vol. 26 (1992), p. 462–485.

[3] T. Yokozeki, S. Ogihara, S. Yoshida, and T. Ogasawara: *Simple constitutive model for nonlinear response of fiber-reinforced composites with loading-directional dependence*, *Compos. Sci. Technol.*, Vol. 67 (2007), p. 111–118.

[4] M. Vogler, R. Rolfes, and P. P. Camanho: *Modeling the inelastic deformation and fracture of polymer composites-Part I: Plasticity model*, Mech. Mater., Vol. 59 (2013), p. 50–64.

[5] G. M. Vyas, S. T. Pinho, and P. Robinson: *Constitutive modelling of fibre-reinforced composites with unidirectional plies using a plasticity-based approach*, Compos. Sci. Technol., Vol. 71 (2011), p. 1068–1074.

[6] K. W. Gan, T. Laux, S. T. Taher, J. M. Dulieu-Barton, and O. T. Thomsen: *A novel fixture for determining the tension/compression-shear failure envelope of multidirectional composite laminates*, Compos. Struct., Vol. 184 (2018), p. 662–673.

[7] M. Arcan, Z. Hashin, A. Voloshin: *A method to produce uniform plane-stress states with applications to fibre-reinforced composites*, Experimental Mechanics, Vol. 18 (1977), p. 141-146

[8] PRF Composites: *Product data prepreg systems RP-528*. [Online]. Available: http://www.prfcomposites.com/. [Accessed: 20-Sep-2016].

[9] Dassault System: *Abaqus 6.14. Documentation*, [Online]. Available: http://abaqus.software.polimi.it/v6.14/index.html. [Accessed: 20-May-2018].