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Hybrid approaches for aircraft primary structure repairs

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ABSTRACT

Currently bonded repairs can only be permitted on those aircraft primary structures suffering cracks/damages having a residual strength well exceeding the design limit load prior to application of the bonded repairs. This paper focuses on the approaches to meet the certification requirement by combining a bonded patch with other methods that enhance residual strength of the damaged structures. An overview of the recent research in this area conducted by Defence Science and Technology Group and its research partner organisations is presented. The outcomes from six individual research programs indicated the hybrid repair methods are promising for primary structure repair applications. Significant residual strength increases were achieved through optimum damage removal and/or inclusion of alternative load paths. These methods also provide significant additional fatigue life post premature bond failure that would allow any possible bond-line defect/damage to be identified by NDI means long before a catastrophic failure. The adhesive bond in the hybrid repairs was proven to provide significant benefit in enhancing the static strength and fatigue resistance. Key issues for the application of these hybrid repair methods and future research directions are also discussed.

1. Introduction

Adhesively bonded patch repairs for aircraft components have been successfully applied in Australia and other countries, saving hundreds of millions of dollars and significantly enhancing aircraft availability [1,2]. Although it is generally appreciated that these repairs have many advantages over repair procedures based on mechanical fastening and have in the past been applied to several metallic primary aircraft components, difficulties in meeting some of the current certification requirements have limited applications of bonded repairs on aircraft primary structures [2,3]. The main obstacles are: i) quality control procedures that can feasibly be applied to bonded repairs undertaken in non-ideal situations cannot demonstrate initial and ongoing bond integrity with sufficiently high probability of reliability; and ii) current NDI techniques are not yet available, or sufficiently reliable, to detect weak bonds in a practical situation. Thus, currently bonded repairs can only be permitted to be applied to those primary structures suffering cracks / damage having a residual strength well exceeding design limit load prior to application of the bonded repair.

Thus, further focused research on bonded repairs aimed at overcoming these certification difficulties should have a huge potential benefit for application of bonded repairs to both military and civil aircraft.

Defence Science and Technology Group (DST Group) has developed a research roadmap for bonded repairs on primary structures. Key issues contained in this systematic approach to meet the certification requirements include: development of reliable procedures to detect weak bonds through advances in NDI (including a novel adhesive bond proof tester) and bond-line structural health monitoring methods [4–9], enhancement of residual strength through optimum damage removal [10–13] and adding alternative load paths [14–19], and improvement of design methodology and application of quality assurance to bonded repairs. The repair design must properly consider all the factors required by certification of a bonded repair including defect and damage tolerance [12,20], fatigue life assessment, service environment factors, etc.

This paper focuses on a subset of the above research strategy, that is, to meet the certification requirement for applications of bonded repairs on primary structures by combining a bonded repair with other methods that enhance residual strength of the damaged structures, such as optimum damage removal and alternative load path addition. In the following sections, an overview of the recent research in this area conducted by DST Group and its research partner organisations will be presented. The outcomes from these research programs indicated that hybrid repair methods are promising for primary structure repair applications. Key issues for the application of these methods and future research directions will also be discussed.

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2. Hybrid repair – Optimum damage removal/bonded patch

The first step in the decision chart for repairs to flight-critical composite structure [2] is to define an optimum damage cut-out. In this section three repair scenarios will be presented, where significant residual strength increases were achieved by applying shape optimization for crack/damage removal for both composite and metallic components, and bonded patch repairs with distinctly different design concepts were applied that provide significant benefit in enhancing the static strength and fatigue resistance.

2.1. Patch covering the damaged area

Several aircraft wing spars were observed to experience in-service cracks growing from the electrical grounding hole and adjacent satellite holes.

The spar is made of high strength aluminium 7175-T73652 alloy. It is 51 mm (2 in.) wide and has a thickness of 2.03 mm at the area around the holes. Under load, this area of the web of the spar is in a stress state of near pure-shear.

Finite element (FE) analyses have long been used to simulate bonded repairs and achieved great success. With significant advancement in experimental instrumentation techniques (Lamb waves analysis, Digital Image Correlation C-scanning and X-ray radiographs) this analysis method has been proven to be able to accurately model composite bonded repairs [21,22].

A three-dimensional (3D) finite element (FE) analysis was conducted to compare repair options, including i) standard cut-out, ii) optimum cut-out, and iii) a bonded patch repair combined with the optimum cut-out (Figs. 1–3).

