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Predicting the effects of geometry on the behaviour of fibre metal laminate joints

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ABSTRACT

The effects of geometry on the bearing response of fibre metal laminate (FML) joints are numerically investigated. Specimens designed to fail in bearing, net-tension and shear-out are analysed using a continuum damage mechanics approach. Plasticity in the aluminium layers, fibre and matrix damage in the composite plies and, importantly, delamination between the plies of the laminate are accounted for. The effects of mesh sensitivity, associated with strain-softening material models, are mitigated using a non-local averaging scheme. Results are compared to experimental bearing stress–strain and bearing stiffness–strain responses, and surface strain measurements. Variations in the development of damage for the different joints are investigated, and the effect of damage on the joint responses is discussed. Very good agreement was achieved for the specimens of interest, without varying the model parameters for the different joint configurations, which highlighted the suitability of the model for FML structural analysis. The combined numerical and experimental information provide an in-depth understanding of the failure sequences of FML joints.

1. Introduction

Fibre metal laminates (FMLs) are a family of advanced composite materials demonstrating a number of favourable characteristics (including high residual and blunt-notch strengths, excellent fatigue performance and low density [1]), which makes them suitable for structural applications in the aerospace industry. FMLs consist of alternating layers of metal and fibre-reinforced plastic. The number and orientation of the prepreg layers can be varied to best suit different applications and a number of variants are commercially available. The development of FMLs is well documented by the works of Vlot et al. [1] and Gunnink et al. [2].

This paper focuses on the behaviour of FMLs in jointed configurations. Such an investigation is warranted since bolted and riveted joints represent potential weak points in a structure. Therefore, understanding their behaviour is critical for safe and efficient structural design.

The accumulation of damage in the fibre-reinforced plastic layers of the FML is fairly well understood (see for example [3–5]). However, the introduction of metallic layers to form a FML significantly increases the complexity of damage progression due to the large mismatch in mechanical properties between the different layers. This problem is compounded under complex loading conditions, such as those present in jointed configurations.

Numerical techniques, such as the finite element method, can be used to effectively examine complex structures and provide detailed information throughout the entire loading history, which may be difficult or prohibitively challenging to obtain with experimental techniques. However, experimental results are crucial for the calibration and validation of numerical models and, therefore, a combined numerical and experimental approach is appropriate for investigating the damaging behaviour of FML structures, and has been applied in the present work.

Finite element studies of FMLs have been conducted on both notched [6,7] and unnotched FMLs [8], along with pin and bolt bearing configurations [9] and riveted joints [10]. Both damaging and linear elastic material properties have been used for modelling the composite layers of FMLs. The pin-bearing investigation of van Rooijen [9] concentrated mainly on the delamination behaviour of FMLs and incorporated only a basic description of in-plane damage in the composite layers. Lapczyk and Hurtado [7] described a model, which used Hashin's [11] failure criteria to account for a number of in-plane damage modes in the composite layer. Hardening plasticity was modelled in the aluminium and delamination between the various layers was captured by interface elements. However, very limited validation was performed.

This paper examines the effectiveness of a finite element damage model in predicting the effects of geometry on the behaviour of various FML joints. The model incorporates a three-dimensional damage model, cohesive elements and a nonlocal damage regularisation scheme. Three distinct failure modes, bearing, shear-out and net-tension, are investigated. The work aims to complement

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our own previously reported experimental results investigating the damage initiation and growth in FML joints [12]. Detailed comparisons between numerical and experimental results are presented to thoroughly evaluate the model.

2. Overview of experimental programme

The material chosen for this study was GLARE® 3 3/2 0.4 L glass-fibre based FML, which was purchased from a commercial materials supplier. The lay-up was [AL/0/90/AL/90/0/AL] (where AL represents an aluminium layer and 0 and 90 refer to the orientation of the composite layers with respect to the loading direction). The nominal laminate thickness was 1.7 mm (aluminium layers: 0.4 mm thick, each composite layer: approximately 0.125 mm thick).

The specimen geometry and loading are shown in Fig. 1a, while a schematic of the experimental set-up is shown in Fig. 1b. The pin-bearing test set-up, used here, is generally considered to represent a worst case scenario for in-service conditions since out-of-plane deformation is unconstrained leading to lower joint strengths. A 6 mm neat-fit hardened steel pin was inserted into the hole and then loaded under displacement control via a specially designed testing frame. The deflection of the pin was measured using displacement gauges. The displacement gauges were placed in contact with the top of the pin, close to the laminate (as shown in Fig. 1b), allowing the upward motion of the pin to be measured. The small "up-arrow", next to the displacement gauge arm in Fig. 1b, indicates the motion of the pin, which was recorded during testing.

A parametric study was carried out in which edge distance to hole diameter (e/d) and width to hole diameter (w/d) ratios were varied, and corresponding failure modes and loads were identified. The failure modes of interest were bearing, shear-out and net-tension, as illustrated in Fig. 1c. The specimen dimensions were: (i) bearing $w/d = 6$, $e/d = 6$, (ii) shear-out $w/d = 6$, $e/d = 1.3$ and (iii) net-tension $w/d = 2$, $e/d = 6$. Each specimen had a length of $L = 135$ mm, 50 mm of which was held by the machine clamp. Three tests to failure were carried out and showed excellent repeatability. Full bearing stress-bearing strain curves were recorded and a microscopy study was undertaken on specimens loaded to ultimate failure and to percentages of their ultimate failure load (Fig. 1d shows the planes of interest in the microscopy study). A complete description of the experimental results is contained in previously published work [12].

