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Damage tolerance investigation of high-performance scarf joints with bondline flaws under various environmental, geometrical and support conditions

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ABSTRACT

The criticality of disbonds on the load-carrying capacity of scarf joints under different environmental conditions was experimentally investigated. Tests were conducted on scarf joints containing bondline flaws of varying lengths and locations under room-temperature (RT), cold-dry (CD) and hot-wet (HW) conditions. The results showed that the residual strength of scarf joints under RT and CD condition decreases exponentially with the size of the bondline flaw up to a threshold length and remains almost unchanged for larger bondline flaws. In contrast, those specimens under HW condition were less sensitive to the presence of disbonds. The effects of scarf angle, adherend composite layup and support condition on the load-carrying capacity of scarf joints with a bondline flaw were also investigated. For specimens where the eccentricity was counteracted by a sandwich support, the residual strength of the joint improved considerably. Fractographic analysis using Micro Computed Tomography and SEM were carried out to examine the effects of the environmental condition on the failure mechanisms of scarf joints.

1. Introduction

Due to their excellent mechanical and physical properties, advanced composites are becoming more prominent in primary aerospace structures [1]. Despite their superior resistance to cracking and corrosion, composites are considerably brittle materials and, therefore, vulnerable to mechanical impact damage. In the case of damage, the design capability of primary composite structures needs to be restored either by component replacement or a certified repair. Structural replacement, however, becomes infeasible for large integrated components due to high cost and time requirements, hence leaving repair as the only practical option [2].

Although the use of adhesive bonding to repair aircraft structure offers many advantages, certification of repaired primary structure poses many difficulties [3,4]. Achieving a good quality bond depends on numerous processes. Inadequate pressure, heating, and surface preparation, curing environment or possible contamination are among the potential causes of "kissing bonds" having weak interfacial strength relative to a properly formed joint [4]. Currently, the bond quality cannot be evaluated using any existing non-destructive inspection technology, although physical flaws within repairs can be successfully detected. While alternative approaches are being considered to address this challenge [5], improved design methodology and damage tolerance analysis of the repair under service conditions is needed to satisfy all the requirements.

The damage tolerance concept is commonly referred to the ability of a structure to withstand large, discrete damage and still maintain design limit strength. In the open literature, very limited studies address the damage tolerance of adhesively bonded scarf joints and repairs. It was shown that the load-carrying capability of scarf joints is adversely affected by impact loading [6–11]. In addition, research conducted by Charalambides [12] shows that changes in the failure modes are evident when bonded composite scarf repairs are immersed in water for periods up to 16 months. Furthermore, the performance of the scarf joint deteriorated when testing of conditioned samples is conducted at temperatures meeting and exceeding the glass transition temperature of constituent components [13]. Traditional design methodologies and guidelines for bonded scarf repairs to non-safety critical structures are based on that of a pristine repair and have not considered damage

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tolerance to a major extent [14–16]. For a primary structure, bonded repairs are not permitted for damage where the residual strength in the absence of the patch would fall below limit load, thus limiting the size of damage that can be repaired with a bonded patch. Development of damage tolerant repairs, particularly if containing crack arresting features, may help expand the application of bonded repairs in future. Since damage initiation and propagation is also difficult to predict, composite repairs can be largely overdesigned [3]. To develop validated design methodologies in support of damage tolerant repairs; it is important to investigate the effects of disbonds on the load-carrying capacities of adhesively bonded scarf joints and repairs under aircraft operating environments.

A simple approach to studying the damage tolerance of scarf joints has been adapted by considering "pre-flawed scarf repairs" [17,18]. The method provides a simple representation of impact or manufacturing defects (in a controlled manner). This paper reports an experimental investigation to characterise the damage tolerance in pre-flawed scarf repairs under different environmental conditions. The effects of adherend layups, scarf angles, initial flaw size/location and boundary conditions on the residual strength of scarf joints under room-temperature, cold-dry and hot-wet environmental condition are studied. Analysing these variables will provide a much wider scope of the sensitivities to bond line pre-flaws than currently exists in the literature.

2. Materials and experimental procedure

2.1. Manufacturing

A hard patch style repair, where both sides of the repair system are pre-cured, was chosen for investigation in this study. The composite adherends were fabricated using an orthotropic layup consisting of 30 plies of high-performance IM7/977-3 carbon/epoxy prepregs. Two laminate configurations were considered. A primary "stiff" laminate $[45/0/0/-45/90]_{3S}$ composed of 40% 0° plies, 40% 45° plies and 20% 90° plies, while the secondary "soft" layup $[-45/90/90/45/0]_{3S}$ that retains only 20% 0° plies, 40% 45° plies and 40% 90° plies. The lay-up was performed onto a flat aluminium tool where 400 mm x 400 mm composite panels were then vacuum-bagged and cured within an autoclave at 180 °C for 6 h under a constant pressure of 100 psi. The nominal cured laminate thickness was approximately 3.9 mm. Scarfed surfaces with an angle of 3° or 5° were machined on one side of each composite panel using a CNC router with tungsten carbide ball nose cutters. The machined surfaces were prepared by lightly sanding the bond area using aluminium oxide 150 grit sandpaper, and degreasing using Methyl Ethyl Keytone (MEK).