Boron/epoxy prepreg was chosen as the patch material. A layup of $[45/\text{-}45/45_3/\text{-}45/45]$ was specified. It matched the stiffness of the spar in the 45° direction, which is perpendicular to the crack direction. EA9394 paste adhesive was chosen for its relatively low temperature cure and high strength.

The analysis of the bonded patch was undertaken for three environmental conditions, namely room temperature/ambient, cold temperature ($-54\,^{\circ}$C)/dry and elevated temperature ($105\,^{\circ}$C)/wet conditions to ensure that structural integrity and repair effectiveness were properly assessed.

The FE analysis results showed that:

- The original configuration (without cracks) exhibited peak stresses at the grounding and satellite holes that were rather high, which facilitated formation of the fatigue cracks.
- The standard cut-out was effective at removing the high stress concentration at the crack tips. However, compared to the original configuration, the peak stress with the cut-out was higher (by around 10%).
- Compared with the original configuration, the optimum cut-out reduced the peak stress by around 12%.
- Bonded patch repair combined with optimum cut-out reduced the peak stress by around 50% compared with the original configuration.
- For cut-out only options, should the cracks re-occur, the stress intensity factor would exceed the material fracture toughness value.

From the above it is clear that the cut-out may effectively increase the residual strength over the cracked structure and the bonded patch can further increase the strength very significantly. The analysis was validated by a full scale static test at room temperature/ambient environment.

Estimated using the simple cubic rule [60], the optimum cut-out and the hybrid repairs would result in a fatigue life of 1.5 and 8 times, respectively, for the spar compared with the original configuration. For relatively short fatigue life requirement, the optimum cut-out alone would be an acceptable repair option. For relatively long fatigue life requirement, and also in a longer crack case, addition of a bonded patch would become necessary to provide sufficient fatigue life and eliminate the possibility of crack reoccurence[1].

The method described represents a typical hybrid approach for application of repair to thin metallic structure, combining optimum damage removal with conventional bonding of a thin overlapping boron patch, which allows non-destructive eddy current inspection of the parent structure performed through the patch.

2.2. Patch around the damaged area

As part of the aircraft battle damage repair (BDR) research program, DST Group was tasked by the Australian Army to develop a repair solution for a helicopter main rotor blade subject to ballistic damage at the main spar section.

The repair requirements were to:

- restore stiffness/strength
- maintain aerodynamics performance
- maintain dynamic balance/natural frequency (not discussed in this paper)
- be applicable within a short timeframe, with limited requirements for tools, materials and technician skills [24]

BDR applications generally only require restoring a short fatigue life capability (50 to 100 flight hours). However, for this dynamic component (due to the high frequency of loading) restoration of high fatigue resistance is required from the repair.

The dimensions of a three-dimensional (3D) specimen are shown in Figs. 4 and 5. The tube specimen has a nominal thickness of 4.31 mm, made using 25 plies of carbon-epoxy biaxial and uniaxial fabric prepreg materials [25]. The specimen is representative of a typical main spar section (spar cell 2 in Fig. 6). A circular hole was cut through the specimen at the centre to represent damage due to ballistic impact and conventional subsequent damage removal.

The main load conditions include a centrifugal force and lift force (a tensile force in x-direction and distributed load in z-direction, respectively, Fig. 6). The lift force results in a bending moment (around y-axis, Fig. 6), which creates a tensile force and compressive force on the spar lower panel and upper panel, respectively. Thus, due to the combined effect of the centrifugal and lift forces, the lower panel is the critically loaded structure.

A test fixture was designed to apply the loads for the 3D spar specimen (Fig. 4). The combination of centrifugal and lift forces was experimentally approximated by applying uneven tension loading along each spar cap. The fixture featured a universal joint mechanism to introduce load path eccentricity and was compatible for use with a standard axial mechanical load frame.

In this study, design and testing of both 3D and two-dimensional (2D) specimens were conducted interactively to progress the repair design-validation process efficiently and cost-effectively. An initial 3D specimen test was conducted to validate and calibrate a full 3D FE simulation model and also to determine the failure onset load. 2D specimens and an anti-bending constraint mechanism (Fig. 7), representative of the critical lower panel location, were then designed based on the FE model to test and compare the proposed repair options. A final 3D test was conducted to validate the selected repair design.

For a single (external) side repair of a 4.3 mm thick laminate panel, conventional repair options would be scarf or step repairs [26]. These methods require removal of material across large undamaged areas, which significantly reduce the residual strength of the structure prior to

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[1] Further discussion will be provided in Section 5 about inspection interval and how the credit of fatigue life enhancement can be given to the hybrid repair