Aspects of battle damage repair of helicopter structures

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ABSTRACT

This paper summarises recent research conducted at the Defence Science and Technology Organisation in the area of aircraft battle damage repair, covering aspects such as ballistic testing, ballistic damage prediction, non-destructive damage inspection, structure residual-strength assessment, repair materials and techniques, repair design approaches, repair implementation and demonstration. The research has been focused on military helicopter composite structures. This paper provides an overview of a wide range of research conducted and detailed information in selected areas. Considerations for future research directions are also briefly discussed.

1.0 INTRODUCTION

A US Air Force (USAF) study carried out in 1989(1), using a wing of 72 aircraft with an average of 1-2% attrition rate per sortie and an 8% per sortie damage rate, found that less than ten aircraft would remain available after ten days of conflict. With a moderate rate of aircraft battle damage repair, defined as reconstituting 50% of the damaged aircraft within 24 hours and 80% of the aircraft within 48 hours, three times as many aircraft would be available in the same 10-day period. This study indicated the importance of battle damage repair (BDR) to maximise aircraft availability during times of conflict.

Battle damage repair is particularly significant for helicopter structures, as they are vulnerable to ballistic impact damage from small arms fire and thus more likely than fixed wing aircraft to suffer battle damage in a combat environment. Hence the availability of an effective and efficient battle damage repair capability is a major requirement.

Owing to their superior mechanical performance and durability, fibre reinforced polymer composite materials are increasingly used in aircraft structures. Some recently developed military helicopters such as Tiger by Eurocopter have nearly all-composite airframe structures. The structural components of these helicopters are assembled using secondary adhesive bonding or co-curing techniques. This style of construction offers many advantages over mechanical fastening in that it can produce lighter and stronger structures that are more resistant to moisture ingress. However, it also presents new challenges to battle damage repair as it may not be possible to replace large components easily in operational situations. In addition, the thin and relatively brittle (compared with their metal counterparts) laminated polymer composite panels, which are extensively used on these aircraft structures, make traditional riveted repair techniques less effective. Suitable battle damage repair methods for both primary and secondary structures based largely on adhesive bonding need to be developed for these helicopters.

In order to support the Australian Defence Force (ADF) to maximise aircraft availability during times of conflict, the Australian Defence Science and Technology Organisation (DSTO), with support from the Co-operative Research Centre for Advanced Composite Structures (CRC-ACS), have been conducting research in the area of aircraft battle damage repair, covering aspects such as ballistic testing, ballistic damage prediction, non-destructive damage inspection, aircraft vulnerability analysis, structure residual-strength assessment, repair materials and techniques, repair design approaches, repair implementation and demonstration, support for battle damage repair manual development, specification of battle damage repair requirements, etc. The research has been focused mainly on helicopter composite structures. This paper provides an overview of recent research conducted in selected areas. Considerations for future research directions are also briefly discussed.

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2.0 BATTLE DAMAGE

2.1 Ballistic testing

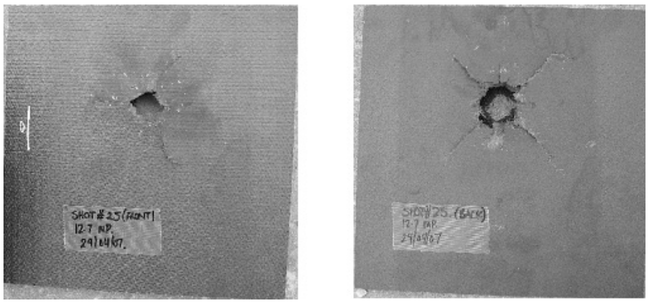
Ballistic testing on aircraft composite structures was conducted. The specimens tested include:

- Monolithic carbon fibre reinforced polymer (CFRP) panels with different thicknesses
- Composite sandwich panels with CFRP skins and Nomex honeycomb cores
- CFRP frame structures
- Composite frame-to-skin joints

Ballistic testing was conducted using projectiles ranging from 5·56mm calibre ball munition to 20mm explosive rounds, with different impact oblique angles and velocities.

