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Predicting the strength of adhesively bonded joints of variable thickness using a cohesive element approach

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ABSTRACT

One major characteristic of bonded structures is the highly localised nature of deformation near sharp corners, ply-terminations, and ends of joints where load transfer occurs. This paper presents an investigation of the use of a cohesive zone model in predicting the strong effects of stress concentration due to varying adherend thickness on the pull-off strength measured by the Pneumatic Adhesion Tensile Testing Instrument. A comparison is made with the point-strain-at-a-distance criterion, where the plastic deformation of the adhesive is analysed using a modified Drücker–Prager/cap plasticity material model. The fracture properties of the cohesive zone model were determined using double-cantilever and end-notch flexural specimens, and the cohesive strengths were measured using tensile and lap shear tests. Comparisons with experimental results reveal that the cohesive zone model with perfectly plastic (or non-strain-softening) cohesive law provides accurate predictions of joint strengths.

1. Introduction

Adhesively bonded structures and joints are increasingly employed in engineering constructions ranging from aerospace, automotive and civil structures, replacing or minimising mechanical fasteners. One major challenge facing the design of adhesively bonded joints to avoid static or fatigue failure is the lack of a strength predictor or a universal failure criterion [1]. Contributing factors to this difficulty include the complex failure modes involving adhesive and adherends, and the high strain gradient near the edge of joints, where most of the load transfer between adherends occurs. For joints between metallic adherends, the two major modes of failure include cohesive failure in the adhesive or adhesion failure at the interface [2]. In the case of composite joints, however, failure can occur in the composite adherends [3,4] in the form of interlaminar failure. Of the various factors complicating the accurate prediction of the failures in bonded joints, the high deformation gradient near stress concentrations, including sharp corners [5], ply terminations in scarf joints [6], and ends of overlap [1], gives rise to intense strain localisation or even singularities [5]. As a result, it is often necessary to evaluate the point stress (strain) or average stress (or strain) over a characteristic distance [7], which must be calibrated against experimental results of representative joints. The failure load of a joint is found when these stress or strain values reach the material strength or strain-to-failure [8].

Recently the authors have found that when applying the point-strain-at-a-distance criterion it is vital to account for the effect of hydrostatic stress on the plastic deformation of structural adhesives in order to correctly predict the strength of adhesively bonded joints of varying thicknesses [9]. It was observed experimentally that as the substructure thickness decreased, the pull-off strength measured by the Pneumatic Adhesion Tensile Testing Instrument (PATTI), as illustrated in Fig. 1, decreased accordingly, due to the rise in strain concentration associated with the flexible substrate. A model of the PATTI test configuration was developed to verify the influence of the thickness on the bond strength measurements. When the adhesive was modelled using the von Mises yield criterion, the predicted strengths were significantly lower than the experimental results from portable pull-off tests, by a factor of two to three. However, by employing the modified Drücker–Prager/cap plasticity criterion [9,10] to model the plastic deformation behaviour of the adhesive, very good correlation between predictions and experimental results was observed [9].

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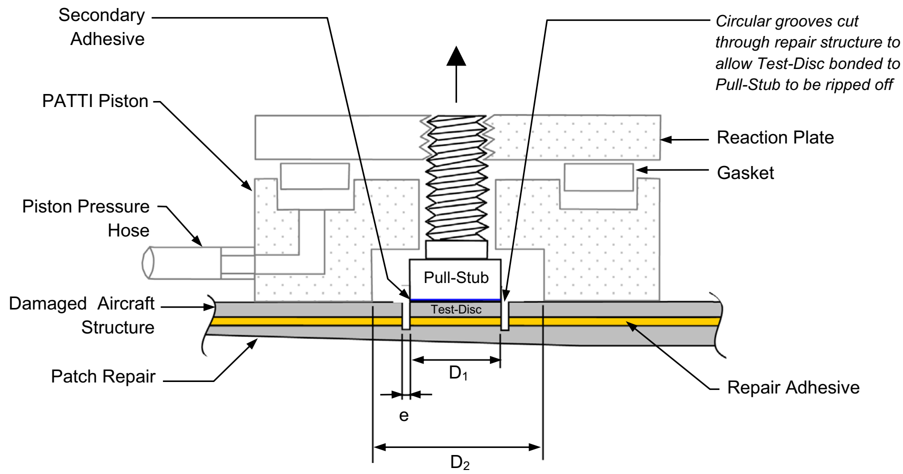

Fig. 1. PATTI test configuration to obtain the residual flatwise tensile strength of bonded repairs on retired aircraft structures.

