MODELLING MIXED-MODE TRANSLAMINAR FRACTURE

M. J. Laffan*, S. T. Pinho, P. Robinson

Department of Aeronautics, Imperial College London, UK. SW7 2AZ
**matthew.laffan@imperial.ac.uk*

Keywords: translaminar fracture, mixed-mode, damage modelling, delamination

Abstract
The work that will be presented concerns the development of a damage model intended to capture the delamination failure exhibited by notched laminates under mixed-mode in-plane loading. The model will be validated against an experimental program which uses a new type of tensile specimen, designed to trigger the desired failure mode. The advantage of the model is that it is able to accurately represent delamination without ply-by-ply modelling or the use of cohesive elements, thus greatly reducing the computational cost of simulating this failure mode.

1. Introduction

Experimental investigation of the translaminar fracture behaviour of notched laminates under mixed-mode I/II in-plane loading has revealed that the dominant failure mechanisms are fibre failure and delamination [1].

At low values of G_{II}/G_{total}, the translaminar fibre-breaking fracture can be treated as a self-similar crack at the laminate level and can be quantitatively characterised in terms of fracture energy (G_{Ic}) [2] or a traction-separation law [3] which have proved useful for numerically simulating translaminar failure [4,5]. However, as the proportion of global mode II loading is increased, the failure becomes delamination dominated. This behaviour cannot be characterised with a single laminate-level material property.

This paper will present a damage model that captures this delamination dominated failure mode in a single shell element using the material elastic properties and the Mode II and III interlaminar fracture toughness alone. The results of the model will be compared to those obtained through an experimental program and to results obtained using the existing modelling capabilities within the commercial finite element code Abaqus.

2. Damage model

A material model has been developed, and implemented as a user material within Abaqus explicit, which is able to capture delamination initiated by in-plane loading using the material elastic properties and interlaminar fracture toughness alone. The model considers a sublaminate of two plies which are able to delaminate under an in-plane load. The strain energy release rate of the sublaminate is calculated as

$$G = -\frac{1}{L}\frac{\partial U}{\partial a} \tag{1}$$

where L is the sublaminate length, a is the delamination length and U is the strain energy of the system

$$U = \int_V \sigma\varepsilon \; \mathrm{d}V \tag{2}$$

For a given loading where the strain energy release rate of the sublaminate exceeds the critical strain energy release rate, G_c, delamination growth is propagated until $G = G_c$. Thus for a given loading where $G > G_c$, a critical crack length is found that satisfies equation (1) for $G = G_c$. As the crack is propagated through the sublaminate, the stiffness of the system is degraded in an appropriate value.

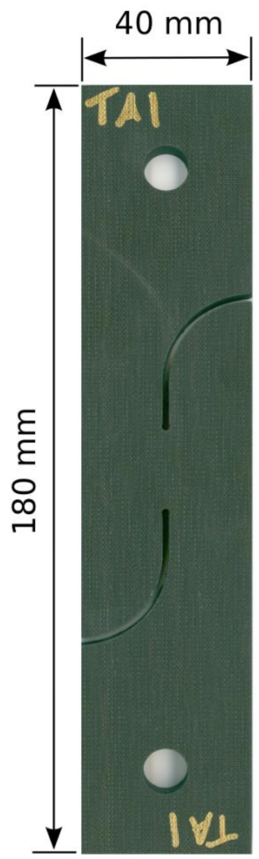

Figure 1. Pin-loaded tensile specimen used for experimental investigation.

3. Experimental program

An experimental program was carried out in order to validate the damage model described in section 2. A tensile specimen, shown in Figure 1, was designed such that the delamination failure mode observed under pure mode II loading of a cracked laminate [1] could be initiated. The material used was M21/T800 with a nominal ply thickness t = 0.18 mm and a lay-up of $(90_3/0/90_3)_4$. Six specimens were prepared using a water-jet cutter and tested under displacement control at 0.5 mm/min

The load-displacement curves of the tested specimens are shown in Figure 2. The specimen response becomes non-linear as a split propagates through the 0° plies of the laminate. The split then acts as an initiation site for mixed Mode II/III delamination. The extent of the delamination was investigated using penetrant-enhanced X-ray radiography, as shown in Figure 3.