These tests in conjunction with an extensive literature review[2] provided in-depth understanding of ballistic damage to aircraft structures.

Figure 1 shows ballistic damage to a composite sandwich panel by a 12·7mm projectile. It shows typical ballistic damage pattern in sandwich composite structure. The damage produced at the projectile exit side is significantly larger than that at the entrance side. Multiple cracks radiate from the perforated hole. Figure 2 shows the damage to a composite frame-to-skin joint by a 12·7mm multi-purpose round, where the triggered explosion caused severe damage.



(a) (b)

Figure 1. Ballistic damage to a thin CFRP skin-Nomex honeycomb sandwich panel by a 12·7mm projectile with normal impact. (a) Entry side; and (b) Exit side.

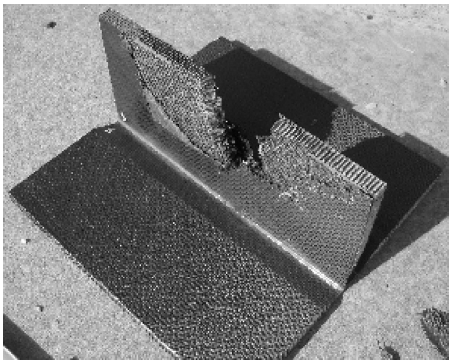


Figure 2. Ballistic damage to a composite frame-to-skin joint by a 12·7mm multi-purpose round. The projectile was shot through the skin panel (the bottom panel) into the frame.

Since the aircraft structure will usually be under load when experiencing ballistic impact during service, structural loading was applied in some of the tests to investigate the effect of structural loading on ballistic damage in composite panel specimens.

Northrop Corporation(3) reported ballistic testing on thin carbon epoxy plates structurally loaded in tension. For the newly developed all-composite-airframe helicopters, the composite materials are not only used as thin skins taking in-plane loads, but are also used in relatively thick frame structures that also experience out-of-plane loads. Thus relatively thick specimens and bending loading were considered(4). Figure 3 shows a test rig to provide bending loads during ballistic testing by a four-point bending mechanism. The load is applied by turning the nuts on the four loading rods evenly to move the front plate towards the rear plate. The rear plate is clamped on a large rigid frame structure. Both the front and rear plates have a square 'window' hole, allowing the projectiles to shoot freely through.

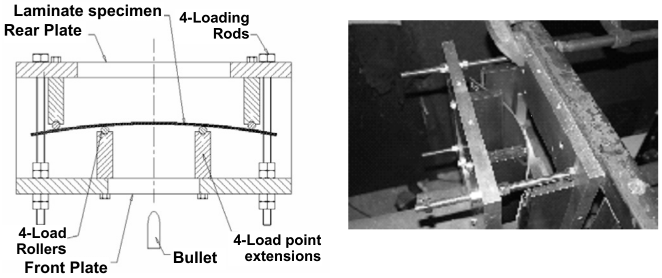


Figure 3. Four-point bending rig used to provide loading to the structure during ballistic testing.

The results showed that only when very high structural loading (> 7,000$\mu\varepsilon$) was applied, did a significant increase in damage occur. The results also showed generally that more damage occurred when ballistic impact was combined with the structural load, than when separately applied (typical examples are shown in Fig. 4).

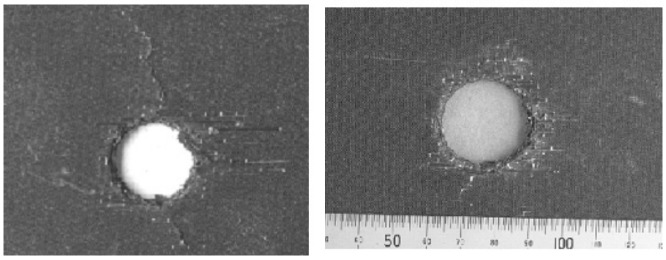
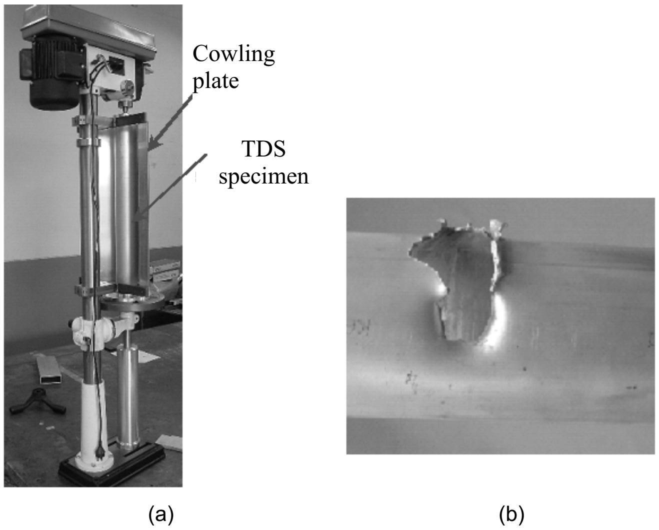


