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DELAMINATION CHARACTERISTICS OF GLARE LAMINATES CONTAINING DOUBLER AND SPLICE FEATURES UNDER HIGH CYCLE FATIGUE LOADING

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ABSTRACT

A modified cohesive zone model (CZM) has been developed to simulate damage initiation and evolution in Glare™ Fibre-Metal Laminate (FML) specimens containing both splice and doubler features under high-cycle fatigue loading. The model computes the cohesive stiffness degradation under mixed-mode loading based on user-defined crack growth rate data and is implemented in a VUMAT subroutine for the FEA software Abaqus/Explicit. To validate the model experimental data has been obtained for a number of Glare 4B specimens containing splice and doubler features monitored using digital image correlation (DIC) to provide full-field displacement and strain data and Acoustic Emission (AE) monitoring to detect damage initiation and propagation. The model was used to predict the initiation and growth of damage in splice joints under quasi-static loading. The results were verified against the cohesive zone model available in Abaqus and then validated against experimental data on Glare specimens. The codes are currently being extended to incorporate a mixed-mode fatigue damage evolution model based on input Paris laws, which have been extracted from high cycle fatigue experiments on Glare specimens containing both splice and doubler joints.

Keywords: *Fibre Metal Laminates, Fatigue, Cohesive Zone Model, DIC, AE*

1. Introduction

FMLs including Glare are manufactured from alternating metallic sheets bonded with fibre reinforced composite layers. Where large panels are required joints including splices (where metallic sheets are positioned side by side with a gap in between, with the gaps staggered to prevent loss of strength and the fibre layers providing load transfer) and doublers (additional external or internal layers introduced to reduce stresses) are used. One of the most common failure modes for FML structures is delamination in these joints [1]. Delamination in fibre composites has been modelled by researchers using a number of different approaches. These include the cohesive zone model (CZM) which incorporates both continuum damage and fracture mechanics concepts [2] and which has been used to model delamination initiation and propagation under high cycle fatigue [3-7]. This paper describes work done to extend this application to FMLs.

2. Experimental work

Fatigue tests were conducted on a series of Glare specimens containing splice and doubler features. Specimens had dimensions 153 mm × 13.5 mm and were manufactured from GLARE 4B which consists of 2024-T3 aluminium alloy sheets 0.4 mm thick and UD-S2 glass fibre reinforced epoxy (GFRP) layers each having 3 plies with the layup [$90^o/0^o/90^o$] and a cured ply thickness of 0.125 mm (Figure 1). They were tested in an MTS servo-Hydraulic (50 kN) machine using the setup shown in Figure 2 with a constant load ratio (trough/peak) of R= 0.1 and a frequency 5 Hz.

