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Fatigue damage tolerance of two tapered composite patch configurations

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ABSTRACT

To avoid high peel stresses around the perimeter of a bonded composite patch repair, the patch thickness often tapers to a fine edge. This paper investigates and compares the damage tolerance of two different configurations of taper design under fatigue loading with different size of initial bondline flaws. The bondline damage at the tip of the doubler repair was simulated by an initial flaw which was created through a Teflon tape. A constant amplitude fatigue loading was applied to all specimens. The crack propagation against the number of cycles was recorded and the fatigue life when the crack reached 100 mm from the doubler tip was reported. Microscope investigations were conducted and provided micro scale evidence on the effects of initial flaw size on the crack initiation pattern of the two doubler design configurations. Finally, the damage tolerance of the two configurations were compared and conclusions were drawn with implications for the design of composite patch repairs. It was found that ply-drop doubler joints showed better damage tolerance than stepped doubler joints under fatigue loading. The experimental results suggested a threshold size of 5 mm for the doubler tip flaw, if any inspection technology should be adopted for damage detection.

1. Introduction

Fibre reinforced polymer (FRP) composites have been adopted as construction materials for automotive, aerospace, civil and marine structures [1–5]. Suitable methods are required when repairing damaged composite parts [6–10] to restore their designed capacities. Two methods are currently widely adopted in composite structures, namely mechanical fastening and adhesive bonding. It has been widely reported that adhesive bonding has benefits such as lighter weight, better load transferring mechanism through larger bonded area and better fatigue performance [1,11–16]. On the other hand, mechanical fastening methods using bolts or rivets were always criticised due to stress concentration resulting from fibre cutting at bolt holes, and increasing the self-weight of structure [1,14,17]. The weight saving is especially more important in modern airplane structures where FRP composites become more extensively used (e.g. Boeing 787 with about 50% FRP by weight [18]), which makes the adhesive bonding methods more desirable [14].

There has been an increase in the demand of replacing mechanically fastened metallic patches with bonded composite patch repair to increase the service life in aircraft operations [19,20]. However, as there is currently no accepted technology for inspecting the quality of the bondline, the application of bonded repairs to primary structure is limited [21,22]. Another issue with adhesive repairs is the lack of inspection method and analytical solution as well as damage tolerance information for ensuring the bondline integrity [6,23]. To credit a bonded patch repair of structural damage to primary aircraft structure, it must restore the static strength, stiffness, damage tolerance and fatigue performance of the original structure. Baker [20] characterised the bonded patch repair into two zones: the middle part of the repair was named 'damage-tolerant zone' and the tapered ends of the patch was called 'safe-life zone'. Two types of joints, doubler overlap joint and skin doubler joint, were proposed as the generic joints to assess the damage tolerance of the damage-tolerant zone and the safe-life zone, respectively.

There have been studies on the damage tolerance of bonded composite patch repair under fatigue loading in the literature. However, most of the work was conducted on repairing of cracked aluminium adherends [19,20,24–26]. For example, the certification requirements on giving full credit to bonded carbon fibre patch repair in slowing crack growth and recovering residual strength of parent aluminium structure were addressed in [20]. Concerns were given to effects of fatigue and environmental durability on the patching efficiency. The skin doubler specimens were proposed

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in [20] for characterising the threshold for damage growth in the safe-life zone, which was used in the design of F111 repair in [27]. Charlkley et al. [24] presented an experimental study on the skin doubler specimens prepared by bonding composite skin doubler repair on aluminium adherend. The skin doubler consisted of eleven plies of unidirectional boron/epoxy and was bonded to the aluminium adherend by FM 73 adhesive. Since the purpose of the study was to determine the debonding initiation load, no initial flaw was introduced in the bondline. The specimens were subjected to constant amplitude fatigue load with a specific load ratio (min/max) at a frequency of 3 Hz. The disbond load was obtained when the strain at the doubler tip dropped by 10%. It reported that, the disbond initiation and propagation locations were dependent on the shape of the skin doubler tip. For skin doubler without a tapered tip (sharp end), the disbond was within the boron/epoxy ply adjacent to the adhesive bondline. For skin doubler repair with a tapered tip, the disbond tended to be mixed: some failure within the ply of boron/epoxy adjacent to the adhesive bondline and some failure at the interface between aluminium and adhesive. The disbond initiation loads of skin doubler repairs with different tip shapes indicated that adhesive stress was not a suitable parameter for describing the disbond initiation of the bondline. Poole [25] reported an experimental programme on the damage tolerance of skin doubler repairs to the cracked aluminium adherend under fatigue loading. Two types of skin doubler repairs were adopted: one was twelve plies unidirectional boron/epoxy patch and the other was sixteen plies unidirectional graphite/epoxy patch. The two patches were 132 mm long and 70 mm wide. Redux 312/5 was used as adhesive bonding the patches to the 2024-T3 aluminium panel of 145 mm wide and 4 mm thick. Initial flaw with a size of $8 \times 10\ mm^2$ was embedded in the bondline at two locations. One was at the tip of the skin doubler repair and the other was located at the side edge of the skin doubler repair immediately covering the crack of the aluminium adherend. Specimens were tested under 110 MPa constant amplitude fatigue loading with a load ratio of 0.05. The experimental results indicated that no debond growth was detected for initial flaw at the tapered edge of the skin doubler repair until the aluminium panel fractured. When located at the side edge of the patch repair covering the crack of the aluminium panel, the initial flaw ($8 \times 10\ mm^2$) grew with the aluminium crack under fatigue loading but had little effect on the fatigue life. Roach [26] reported a similar experimental program on the damage tolerance of boron/epoxy composite tapered skin doubler repair bonded to 2024-T3 aluminium adherend. The tapered skin doubler patch consisted thirteen plies boron/epoxy (type 5521/4) with a stacking sequence of $(0/+45/-45/90)_3$. FM-3 was used as adhesive. The stiffness ratio between skin doubler and aluminium was 1.2. The initial flaw (0.75″ or 1″ diameter) at the tip of the skin doubler repair was created by Teflon tape. Specimens were tested under fatigue loading at a range of 25.86–143.06 MPa. The experimental results showed that the large initial bondline flaw at the tip of the tapered skin doubler repair did not decrease the overall composite doubler performance. The size of the initial flaw remained almost unchanged until the fracture of the cadmium plate under fatigue loading.