Figure 4. Visible damage (exit side) caused by 20mm projectiles with normal impact on 3mm thick CFRP composite panels. (a) Shot with 9,000$\mu\varepsilon$ structural loading; and (b) 9,000$\mu\varepsilon$ structural loading applied after the panel was shot with no structural loading.

Ballistic testing was also conducted on helicopter tail drive shafts (TDS), which are a primary structure and vulnerable to ballistic damage. For the purposes of this work, a three-part drive shaft system such as that used by the Black Hawk helicopter was assumed. That is, a series of approximately horizontal drive shafts that run back from the main gearbox along the tailboom of the aircraft, to an intermediate gearbox at the base of the tail pylon. There, a gearbox transfers the drive to a shaft running up the pylon to the tail rotor gearbox, which then drives the tail rotor output shaft. The horizontal drive shafts have a higher rotational speed and lower section area, compared with the pylon drive shaft and tail rotor drive shaft, and thus are most critical in terms of vulnerability. Specimens made of aluminium alloy were used in these tests as this is the material of construction for most horizontal drive shafts. Figure 5(a) shows the test rig that can generate a high spinning speed during the ballistic testing. Figure 5(b) shows typical damage caused by a 20mm projectile, which resulted in significant structural damage and unbalance.



(a) (b)

Figure 5. Tail drive shaft ballistic testing. (a) Spinning rig, (b) 20mm projectile damage. Unbalance = 15gR (*R* = shaft diameter).

2.2 Non-destructive inspection

DSTO has conducted non-destructive inspection (NDI) to detect ballistic damage in aircraft composite structures that is not visible from external surfaces after ballistic impact. The specimens tested include:

- Monolithic CFRP panels
- Composite sandwich panels with CFRP skins and Nomex honeycomb cores
- Composite frame-to-skin joints

The NDI methods applied include:

- Tap test
- Ultrasonic A-scan
- Thermography
- BaNDIcoot Scan
- Ultrasonic C-scan
- X-ray Radiography

The above first four methods are considered suitable for BDR applications in terms of portability and the C-scan and X-ray methods are mainly used as a yard-stick to assess other methods. Most of these NDI methods are well known, except for the BaNDIcoot Scan device (Fig. 6), which was developed by the Commonwealth Science and Industry Research Organisation (CSIRO), and is based on measurement of the vibration impedance of the material inspected(5). This device is not only highly portable (similar to A-Scan), but can also generate a damage map. Figure 6 also shows a highly portable thermography device developed by DSTO.

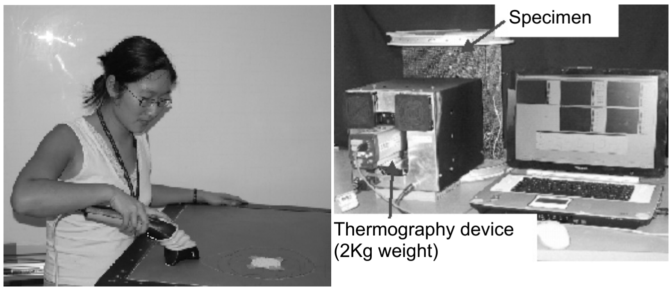


Figure 6. A BaNDIcoot scan device (left) and thermography device (right).

