MODELLING FATIGUE DAMAGE IN FIBRE METAL LAMINATE ADHESIVE JOINTS

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ABSTRACT

This study concentrates on the development of a constitutive damage model for use at the interfaces of metals and fibre composites under high-cycle fatigue loading. The model is implemented through a user-defined VUMAT subroutine in the Abaqus/Explicit software. This subroutine is based on a novel cohesive zone model using a trapezoidal traction-separation law which enables the definition of cohesive interfacial properties representative of those observed for Glare® fibre-metal laminates (FMLs). By considering elastic-plastic damage behaviour, this model provides more accurate results for the simulation of toughened epoxy matrices than the commonly used bilinear cohesive zone model. The FE model is verified against experimental data taken from Glare® specimens under high-cycle fatigue loading. It is shown that the fatigue model – which is based on a modified Paris law – is in good agreement with experimental results in terms of the fatigue crack growth observed in FMLs in the presence of such internal features.

1 INTRODUCTION

Due to the limitations on the sizes of the metal sheets needed to manufacture FMLs, large structures need to include adhesive joints. The most common joints used are the so-called 'splices' and 'doublers'. In order to obtain wider panels aluminium sheets are positioned side by side with a gap in between. The gaps are staggered through the thickness to prevent loss of strength with the fibre layers providing load transfer. This is known as splicing. Splices can be strengthened by adding additional layers (doublers) externally or internally to reduce stresses [1]. The most critical failure mode for FML structures is delamination in these joints [1]. Delamination in laminate interfaces has been analysed in the literature 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]. In most cases however, the material behaviour away from the damaged interface has been considered to be elastic. This study extends this to include an elastic-plastic damage model to simulate the ductile damage which occurs in splice and doubler joints found in FML structures.

2 FATIGUE DAMAGE MODEL

In order to predict the tensile behaviour of splice and doubler joints under high- cycle fatigue loading, two-dimensional FE models were created. This involved extracting the geometry and thickness of each layer from detailed scans of the actual specimens, as shown in Figure 1, and meshing them using linear continuum elements (CPS4R), Figure 2, before meshing the interfaces using two-dimensional cohesive

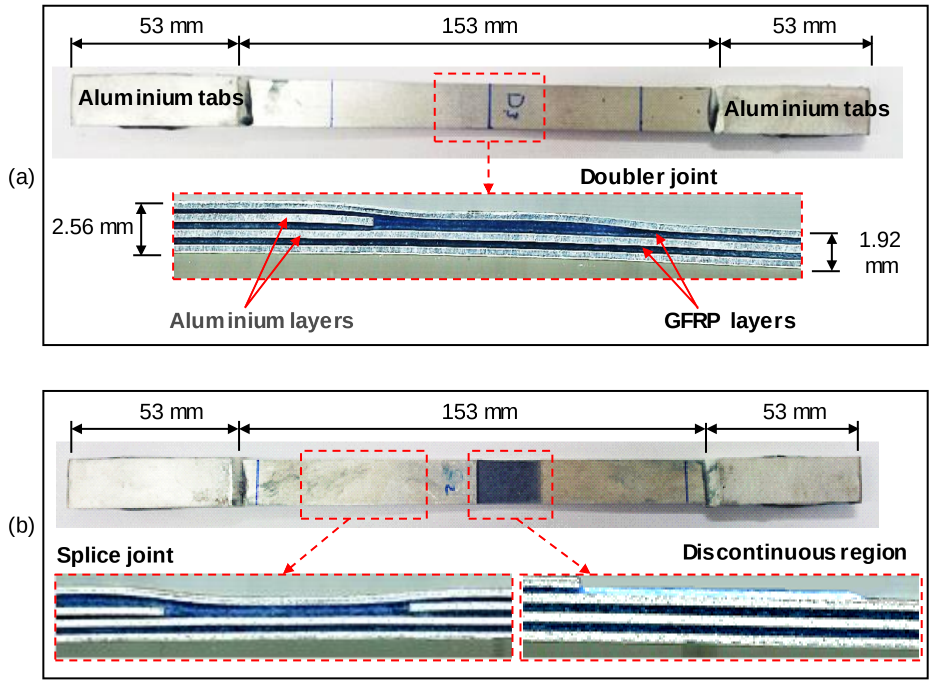

Figure 1: Specimen design for (a) doubler and (b) splice joints.