3. Composite damage model description

The meso-scale continuum damage mechanics (CDM) model described below predicts micro-scale damage in the matrix material (such as micro-cracking and void nucleation), which causes stiffness reductions at low load levels, as well as catastrophic damage associated with fibre failure. Internal state variables are introduced to account for different damage modes and these degrade the elastic properties, thus simulating the effect of damage. This is described by the total stress–strain relationship in Eq. (1):

$$\sigma = D^s(d_i) : \varepsilon \tag{1}$$

where D^s is the secant stiffness tensor and can depend on a number of damage variables, d_i. These damage variables do not decrease thus ensuring material "healing" is always avoided.

The damage model in this paper is similar to the model described by Ladevèze and Le Dantec [13]. The starting point for the model in Ref. [13] was a plane-stress version of the material's damaged strain energy, whereas a three-dimensional version is used here. This ensures the stress components contributing to damage evolution take into account contributions from the thickness direction. For the present model, the material's damaged strain energy is defined as:

$$\begin{aligned} E_D = \frac{1}{2}\Bigg[& \left(\frac{\sigma_{11}^2}{E_{11}^0(1-d_1)}\right) + \left(\frac{\sigma_{22}^2}{E_{22}^0(1-d_2)}\right) + \left(\frac{\sigma_{33}^2}{E_{33}^0}\right) - 2\left(\frac{\sigma_{11}\sigma_{22}\nu_{12}}{E_{11}^0}\right) \\ & - 2\left(\frac{\sigma_{11}\sigma_{33}\nu_{13}}{E_1 1^0}\right) - 2\left(\frac{\sigma_{22}\sigma_{33}\nu_{23}}{E_{22}^0}\right) + \left(\frac{\tau_{12}^2}{G_{12}^0(1-d_{12})}\right) \\ & + \left(\frac{\tau_{13}^2}{G_{13}^0}\right) + \left(\frac{\tau_{23}^2}{G_{23}^0}\right)\Bigg] \end{aligned} \tag{2}$$

where E^0, G^0 and ν are the ply elastic properties, and d_1, d_2 and d_{12} are the scalar damage variables in the fibre, transverse tension and shear directions, respectively. Note that damage in the fibre

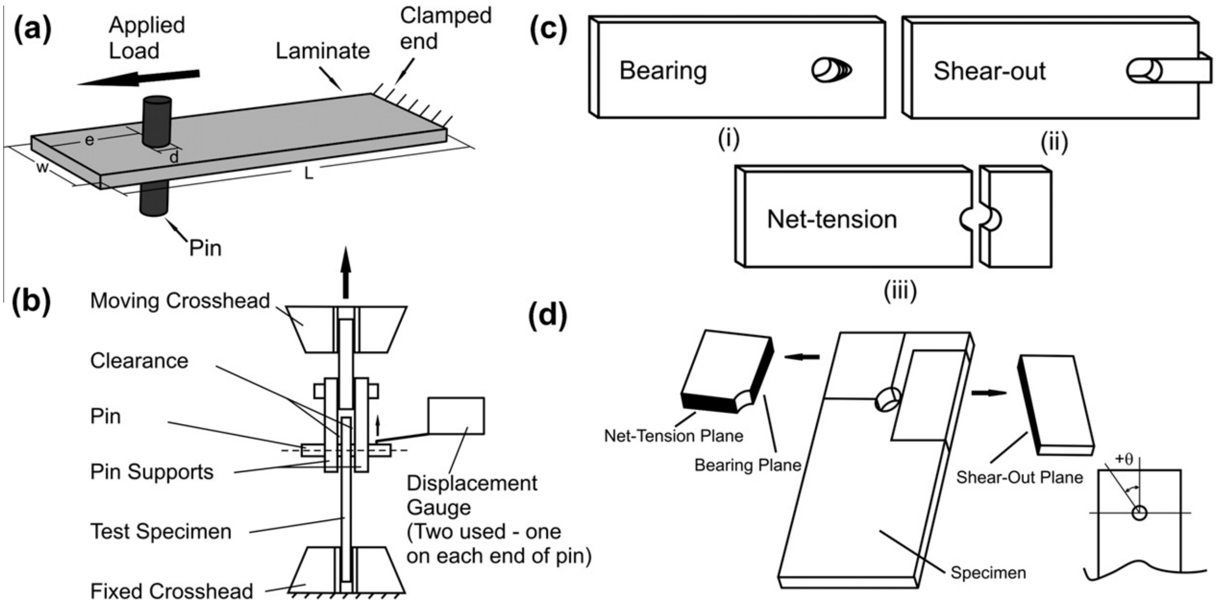

Fig. 1. (a) Pin-bearing test configuration and typical joint geometry. (b) Schematic showing salient features of the experimental set-up. (c) Schematic of failure modes. (d) Definition of planes of interest and circumferential coordinate, θ.