The damage pattern of the monolithic CFRP panels is illustrated in Fig. 7. The hole made by the projectile has a conical shape, with the exit side larger than the entrance side. The delamination area is much larger than the visible damage area, so needs to be accurately detected using NDI techniques.

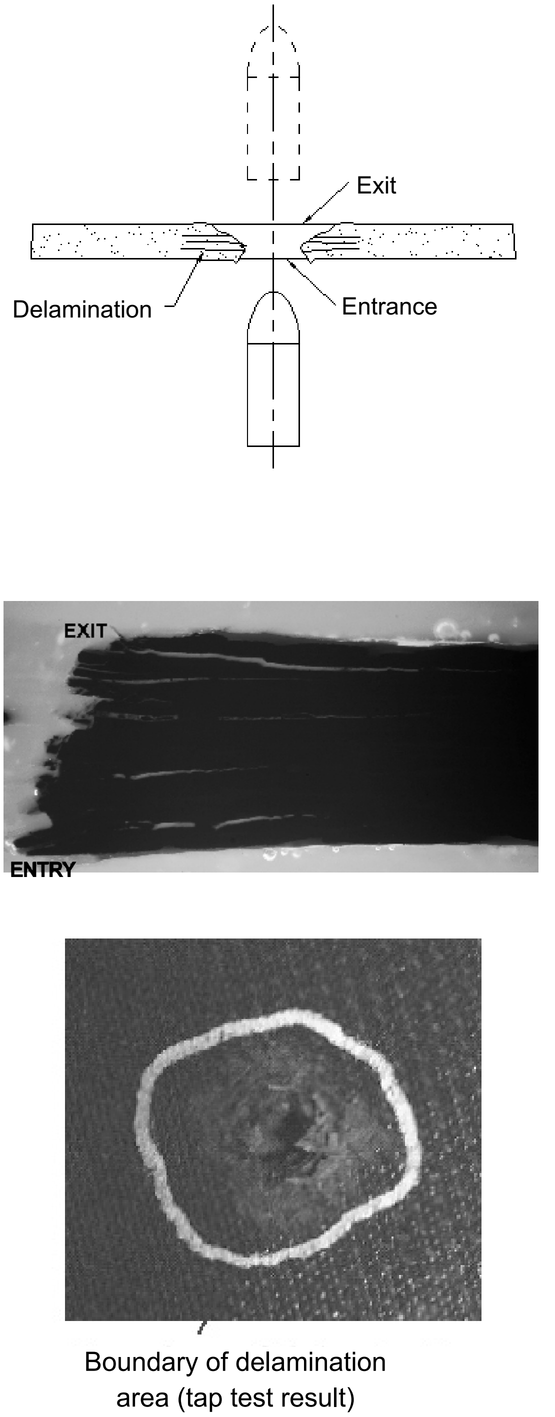
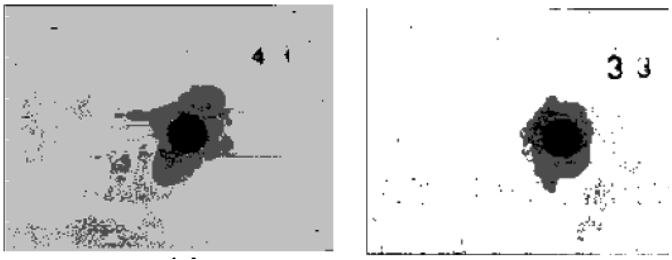


Figure 7. Ballistic damage pattern of a monolithic CFRP panel. Top: illustration of damage pattern. Middle: view of a sectioned specimen. Bottom: view from exit side of a specimen with a line marking the boundary of delamination area as determined in a tap test.

Regarding the structural-loading effect on ballistic damage, the NDI results also confirmed that with high structural loading ($> 7000\mu\varepsilon$), a significant increase in damage occurred. The results also verified that more damage occurs when ballistic impact is combined with structural load, than when separately applied (refer to Fig. 8).

