IMPLEMENTATION OF NOVEL DESIGN AND VALIDATION APPROACHES FOR BONDED REPAIRS OF A COMPOSITE AIRCRAFT COMPONENT

John J. Wang[1], Paul Chang[2], Alan A. Baker[3], Andrew Litchfield[4] and Michael Vuong[5]

[1, 2] Defence Science and Technology Group, 506 Lorimer St, Fishermans Bend, VIC, Australia, www.dst.defence.gov.au. john.wang@dsto.defence.gov.au; paul.chang@dsto.defence.gov.au
[3, 4, 5] Advanced Composite Structures Australia, 198 Lorimer St, Fishermans Bend, VIC, Australia, www.acs-aus.com. a.baker@crc-acs.com.au; a.litchfield@crc-acs.com.au; m.vuong @crc-acs.com.au

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ABSTRACT

Design and experimetal validation were carried out for a bonded repair to a composite helicopter main rotor spar subject to ballistic damage. The research addressed a number of challenges for bonded repairs for primary structure applications. Building block design and testing of 3D and 2D specimens were combined in an optimum way to progress the repair design-validation process efficiently and cost-effectively. FEM analyses and experimental work were carried out interactively to achieve a reliable repair design. Novel repair concepts were applied that facilitated meeting certification/authorisation requirements and other special requirements for battle damage repairs. These include adopting shape optimisation for damage removal to increase the residual strength prior to application of bonded repairs, and special bonded patch design that eliminated adhesive failure as a critical failure mode in the repair system. The experimental results agreed well with the FEM model prediction and confirmed the effectiveness of the repair design.

1 INTRODUCTION

Adhesively bonded repairs are effective at restoring static and fatigue strengths of damaged aircraft composite structures. However, there are significant challenges in implementing these repairs. A reliable repair design for important structures requires a building block approach, involving significant testing and modelling at multiple structural levels which generally is a costly and time consuming process.

Bonded repair to thick composite structures are particularly challenging. Scarf or step joint repairs are suitable for these applications, however, these repair methods require removal of pristine material over large areas of the parent structure, resulting in significant reduction of the residual strength of the structure prior to the application of a bonded repair, which could result in failure to meet the current repair certification requirement for bonded repairs on aircraft primary structures [1].

For military aircraft, a battle damage repair (BDR) capability is vital for mission continuation or a ferry flight to the base for an aircraft subject to battle damage. Battle damage repairs have specific requirements [2]. These repairs must be conducted rapidly using portable tools and materials [3], and the repair design and implementation methods must ensure sufficient reliability. Though for BDR applications a relatively short fatigue life (50 to 100 flight hours) is required, for dynamic components such as a helicopter main rotor blade or tail draft shaft, due to the high frequency of loading, restoration of high fatigue resistance is needed from the repair. Note also that for large military operations a depot level BDR would also be required. In such cases, rapidness of repairs is the key requirement, whilst a wider range of materials and facilities would be available [2, 4].

This paper summarises the design and experimetal validation work carried out at DST Group for a bonded repair to a composite helicopter main rotor spar subject to ballistic damage. The research addressed a number of challenges for bonded repairs. Building block design and testing of 3D and 2D specimens were combined in an optimum way to progress the repair design-validation process efficiently and cost-effectively. FEM analyses and experimental work were carried out interactively to achieve a reliable repair design. Novel repair concepts were applied that facilitated meeting certification/authorisation requirements and other special requirements for battle damage repairs.

This paper focused on the strength restoration aspect. Other requirements for a repair to a rotor blade, such as mass balance, natural frequency retention, aeroelastic performance, etc. are not discussed here.

2 THREE-DIMENSIONAL SPECIMEN AND INITIAL TESTING/SIMULATION

The dimensions of the 3D specimen considered are shown in Fig. 1. It was made using 25 plies of carbon-epoxy biaxial and uniaxial fabric prepreg materials [5] with autoclave curing. The tube specimen has a normal thickness of 4.31 mm and is used to simulate a helicopter main rotor blade spar section. A circular hole was cut through the specimen at the centre to represent damage due to ballistic impact and subsequent damage removal.