It should be noted that, the above mentioned studies were all conducted on the damage tolerance of skin doubler repairs when bonded to aluminium adherends. Considering the increasing use of the fibre composite in airplane primary structures, it is necessary to understand the damage tolerance of skin doubler repairs when bonded to composite adherends. However, the existing experiences in aluminium adherends cannot be directly transferred to composite adherends which may have different disbonding and damage mechanisms. This paper presents an experimental study on the damage tolerance of tapered skin doubler repairs bonded on graphite/epoxy laminate adherend when subjected to fatigue loading.

Two types of tapered skin doubler joints, representative of repairs, were compared in this paper, named stepped doubler and ply-drop doubler, in terms of sensitivity of their fatigue behaviours to the embedded initial bondline flaw. Various initial flaws were introduced in the doubler bondline, by changing the flaw length and flaw width. Constant amplitude fatigue loading was determined through laminate coupon tests, to ensure a microstrain of 2800 is obtained in the laminate adherends under the peak load. The crack propagation was monitored and measured by a microscope during the fatigue loading. Fatigue life was determined when the crack reached a length of 100 mm. If there was no crack growth or the crack grew but did not reach the length of 100 mm, the fatigue loading was applied continuously up to 180,000 cycles. The failure modes, fatigue life and microscope observations of the crack initiation of both stepped and ply-drop doublers were reported and compared. The results of the work provide fatigue performance data that can be used to aid repair design, and to validate analysis methods.

2. Experimental program

2.1. Materials

Unidirectional graphite/epoxy ply of IM7/977-3 was used to prepare the laminate adherend and the skin doubler repair. The material properties adopted in subsequent analysis are based on those from Ref. [28] and listed in Table 1. Film adhesive FM300-2K was used to bond the doubler repair to the laminate adherend. The nominal weight of FM300-2K is 391 gsm with a nominal thickness of 0.33 mm. The lap shear strength at 24 °C is 40.7 MPa [29].

2.2. Skin doubler joint specimens with initial flaws

Thirty plies of IM7/977-3 were used to prepare the adherend and doubler laminate with a stacking sequence of $[45/0/0/-45/90]_{3S}$. This layup represents laminate more likely found in an aircraft structure (eg. wing skin) where the layup has been optimised. Each ply of IM7/977-3 is 0.13 mm thick resulting in a nominal thickness of 3.9 mm for both laminate adherend and skin doubler repair.

Two types of doubler repair were selected. The first configuration (referred to as a "stepped taper" herein) is achieved by terminating each successive ply in the patch at a fixed distance short of the preceding ply. With this configuration, the first ply of the repair (adjacent to the bondline) is the longest ply. The second configuration (referred to as a "ply-drop taper" herein) is achieved with the shortest ply being placed adjacent to the bondline and each subsequent ply extending a fixed length beyond the preceding ply. The recommended doubler design is generally the ply-drop doubler, however there may be instances where the stepped doubler configuration is adopted, particularly if laminating/bonding pre-cured straps (e.g. battle damage repair [25]). The doubler panel was manufactured by staggering equal-size plies with a 3 mm offset to achieve the stepped taper at one end, and the ply-drop taper at the other, as shown in Fig. 1.

The parent laminate was manufactured in the same process as the skin doubler panel but without tapered ends. The top and bottom surfaces of the parent laminate were made smooth with a caul plate, whilst the top surface of the doubler panel was prepared with a silicon intensifier. When bonding the tapered skin doubler repair to the parent laminate, the adhering surfaces of the panels were degreased with Methyl Ethyl Ketone (MEK). Then FM300-2K was used as adhesive and cured under full vacuum condition in an oven at 125 °C for 120 min. The detailed configurations