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Theoretical and experimental research into optimal edge taper of bonded repair patches subject to fatigue loadings

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Abstract

Finite element (FE) analyses were conducted for double lap, metal-to-metal bonded repair joints with different linear edge taper angles, or optimal taper profiles using the shape optimisation approach. Various adhesive failure criteria were applied and compared. A fracture mechanics approach was also applied in the FE analyses, in which an initial crack was pre-set at the edge of the adhesive bond line. The energy release rates were calculated and the results were used to evaluate the fatigue resistance. FE results predicted that the taper angle should strongly affect the fatigue performance of the repair patch. Compared with the 90° taper case, the peak stresses in the 6° taper case reduced by around 60%, and the stresses in the 3° taper case reduced by around 80%. The optimum design was able to reduce the peak stresses by about 50% compared with the widely used 6° linear taper (i.e. 1:10) with the same taper length. Thus, it appeared to be the best in terms of the fatigue resistance vs. taper region length. The calculated energy release rates also indicated a similar trend for the fatigue resistance as a function of the edge taper configuration. Experimental results agreed well with the numerical predictions. In particular, the predicted crack initiation loads, based on estimated threshold value of mode 1 energy release rate, correlate well with experimental results and the high fatigue resistance of the optimal design was confirmed.

Keywords: Finite element stress analysis; Fracture mechanics; Lap-shear; Fatigue; Repair

1. Introduction

Composite or metal patches bonded with structural film adhesives have been widely employed to repair cracked aircraft components in military and civilian aircraft. Peak peel and shear stresses normally occur at the edges of the patches under structural loading. Tapering the patch edges can reduce the peak stresses and thus improve static and fatigue strengths of the repairs.

Fig. 1 shows a schematic of a bonded repair to a cracked plate for which Baker [1] proposed that two distinctly different regions exist in terms of structural integrity requirement. The central damage-tolerant region is the zone where a significant disbond between the patch and plate can be tolerated. This is because small disbonds reduce the repair effectiveness only slightly and disbond growth under repeated loading is slow and stable. The ends of the patch are tapered, thinning down to the edges. In this zone, disbonds cannot be tolerated because as the disbond grows it moves into a region of increasing patch thickness and consequently a greater driving force for disbond growth could result in patch separation. Thus, proper design of the taper region is critically important for applications of the patch repair.

The effect of taper profile on the crack initiation and fatigue resistance of patch repairs has been investigated by a number of researchers [1–3].

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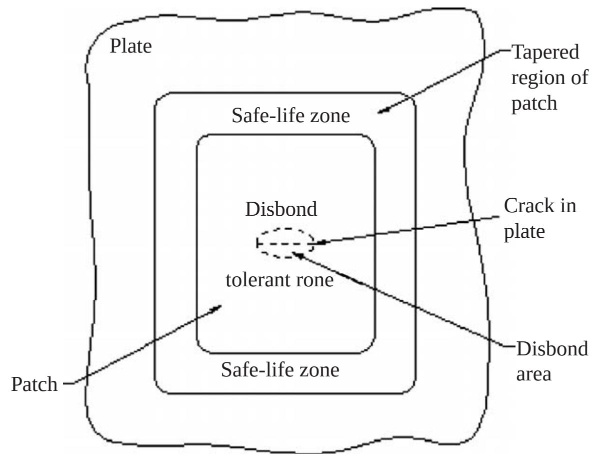

Fig. 1. Damage-tolerant and safe-life zones in a bonded repair.

To represent the two regions mentioned above Chalkley et al. [1] proposed testing of two types of generic joint:

(1) The double overlap-joint fatigue specimen (DOFS), which represents the damage-tolerance region where the patch spans the crack.
(2) The skin symmetrical doubler specimen (SDS), which represents the safe-life region at the taper edge of the patch.

Chalkley et al. [1] conducted fatigue testing on the above-mentioned specimens and undertook relevant analytical simulation. The specimens were made of boron/epoxy laminate outer adherends and an aluminium inner adherend bonded with FM73 adhesive. For the SDS specimens, four different edge tapering types were designed and tested. They found that the disbond growth in the DOFS specimens is shear-dominated and the growth rate can be well correlated to the maximum adhesive shear strain. On the other hand, in the case of SDS specimens, neither a stress/strain nor a fracture mechanics based criterion could provide a good correlation between the measured and predicted crack initiation loads for the specimens tested with the different edge tapering types. It was suggested that further experimental and theoretical investigations need to be carried out to improve the prediction for the SDS specimens.

Johnson and Dillard [2] studied the effect of linear edge tapering of adherends on fatigue strength of single lap joints. Experiments were conducted using specimens made with FM 300 or EC 3445 adhesive and graphite/epoxy adherends with taper angles of 5°, 10°, 30° and 90° (untapered). Experimental results showed that the fatigue resistance increased as the taper angle decreased. In the computational work they estimated the disbond threshold value of the strain energy release rate for crack initiation in the adhesive using test data from the 90° taper angle specimens and then, based on this threshold value, predicted crack initiation stresses in other taper angle cases. Excellent agreement between the prediction and experimental data for the specimen geometry studied was reported.

Taper contour optimisation is an important, relevant issue. One of its practical significances is that in some cases where the patch size is limited by geometry of the components, only a patch with curved optimal taper profile could provide sufficient repair strength. Extensive analytical research has been reported in this area [4–6]. Relevant experimental work has not been reported which is needed to validate and help further develop the optimal design.

The present work is a continuation of the study carried out by Chalkley et al. described above [1]. In the present work, both computational and experimental investigations were undertaken to study the effect of the taper profile on crack initiation and fatigue resistance of the skin SDS, aiming to achieve the optimal design of the taper profile. Only aluminium specimens were used so as to eliminate residual thermal shear stresses and other complications, such as complex failure mechanisms, with composite adherends.

2. Method

2.1. Experiment

SDS specimens with five different tapering configurations were manufactured (Fig. 2), namely four linear tapering angles, 3°, 6°, 45° and 90° and a precise curved taper contour that was designed using finite element (FE) optimisation method (as detailed in Section 2.2). The material for the adherends was Al 2024-T3 and the adhesive was FM73. The material properties are listed in Table 1. The thicknesses of the central adherend, outer

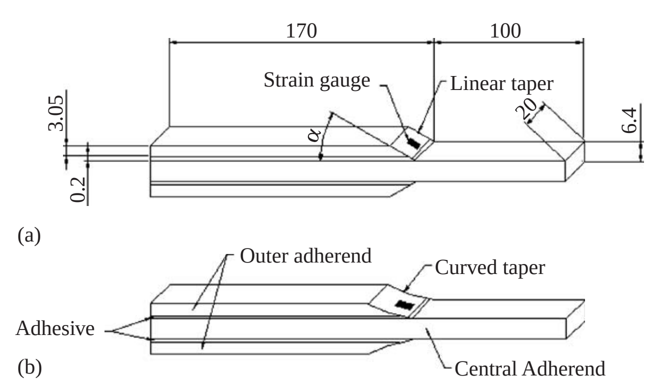

Fig. 2. Specimen types and dimensions (dimension in mm): (a) linear taper ($\alpha = 3°$, 6°, 45° and 90°) and (b) curved taper (optimal taper profile).