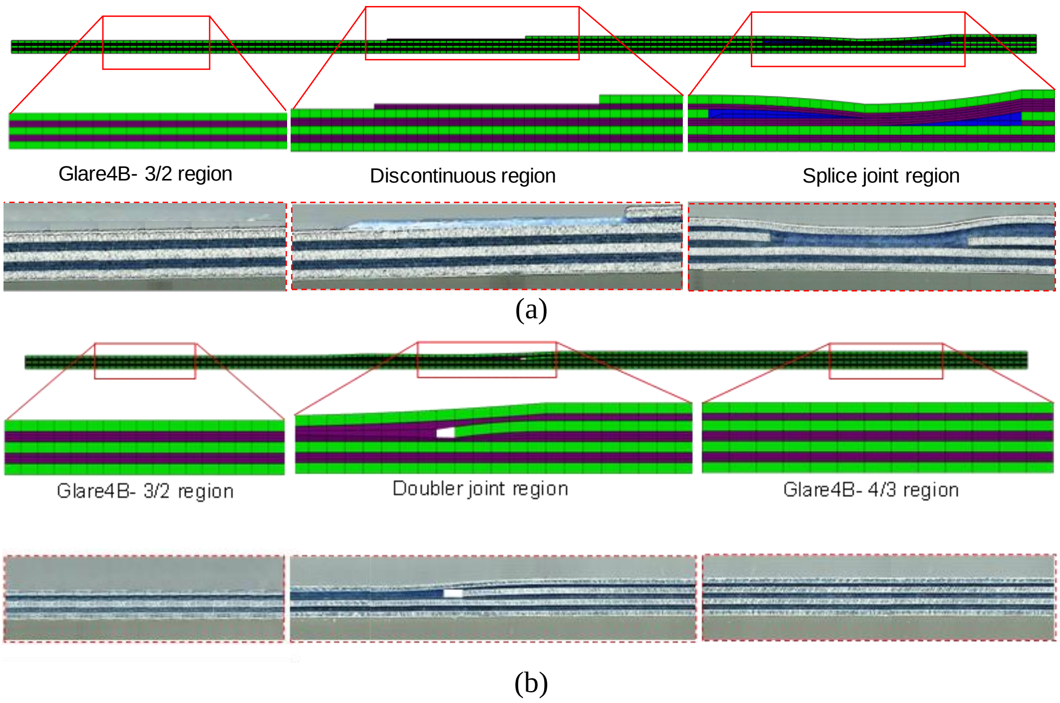

Figure 2: Finite element mesh of the Glare specimen (top) based on optical scans of real specimens (bottom), (a) splice, (b) doubler.

elements (COH2D4). A two-stage was approach was then implemented to model the fatigue behaviour. First a static damage model, using a mixed mode cohesive zone model (CZM) (Figure 3) based on a quadratic nominal stress criterion for damage initiation and a power law failure criterion for damage evolution was used to calculate the static damage variable. Then a fatigue analysis was developed based on the static damage model but incorporating cyclic degradation using a fatigue damage degradation law to determine the fatigue damage variable.
Finally the two were combined following a load envelope approach to determine the total damage variable and hence the fatigue damage evolution. This model was then implemented in the FEA software Abaqus/Explicit using a VUMAT subroutine.