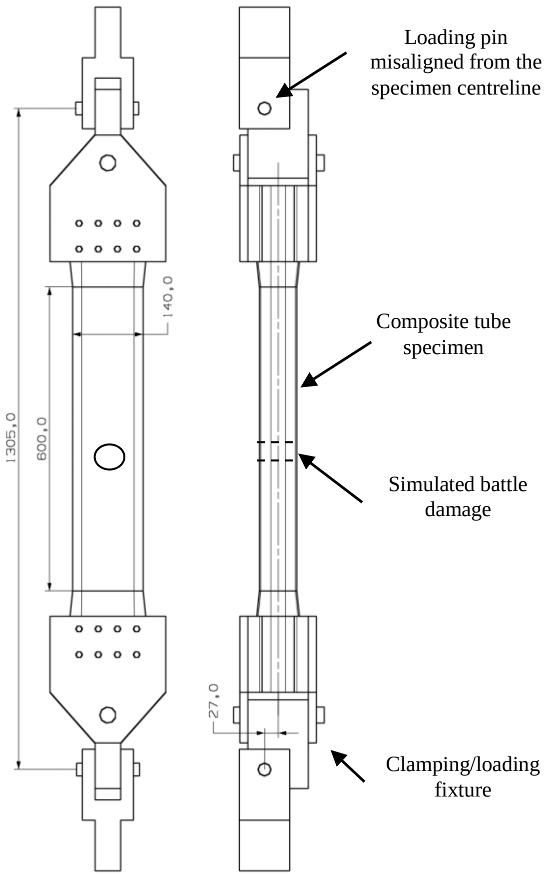


Figure 1: 3D specimen and test fixture

The specimen was mounted on a 2 MN Instron tensile test machine. Strain gauges were installed on the specimen to measure the stresses at various key stress concentration locations and the remote stress. LVDTs were used to measure out-of-plane deformation.

A test fixture was designed to meet the loading requirement for the spar specimen (Figure 1). The combination of centrifugal and lift forces on a helicopter blade 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.

A full 3D FEM model was built to simulate the specimen under the test loading condition. The strain survey test indicated that:

- The FEM prediction closely matched the strain gauge and LVDT readings, and

- The 3D specimen significantly constrained the bending deformation of the specimen surfaces where the damage is located (refer to Fig. 1).

The above provided justification to use 2D (flat panel) specimens with out-of-plane bending constraint, supported by a FEM analysis, to test repair options. This is an option with much lower cost than using costly 3D specimens for this purpose.

In the final stage of the initial 3D specimen test, the specimen was loaded until damage onset occurred, as indicated by strain gauge readings at the hole edge and clear visual damage at that location. This damage onset load was later used to compare with the damage onset load of the repaired specimen to assess the repair effectiveness as described in Section 4.

3 REPAIR DESIGN AND 2D SPECIMEN EVALUATION

3.1 Repair Design

For a single (external) side repair of a 4.3 mm thick laminate panel, conventional repair options for laminates of this thickness would be scarf or step repairs [6]. These methods require removal of material in large undamaged areas, which significantly reduces the residual strength of the structure prior to application of bonded repairs. As discussed, the lower residual strength in the absence of the repair increases the difficulty to meet the current bonded repair certification requirements for primary structure applications. Scarf and step repairs generally have a high demand on technician skills, repair facilities and repair time, which are also unsuitable for BDR applications.

A novel, alternative approach was considered to increase the residual strength prior to application of bond repairs by optimum damage cut-out [1, 7], and then an overlap patch was bonded to further increase the strength recovery. A FEM simulation indicated that the optimum hole shape (Fig. 2) designed using the shape optimisation approach described in Reference [7] resulted in over 30% increase of the residual strength compared with the circular hole damage removal, which in turn has higher residual strength than an untrimmed damage case with sharp cracks present.