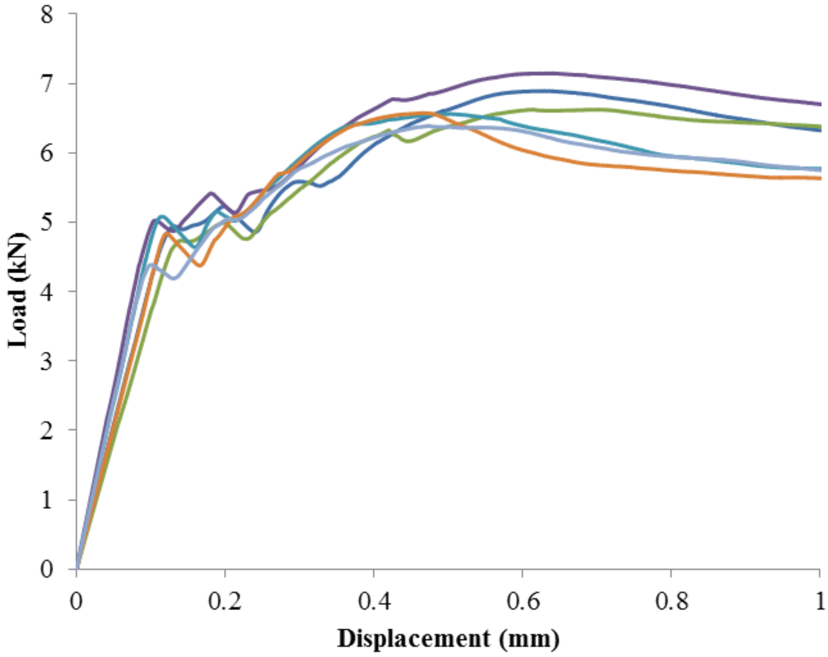

Figure 2. Load-displacement curves of tested specimens.

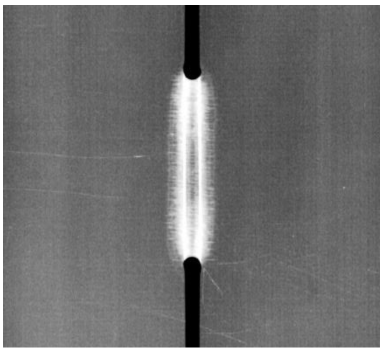

Figure 3. Delamination pattern of tested specimen obtained through penetrant enhanced X-ray radiography.

4. Numerical study

Finite element analyses of the tensile specimen shown in Figure 1 will be presented and compared to the experimental results in order to validate the model described in section 2 of this paper.

Results of the model will also be compared to those obtained using cohesive elements. It will be shown that the damage model is able to predict both the mechanical response and the delamination patterns using a single layer of shell elements, thus significantly reducing the computational cost of the analysis when compared to using cohesive elements.

References

[1] M. J. Laffan, S. T. Pinho, P. Robinson "Mixed-mode translaminar fracture of CFRP: Failure analysis and fractography". *Composite Structures*, 95: 135-141, 2013.
[2] M. J. Laffan, S. T. Pinho, P. Robinson and L. Iannucci "Measurement of the in situ ply fracture toughness associated with mode I fibre tensile failure in FRP. Part II: Size and lay-up effects". *Composites Science and Technology*, 70 (4): 614-621, 2010.
[3] R. Gutkin, M. J. Laffan, S. T. Pinho and P. Robinson "Modelling the R-curve effect and its specimen-dependence". *International Journal of Solids and Structures*, 48: 1767-1777, 2011.
[4] S. T. Pinho, L. Iannucci, P. Robinson "Physically based failure models and criteria for laminate fibre-reinforced composites with emphasis on fibre kinking. Part II: FE implementation". *Composites Part A: Applied Science and manufacturing*, 37 (5), 766-777, 2006.
[5] C. Bouvet, S. Rivallant, J. J. Barrau "Low velocity impact modelling in composite laminates capturing permanent indentation". *Composites Science and Technology*, 72 (16): 1977-1988, 2012.