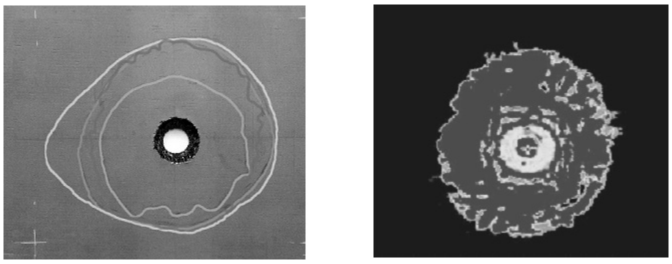


(a) (b)

Figure 8. C-scan images of 3mm thick CFRP panels with ballistic damage resulting from 20mm projectiles with normal impact. (a) Shot with 9,000$\mu\varepsilon$ structural loading; and (b) 9,000$\mu\varepsilon$. structural loading applied after the panel was shot with no structural loading.

Ballistic damage on thin-skinned honeycomb sandwich panels is more complicated, involving delamination in the skins, debonding between the skins and honeycomb core, and core damage. This damage can extend to a significantly larger area than the visible damage area (Fig. 9).

Figure 10 provides damage detection using thermography. Thermography rapidly detects damage over a large area and thus is;



(a) (b)

Figure 9. Damage of a honeycomb specimen detected using various NDI techniques. (a) Outline of the total damage area detected by, from outmost, tap test (initial), tap test (refined), BaNDIcoot and A-scan, superimposed on the exit surface; (b) BaNDIcoot damage map image.

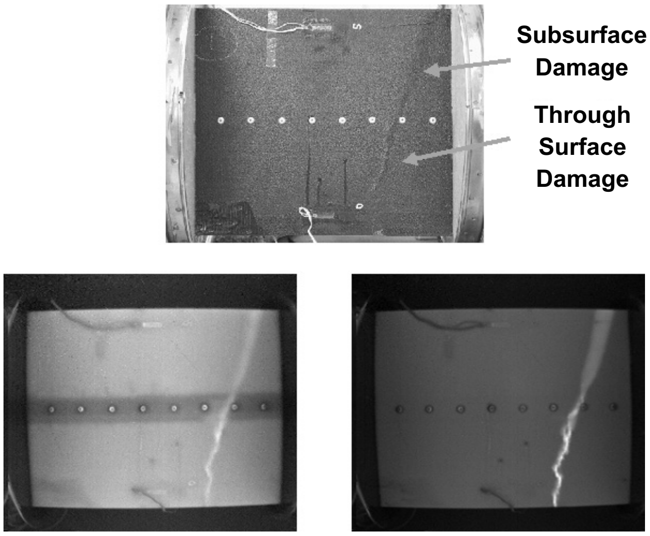


Figure 10. Thermography of frame-skin junction specimen.
Upper: specimen; Lower left: 1 sec after flash event;
Lower right: 6 sec after flash event.

The NDI work conducted provided an understanding of the damage extent in various specimens, and of the suitability of a range of NDI techniques for BDR applications. It was found in most cases that the different methods gave similar results. It was also found that proper training in both using the NDI technologies and interpreting the results is very important for NDI to be effective in real BDR scenarios.

Further NDI work is planned in the following areas:

- To assess emerging NDI methods and apply them to a wide range of specimens
- To explore the possibility of generating specimens, with typical damage and previously characterised using advanced NDI techniques operated by experienced technicians, that can be used for NDI training

2.3 Damage simulation

Simulation of ballistic damage may provide an understanding of the damage mechanism. It may also possibly replace some of the very costly ballistic testing.

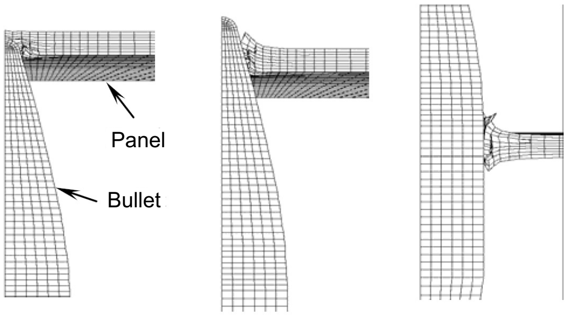
Simulation of ballistic impact to monolithic CFRP panels was conducted(6) using two available simulation tools; namely the FATEPEN (fast air encounter penetration) package(7) that is a set of fast-running algorithms based on a combination of simplified analytical and empirical models, and the Dyna3D explicit finite-element software(8).