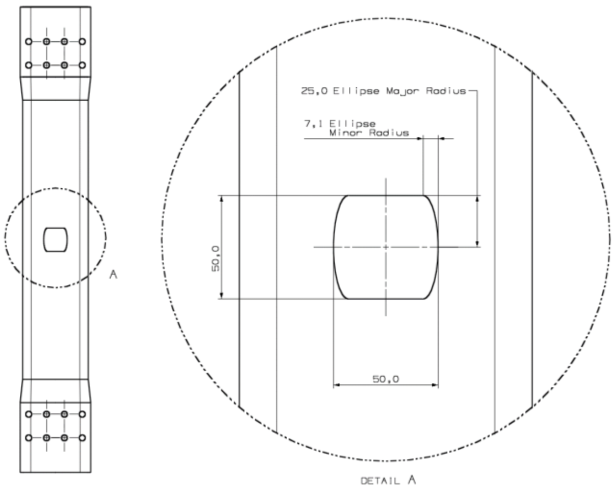
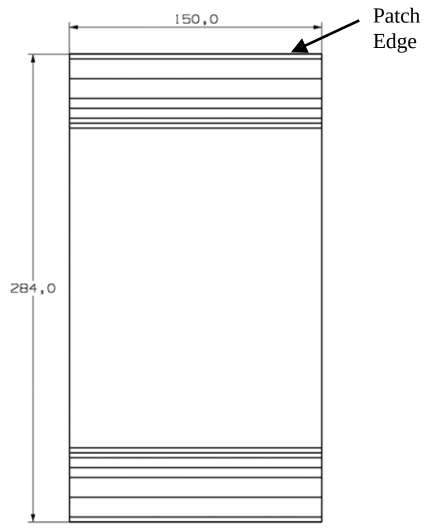
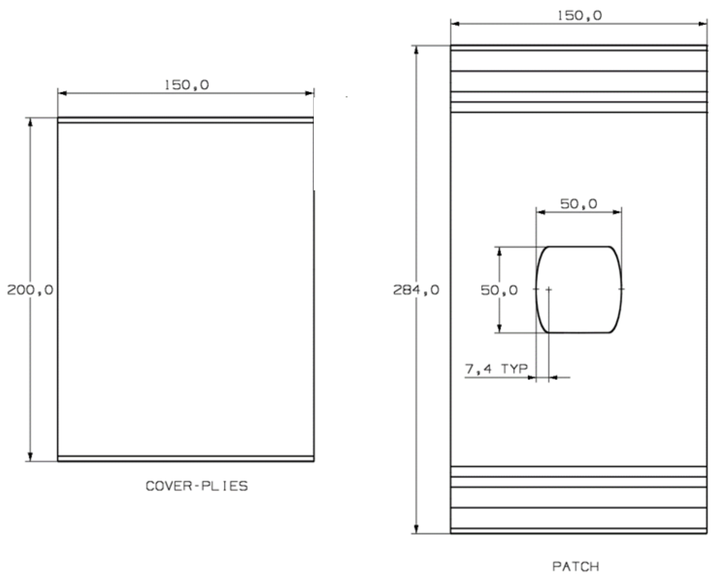