In both modelling approaches, the characteristic distance was calibrated against experimental data from tensile butt joints. Although the modified Drücker–Prager/cap plasticity material captures the behaviour of the FM300 film adhesive well, it requires the calibration of a characteristic length, selection of failure criterion and the generation of the Drücker–Prager yield surface. Comparing to the von Mises yield criterion, the Drücker–Prager/cap plasticity model requires the determination of an additional five material properties [9] from experiments involving different geometries. So the improvement in prediction accuracy comes at the price of increased cost of model identification.

Cohesive zone models (CZM) have been recognised as a promising technique for simulating the onset and progression of damage in adhesively bonded joints [8]. Campilho et al. [11] recently demonstrated the potential of CZM in predicting the strength of single-lap adhesive joints, and concluded that a trapezoidal shaped cohesive law provides best fit with experimental data. Since the material properties required by the cohesive models, such as the fracture toughness and strength, are more widely available than the parameters needed by the Drücker–Prager/cap plasticity model, the CZM approach is a very appealing technique for adhesively bonded joints. Unlike the cap plasticity material model, which uses the maximum strain at a characteristic distance to predict the fracture load, the cohesive element approach predicts the stress–displacement response of the material where the maximum stress at damage initiation represents the fracture strength, followed by the damage evolution that represents the "*stress-softening*" of the material due to the accumulation of microscopic defects. The aim of this paper is to evaluate the performance of a cohesive element-based computational model in predicting the PATTI pull-off strengths. The effect of the shape of the cohesive law on the pull-off test strength prediction will also be investigated.

2. Experimental work

2.1. PATTI tests

To quantify the effects of panel thickness and tapering on the bond strength measured using the PATTI, two panels of 3 mm thick 7075 T6 aluminium alloy were bonded with Cytec FM300 film adhesive. This is the same adhesive used in bonding doubler repairs on the F-111 aircraft [12]. The edge of one panel was milled to form a 3° taper, simulating the taper typically employed in repairs. The surface preparation method used on the bonding surfaces was described in earlier work [9] and has been shown [13] to produce a comparable strength and cohesive fracture mode to those prepared by the standard grit-blast silane treatment method under dry conditions. The FM300 film adhesive was staged at 80 °C for 20 min prior to bonding [14] at 177 °C for 90 min.

Individual discs required for the PATTI test were created by boring circular grooves through the non-tapered adherend and the adhesive layer, as shown in Fig. 2. The inner diameter, D_1, and the width, e, of the groove were 12.7 mm and 2.0 mm respectively. The test discs were cut at four different positions along the tapered and uniform thickness regions to emulate PATTI tests on structures of different thicknesses. With a very small tapering angle (3°), the substrate thickness increases slightly with the distance from the edge, as indicated in Fig. 2b, changing from *"thin"* to *"thick"*. The substrate thickness for tapered discs was identified according to the thinnest region. Specimens were cut at locations with thicknesses of 0.7 mm, 1.3 mm and 1.7 mm. Constant thickness discs were also cut with a thickness of 3.0 mm. Stubs were then bonded onto the newly bored circular discs with Hysol®EA9309.3NA epoxy paste adhesive and cured at room temperature for 72 h.

PATTI tests were conducted at the rate of approximately 6.9 MPa/s (1 psi/s). The maximum pressure, P_B, supplied into the gasket prior to the detachment of the test-disc (along with the stub) from the bonded panel was recorded. This pressure was converted to the tensile pull-off strength of the stub, σ_{PATTI} through following equation:

$$\sigma_{PATTI} = \frac{P_B A_G - C}{A_{TS}} \quad (1)$$

where A_g is the contact area between the gasket and the piston, A_{TS} represents the area of the test-disc, and C=3.11 N is a constant related to the piston in the PATTI tester and is provided by the manufacturer of the test equipment.

2.2. Double cantilever beam test

The use of cohesive elements requires as input the fracture strength and fracture energy of the adhesive in both modes I and II. The two fracture strengths were previously measured by tensile butt joints and single lap shear joints [9] and are summarised in Table 1. These values are the local strengths of the adhesive of a thin layer, which is affected by the constraint imparted by the stiff adherends. Although both test configurations involved mixed-mode loading, the mode-mix ratios were very small and hence neglected. The critical fracture energy for mode I was measured