The bonding of the panels was achieved using an aerospace grade high-performance film adhesive FM300-2K which includes a scrim cloth. A cured bondline thickness of approximately 0.2 mm was achieved, which is in the range of 0.15–0.25 mm, shown to provide optimal performance of scarf bonded joints [19]. The film adhesive was initially B-staged to remove volatiles and improve overall curing [13]. This was done by cutting the sheets of adhesive into appropriate sizes for bonding the scarfed surfaces, placing the adhesive films into an oven at 80 °C for 20 min, and then removing them to cool prior to being used to bond specimens. To create the artificial bond line flaws, thin PTFE release film was embedded into the bond line interface between the adhesive layer and composite adherend prior to the curing process. All flaws extend the full width of the samples. The length and locations of the Teflon inserts were varied along the bond line of the scarf. Note that a theoretical bond length of a 3° scarf angle, on a 3.9 mm thick laminate, is approximately 75 mm. Thus, the de-bond lengths considered in this study were 10% (7.5 mm), 20% (15 mm) and 40% (30 mm) of the bond line. Fig. 1 illustrates scarf joint cases tested in this study.

After the laminates, adhesive and Teflon film sheets were prepared, the panels were assembled on a flat tool and secured in position with high-temperature tape. A major challenge was ensuring the right amount of overlap between the two scarfed panels to achieve the desired final specimen configuration (nominally flush). Some trial and error was required to optimise the extent of overlap prior to cure. Once the panels, adhesive and PTFE insert were positioned and secured, the panel was covered in release film and vacuum bagged for curing. The bonded laminates were cured in an oven with bagging under full vacuum with an applied external atmospheric pressure, at 120 °C for 120 min. Finally, the specimens were cut into narrow width coupons 20 mm wide on a wet diamond saw and were approximately 320 mm long with a maximum bond region of 75 mm located in the centre of the sample. Examples of the manufactured specimens can be seen in Fig. 2.

The effects of boundary condition on the scarf joint strength of stiff laminates were also assessed in this study. To this end, either a doubler or sandwich support was bonded on one side of the scarf joint for selected cases. Nomex honeycomb cores with a thickness of 20 mm were used for the sandwich media, FM300-2K for bonding, and IM7/977-3 for the supporting laminate. The doubler laminate consisted of a $[45/0/0/-45/90]_{2S}$ with a nominal thickness of 2.6 mm while the sandwich was supported by a $[45/0/0/-45/90]_{4S}$ laminate with a 5.2 mm nominal thickness. A depiction of the sandwich and doubler support cases can be seen in Fig. 1. It is worthy to note that during the experiment, loads were applied to the scarf joint section only, and no direct load were experienced by the different supports.

2.2. Environmental conditioning

Three testing conditions were chosen in this study, representative of the range adopted for a high performance composite airframe: Cold Dry (CD) at −55 °C, Room Temperature (RT) at 25 °C and Hot-Wet (HW) at 100 °C with pre-conditioning. Environmental conditioning was done in accordance with ASTM 5229 [20], where the conditioning process was conducted in an Angelantoni SU600 environmental chamber. The aging process occurred at 70 °C and 85% relative humidity via water vapour. The test samples were conditioned until they were considered fully saturated, or effective moisture equilibrium was reached. This was done through routine measurements of small composite travellers cured under identical conditions. Measurements were taken of the total weight gain over the entire duration that the samples were subjected to conditioning. It is assumed that the majority of the moisture being absorbed occurred in the laminates through thickness direction. Samples were not pre-dried before the conditioning process and were placed in the environmental chamber post manufacture with no additional treatments. The purpose of conditioning was to fully saturate the samples that was achieved through the aforementioned periodic measurements until less than a 0.01% weight gain was achieved over two weeks where samples were in the conditioning process for 192 days. Final weight gain of the specimens was approximately 0.55% and showed excellent consistency.

As testing of the scarf specimens could be conducted under various temperatures only, without the adjustment of relative humidity, it is expected to have a moisture loss in the specimens during testing. Therefore, the moisture uptake of the composite travellers was also measured to show the weight loss during experiments. The average moisture loss of the travellers was 0.053%, which is noted as less than a 10% weight loss during the experimental process. Thus, a sufficient amount of moisture remained within the specimens during testing under HW condition.