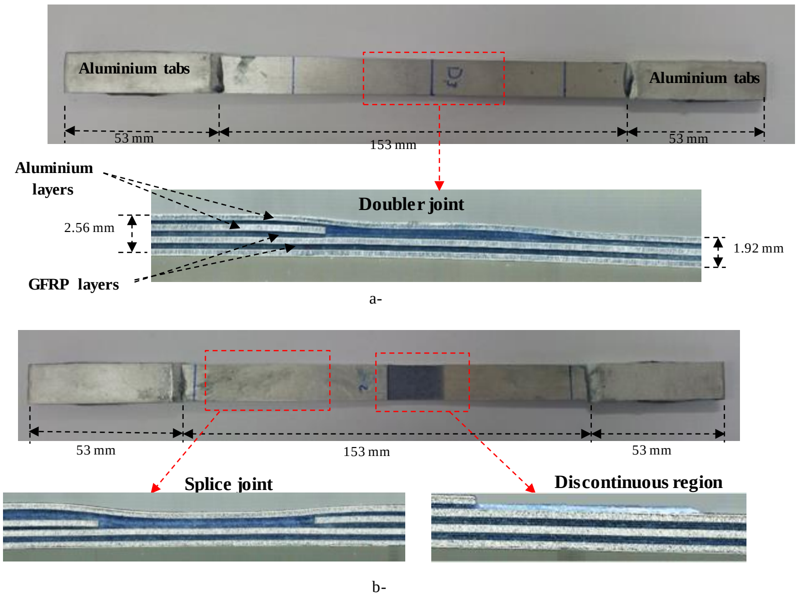

Figure 1. Specimen design for a) doubler b) splice

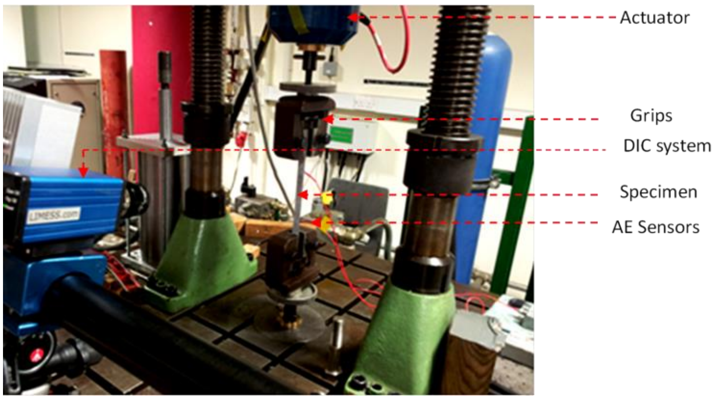

Figure 2. Experimental fatigue test setup

3. FE model

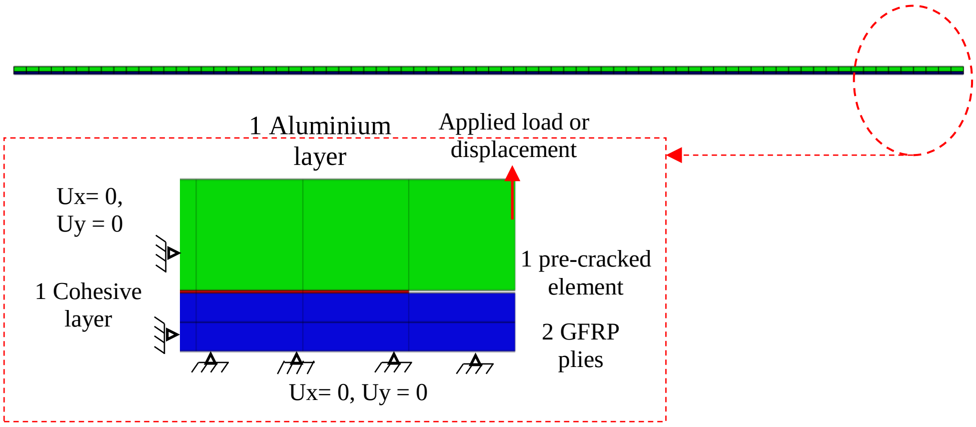

Figure 3. Simplified model

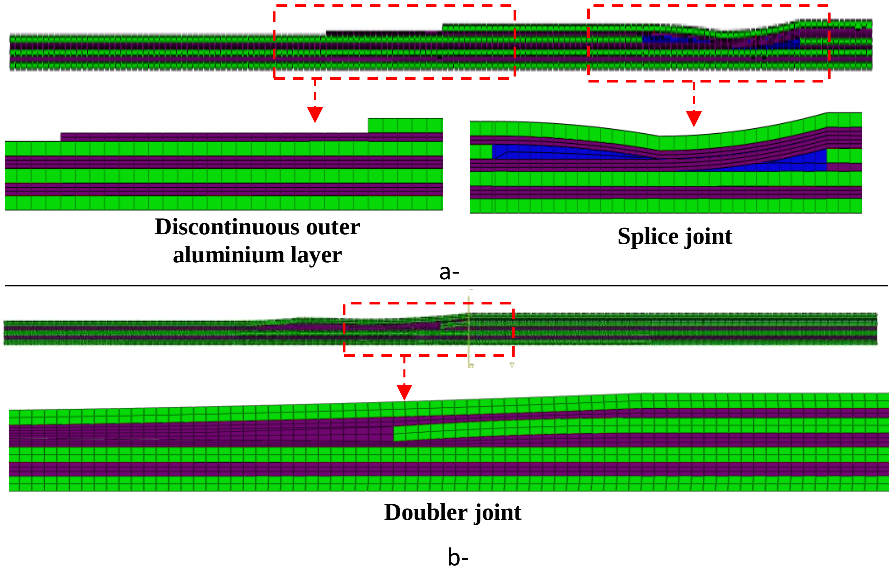

Figure4. 2D mesh for Glare4B specimens a) Splice b) Doubler

Two types of model were created to analyse the delamination behaviour of the joints. Initially a simplified model was generated as shown in Figure 3 in order to validate the cohesive zone approach for static loading. Following this a more accurate model of the specimens was created to explore the effect of fatigue loading. This involved extracting the geometry and thickness of each layer from scans of the actual specimens, as shown in Figure 4, and then meshing them using linear continuum elements (CPS4R). The interfaces were then meshed using two dimensional cohesive elements (COH2D4). In both cases a mixed mode cohesive zone model (CZM) (Figure 5) was assumed using a quadratic nominal stress criterion for damage initiation (equation 1) and a power law failure criterion (equation 2) for damage evolution. Strain energy release rates G_I and G_{II} where calculated using equations 3 and 4 and the power law parameter ϕ was determined by the best fit to mixed-mode delamination data from the literature [8]. Finally the model was implemented in the FEA software Abaqus/Explicit using a VUMAT subroutine.

$$\left(\frac{\sigma_I}{\sigma_{Ic}}\right)^2 + \left(\frac{\sigma_{II}}{\sigma_{IIc}}\right)^2 = 1 \qquad \ldots (1)$$

$$\left(\frac{G_I}{G_{Ic}}\right)^{\phi} + \left(\frac{G_{II}}{G_{IIc}}\right)^{\phi} = 1 \qquad \ldots (2)$$

$$G_I = \int_0^u \sigma_I \; du_I \qquad \ldots (3)$$

$$G_{II} = \int_0^u \sigma_{II} \; du_{II} \qquad \ldots (4)$$

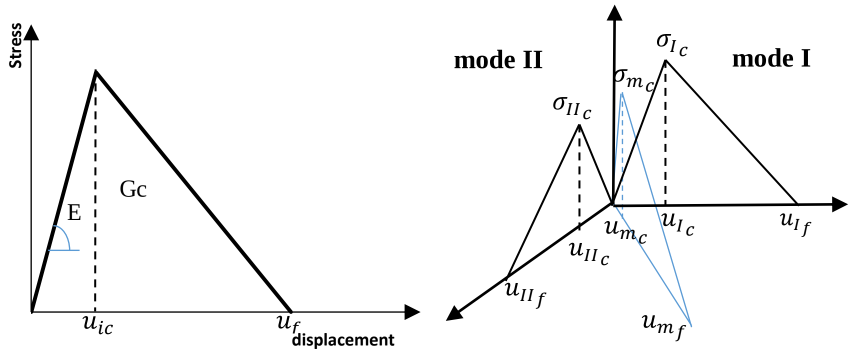

Figure5. Mixed mode cohesive law