Figure 2: 3D specimen with optimum shaped damage removal

A thin repair patch (9 plies) was applied due to the aerodynamic consideration for a rotor blade. To minimize shear and peel stresses the patch was tapered at its edges by stepping plies from a single ply up to the full thickness at an optimum transfer length (Fig. 3) determined from a detailed FEM analysis. To limit adhesive stresses above the hole edge (another critical location), a novel design was adopted by cutting though the majority of plies in the patch with a same shaped hole as that in the parent structure (Fig. 3b, right side). A thin, softer cover skin was used to provide a seal and limited load transfer over the hole (Figure 3b, left side). With this patch design approach, the strength increase from the patch was achieved through increasing the load and loading capacity in the load bypass region of the specimen, plus an adequate, additional load through the softer skin cover over the hole. When properly designed, this repair configuration can effectively eliminate failure initiation in the adhesive layer (and resultant first composite ply failure due to high adhesive stress). A FEM analysis indicated that the patch repair combined with the optimum damage removal can increase the loading capacity significantly compared with the specimen with the circular hole. A conventional patch design without a cut-out in the middle (Fig. 3a) was also used for comparison. Due to the high stress in adhesive layer above the hole edge, initial failure in the adhesive is expected. As indicated in Reference [8], this initial failure occurs in the "damage tolerant" region. For a practical application of this design, the disbond growth rate as a function of fatigue loading needs to be known. Since for a parent/patch made of composite materials (in contrast to metallic materials) failure may occur in the first ply of the composite patch rather than in the adhesive layer in this region, this may make the damage tolerance assessment more complicated.



(a) Configuration A



(b) Configuration B

Figure 3: Repair patch configurations

3.2 Two-dimensional Specimen Evaluation

Flat specimens of 450 mm x 150 mm (length x width) were manufactured. Five types of specimens were considered, namely, a pristine specimen, a damaged specimen with a circular hole, a damaged specimen with an optimum cut-out, and repaired specimens with the 2 configurations of repair patches as described in Section 3.1 above. The adhesive used was FM300-2K film adhesive (for field BDR applications paste adhesive such as EA9394 could be used).

All the repaired specimens were bonded with a bending constraint mechanism on the side opposite to the patch side (15 mm thick Nomex honeycomb and a laminate panel). The anti-bending mechanism only constrained the out-of-plane deformation of the test specimens.

The test results are summarised in Table 1. Clearly the damage reduced the strength of the pristine specimen very significantly. Optimum damage removal alone increased the loading capacity by 44% and 21% respectively in terms of damage onset and ultimate loads, respectively. In terms of damage onset load, the conventional repair patch design (Configuration 1) and the novel repair design (Configuration 2) achieved 28% and 88% increase, respectively. Note that, as indicated from strain gauge readings, the onset of failure with the conventional repair patch design (Configuration 1) was the adhesive failure at the hole upper and lower edges (Fig. 2), whilst the onset of failure with the novel repair patch design (Configuration 2) was the laminate failure at the hole side edges (Fig. 2), which was expected (refer to the earlier discussion in this section). Similar improvement in terms of the ultimate load was achieved from the two patch repair configurations. It was over 60% increase compared with that of the damaged specimen without repair, and was 78% of the pristine specimen's ultimate load.

Specimen type	Damage onset load (kN)	Ultimate load (kN)
Pristine	-	560
Damage with 50mm hole	180	270
Damage with optimum cut-out	260	325
Repair configuration 1	230	440
Repair configuration 2	340	435

Table 1: Summary of 2D specimen test results.

Note that the increase of damage onset load with Configuration 2 repair design is significant to a component subject to high frequency dynamic loading (such as the rotor blade) which requires high fatigue resistance as discussed earlier.

4 FURTHER EVALUATION OF 3D SPECIMEN

The initial damage on the hole edge of the 3D specimen was trimmed off and the hole diameter was enlarged from 60 mm to 65 mm. Repair Configuration 2 was implemented. The specimen was tested on the 2 MN Instron tensile test machine (Fig. 4) with a loading rate of 1 mm/min on displacement control.

The results between a 3D FEM simulation and strain survey again agreed well (Fig. 5 and Fig. 6).

Figure 4: Testing of a repaired 3D specimen

The failure onset load was around 410 KN, which indicated a strength increase of around 80% due to the repair. The failure was initiated in the laminate rather than in the adhesive layer as anticipated.