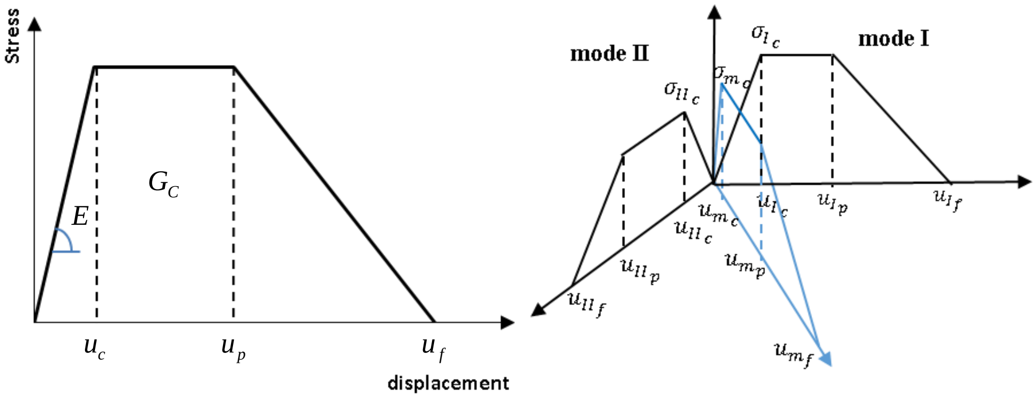

Figure 3: Mixed mode cohesive law.

Fatigue loading was represented by a constant amplitude load equal to the maximum load level in the actual fatigue cycle. Only the envelopes of the loads and displacements are then analysed following a 'cycle-jump' strategy [3-7]. As shown in Figure 4, 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.

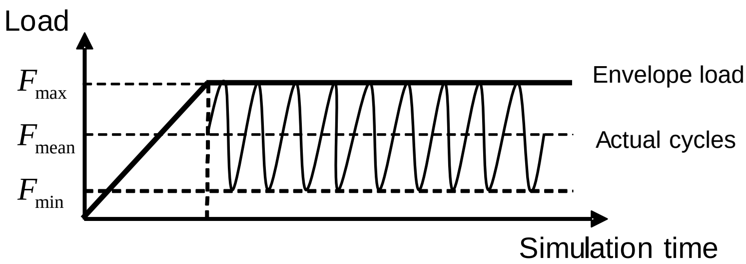

Figure 4: Schematic of fatigue modelling envelope load.

The fatigue damage approach adopted to calculate crack growth rate in this model is a normalised Paris law according to [8, 9] as follows:

$$\frac{da}{dN} = C\left(\frac{\Delta G}{G_c}\right)^m \tag{1}$$

Where da/dN is the crack growth rate (the 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 for crack length a versus number of cycles N. The total critical strain energy G_c is a material property for the interface cohesive layer which represents the area under the curve of the trapezoidal traction–separation relation for pure mode II. The change in mode II strain energy can be calculated as in [8, 9] as follows;

$$\Delta G = (1 - R^2)\, G_{\max} \tag{2}$$

where, R is the load ratio (minimum fatigue load divided by maximum fatigue load) which is 0.1 in this study and $G_{\max}$ is the maximum strain energy in mode II. The fatigue damage variable D_f is calculated based on effective element length ($L_{I.P}$) which is the length associated with a single cohesive integration point in the direction of crack propagation. The delamination will propagate with a distance $L_{I.P}$ after a certain number of cycles to failure N_f with a constant crack growth rate $\frac{da}{dN}$ which is calculated using the Paris law given in Equation 1 based on both pure mode II strain energy release rate ratio and experimental fatigue parameters as follows;

$$N_f = L_{I.P} \times {}^{1}\!\Big/\!{\frac{da}{dN}} \tag{3}$$

$$t_f = {}^{N_f}\!/_{\omega} \tag{4}$$

$$D_{\text{rate}} = {}^{\Delta t}\!/_{t_f} \tag{5}$$

$$D_f = D_f + D_{\text{rate}} \tag{6}$$

where t_f is the failure time for each element in the direction of crack propagation, ω is the user-defined loading frequency and D_{rate} is the calculated fatigue damage after every time step (Δt) in the explicit analysis. Finally the total damage variable (D_t) can be calculated from the summation of the static damage variable (D_s) and the fatigue damage variable (D_f) as follows:

$$D_t = D_s + D_f \tag{7}$$

3 RESULTS AND CONCLUSIONS

Results show delamination growth in the splice model under high cycle fatigue loading in the discontinuous region (Figure 2) at the aluminium/GFRP interface. Figure 5 shows fatigue damage variable contours at the outer aluminium/GFRP interface for a series of cohesive elements in the splice specimen model. The fatigue damage variable takes values between zero for undamaged elements and one for fully damaged elements. Contours start from zero in the elastic region corresponding to undamaged cohesive elements (blue). As the load is increased delamination propagates in the constant-stress region of the trapezoidal traction-separation law (green - partly damaged interface elements). This is followed by fatigue degradation in a number of the cohesive elements in the softening –region (red – damage variable one). Finally the delamination grows across all the cohesive elements. Good correlation was observed between the predicted FE results and those obtained experimentally by Alderliesten [10]. Ongoing work includes implementing this fatigue model in the pre-cracked doubler specimen model.