The simplified model was loaded statically as shown in Figure 3. Fatigue loading on the other hand can be represented by a constant amplitude load equal to the maximum load level in the actual fatigue cycle. Only the envelopes of loads and displacements are then analysed following a 'cycle-jump' strategy [3-7] .As shown in Figure 6, the force applied to the model is increased gradually from zero to the peak load (F_{max}), and a fatigue degradation law is then activated to model fatigue crack growth and the corresponding reduction in overall stiffness and increase in axial displacement. Future results of fatigue tests will use this approach to calculate crack growth rate using a normalised Paris law:

$$\frac{da}{dN} = C\left(\frac{\Delta G}{G_c}\right)^m \qquad \ldots (5)$$

Where *da/dN* is the crack growth rate (increment in crack area with increasing number of cycles) and *C* and *m* are best fit coefficients to experimental data in a log-log plot.

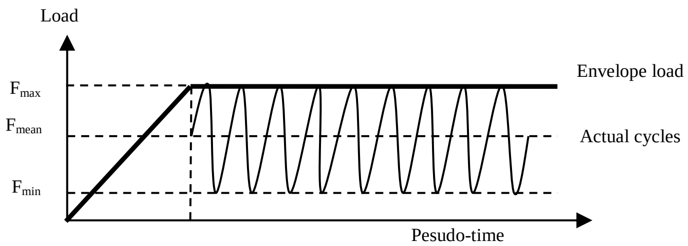

Figure 6. Schematic of fatigue modelling envelope load

4. Results and conclusions

The experimental results illustrated in Figure 7 show that the fatigue life for the doubler specimens was higher than for the splice specimens, as the doubler joint exhibited high fatigue damage tolerance compared with the splice joint. The results also showed that delamination onset and growth occured in the external discontinuous Aluminium/ GFRP interface for the splice specimens, while the doubler specimens did not show any delamination. The FE results for the simplified model in Figure 8 show good correlation with the ABAQUS cohesive zone model as expected. Although there is a small difference in simulation time (pseudo-time) for damage initiation, the damage evolution parameter is identical and the small differences are attributed to small oscillations in stresses in the VUMAT subroutine which is currently free of any viscous regularisation or damping. Ongoing work focuses on adding a Paris law-based fatigue damage evolution rule as described above.