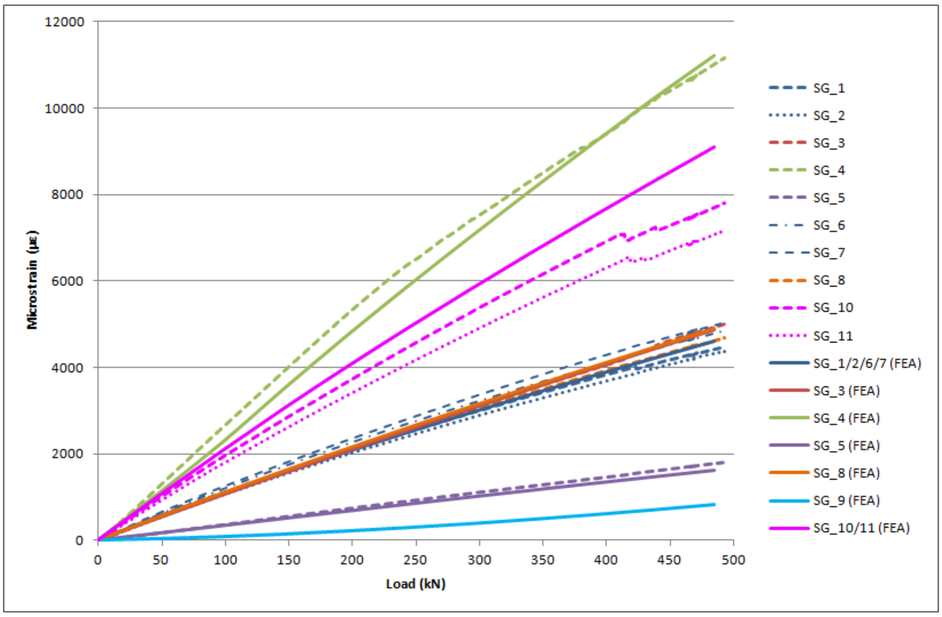


Figure 5: Strain-load results, repair configuration 2

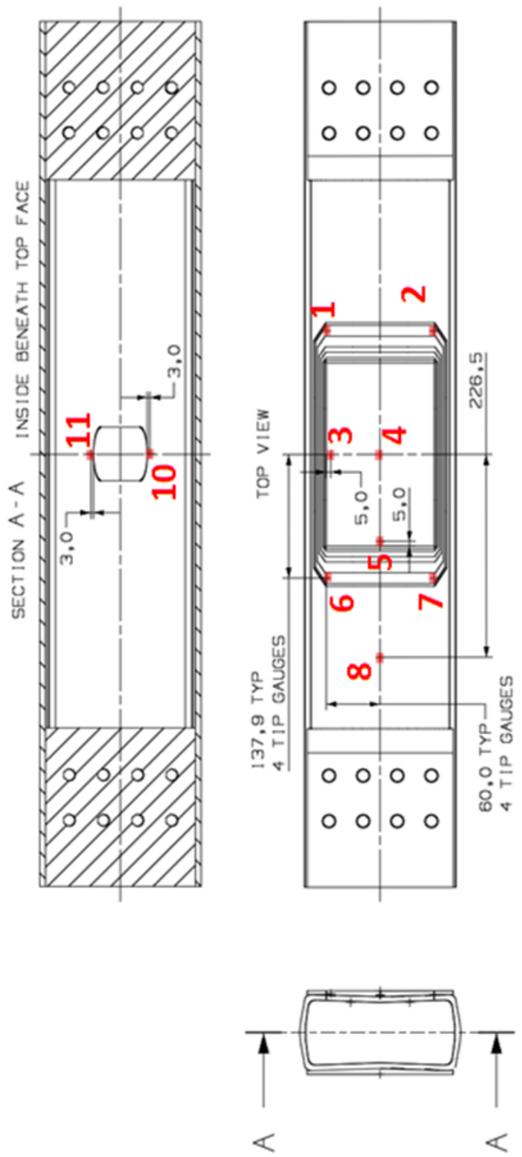


Figure 6: Strain gauge positions for repair configuration 2

For a battle damage scenario this strength increase is highly significant and would probably allow a capability for a continuing mission or at least for a ferry flight to a more capable repair depot for component replacement, which would not be possible without the repair.