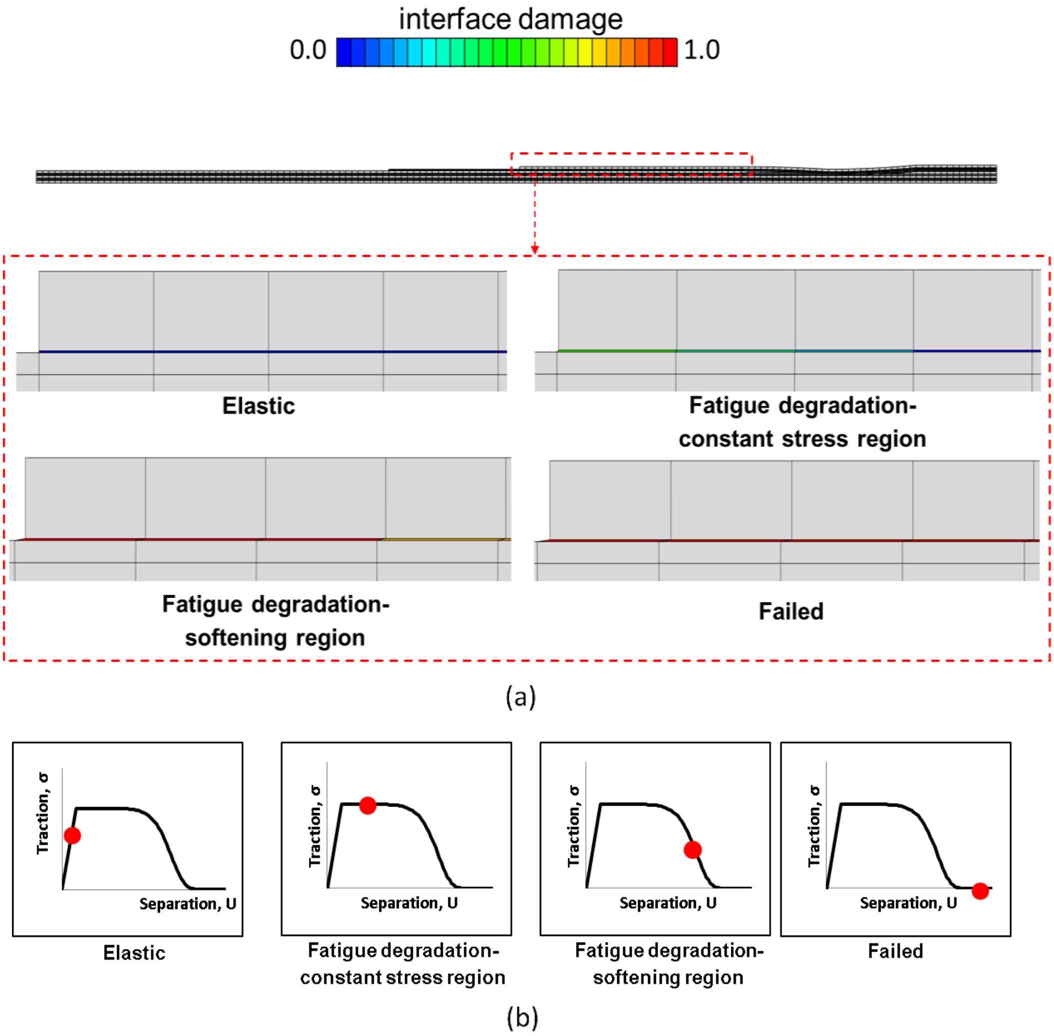

Figure 5: (a) Fatigue damage variable (SDV) contour plots for cohesive elements in the splice specimen at 50% severity. (b) Traction-separation curves for fatigue damage degradation (red circles refer to the progression of damage).

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