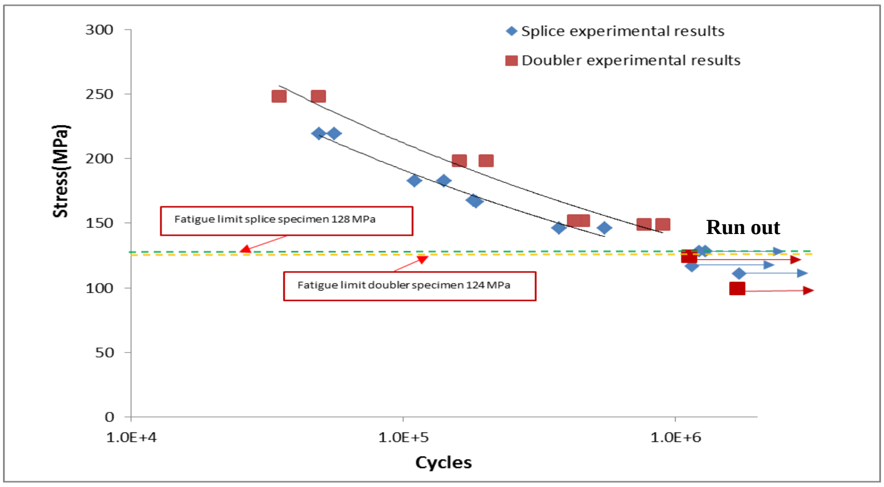

Figure 7. S-N curve comparison for doubler and splice specimens

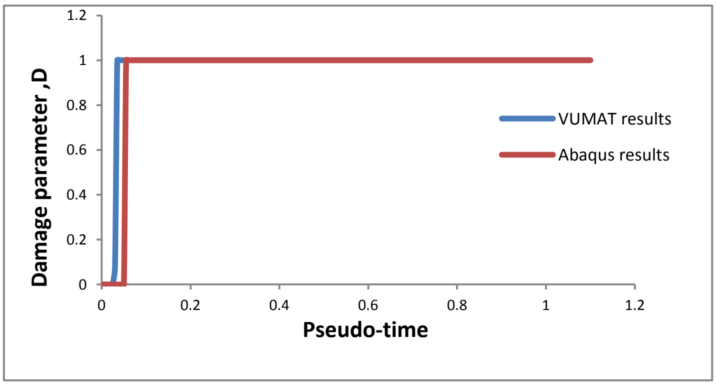

Figure 8. Comparison of evolution of static damage parameters

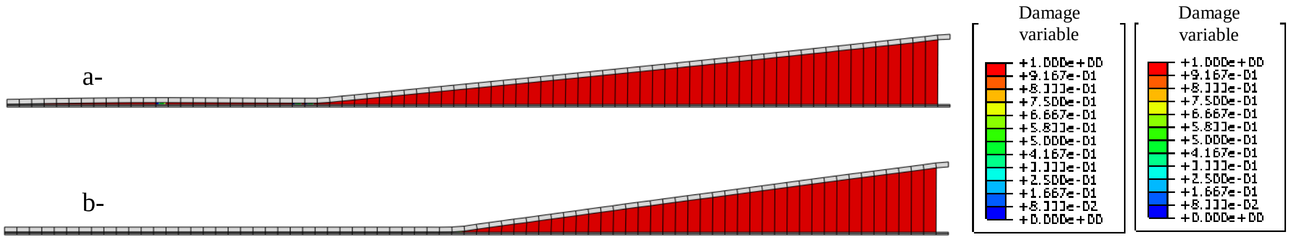

Figure 9. Comparison of evolution of static damage parameters, a- VUMAT results, b- Abaqus results

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