9 CONCLUSIVE REMARKS

Design and experimetal validation work were carried out for a bonded repair to a composite helicopter main rotor spar subject to ballistic damage. The research addressed a number of challenges for bonded repairs. Building block design and testing of 3D and 2D specimens were combined in an optimum way to progress the repair design-validation process efficiently and cost-effectively. FEM analyses and experimental work were carried out interactively to achieve a reliable repair design. Novel repair concepts were applied that facilitated meeting certification/authorisation requirements and other special requirements for battle damage repairs. These include adopting shape optimisation for damage removal to increase the residual strength prior to application of bonded repairs, and special bonded patch design that eliminated adhesive failure as a critical failure mode in the repair system.

The 2D test results showed that optimum damage removal alone increased the loading capacity by 44% and 21% respectively in terms of damage onset and ultimate loads, respectively, compared with a circular hole damage removal, which in turn has higher residual strength than an untrimmed damage case with sharp cracks present.

In terms of damage onset load, the conventional repair patch design and the novel repair design achieved 28% and 88% increase, respectively. Similarly the 3D specimen test results indicated a strength increase of around 80% in terms of the failure onset load due to the novel repair applied. In both 2D and 3D specimen tests, the onset of failure with the conventional repair patch design was the adhesive failure at the hole upper and lower edges, whilst the onset of failure with the novel repair patch design was the laminate failure at the hole side edges, that is, the adhesive failure was eliminated as a critical failure mode by the novel repair patch design. The test results agreed well with the FEM prediction.

For a battle damage scenario this strength increase is highly significant and would allow a capability for a continuing mission without maneuver restriction or at least for a ferry flight to a more capable repair depot for component replacement, which would not be possible without the repair.

The novel design and validation approaches demonstrated in this study would be suitable not only for BDR applications but also for bonded repairs of composite structures during peace time.

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REFERENCES

[1] A. A. Baker, A. Gunnion and J. Wang, On the Certification of Bonded Repairs to Primary Composite Aircraft Components, *The Journal of Adhesion.*, **91**, 2015, pp4–38.

[2] J. Wang and A. A. Baker, Aspects of Battle Damage Repair of Helicopter Structures, *The Aeronautical Journal*, **114** (1155), Royal Aeronautical Society, UK, 2010.

[3] J. Wang, Z. Zhou, R. Vodicka and W. K. Chiu. Selection of Patch and Adhesive Materials for Helicopter Battle Damage Repair Applications. *Journal of Composite Structure.* V91. 2009. 278–285.

[4] J. Wang, A. Gunnion and A. A. Baker A. Battle damage repair of a helicopter composite frame-skin junction. Part 1: depot repair. *Journal of Composites:* Part A.V40, 2009. 1433–1446.

[5] HexPly® M18/1 180°C curing epoxy matrix, Product datasheet, Hexel, June 2005.

[6] A. Gunnion and C. Wang, Chapter 14 Repair Technology, AIAA Book: Composite Materials for Aircraft Structures. Third Edition. Editors Baker A and Scott M. Published by American Institute of Aeronautics and Astronautics. ISBN: 978-1-62410-326-1, 2016.

[7] C. H. Wang and A. J. Gunnion, Optimum Shapes for Minimising Bond Stress in Scarf Repairs, *Proceedings of the 5th Australasian Congress on Applied Mechanics, ACAM 2007*, 10-12 December 2007, Brisbane, Australia.

[8] A. A. Baker. Fatigue Studies Related to Certification of Bonded Composite Crack Patching for Primary Metallic Structures. *Proceedings of the FAA-NASA Symposium on Continued Airworthiness of Aircraft Structures,* Atlanta, August 1996, pp. 28-30.