In the FATEPEN simulation, the projectiles were approximated as tapered steel cylinders. The input data include panel size, thickness and hardness, projectile hardness, impact speed and oblique angle. The relevant outputs are projectile residual velocities, ballistic limit velocities of the panels and penetration hole sizes.

In the Dyna3D simulation, the speed and acceleration coupling option and the erosion contact option(8) were used to tackle the contact between the bullet and composite panel and erosion of the composite panel. Dyna3D composite material option was available to simulate the specimen panel material. The projectile was modelled initially as an elastic-perfect plastic material. With this material, the deformation was found to be very small and thus rigid material properties could then be used for subsequent calculations, which had the advantage of greatly reducing the computational time required.

The simulation results showed that residual velocities and hole areas predicted by FATEPEN are comparable to, but do not accurately agree with, the measured residual velocities and the visible damage area on the specimens. On the other hand, residual velocities predicted by Dyna3D are closer to the measured velocities than those calculated via FATEPEN. Hole areas predicted by Dyna3D are comparable to the visible damage areas on the specimens. Delamination areas predicted by Dyna3D agree reasonably well with the measurement. Hence Dyna3D appears to be a useful tool for evaluating delamination damage and thus structure residual strength of composite panels after ballistic impact. Figure 11 plots a typical penetration process simulated using Dyna3D. Figure 12 plots the comparison of delamination areas predicted using Dyna3D and measured in experiment.

As part of the efforts for ballistic impact simulation, high strain rate material testing was conducted using DSTO's Split Hopkinson bar test facility. Figure 13 shows some typical results.



(a) 4μs (a) 14μs (c) 80μs

Figure 11. Dyna3D simulation of penetration of a 2·57mm thick CFRP panel by a 12·7mm projectile with an impact speed of 438ms^{-1}.

2.4 Residual stiffness and strength

Knowledge about the residual stiffness and strength of aircraft composite structure with ballistic damage is important for determining the appropriate action following battle damage. If a repair is necessary, it would be important for determining requirements for the repair in terms of stiffness and strength restoration.

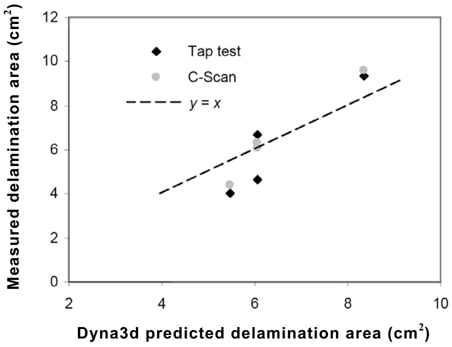


Figure 12. Comparison of Dyna3D predicted and measured delamination areas.

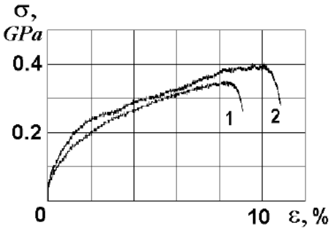


Figure 13. Through-thickness compression stress-strain relationship of a CFRP material at high strain rates. Split Hopkinson bar test results$^{(9)}$. Curve 1 – 1500 1/s and Curve 2 – 2000 1/s.

The residual strength and stiffness of a composite panel subjected to a bending load was initially measured as part of the program to investigate the effect of structural loading on ballistic damage in composite panels. The specimens were loaded in the 4-point bending rig up to ultimate failure (Fig. 14). The results showed that as the structural load increased during ballistic testing, a slight reduction in residual bending stiffness (around 10%) occured. However, structural loading during ballistic testing did not significantly affect the residual strength, probably owing to the progressive failure manner of the test specimens under 4-point bending loading. This is quite different from the tensile test results reported by the US Air Force$^{(3)}$, which showed that a pre-loading resulted in up to 20% residual strength reduction.

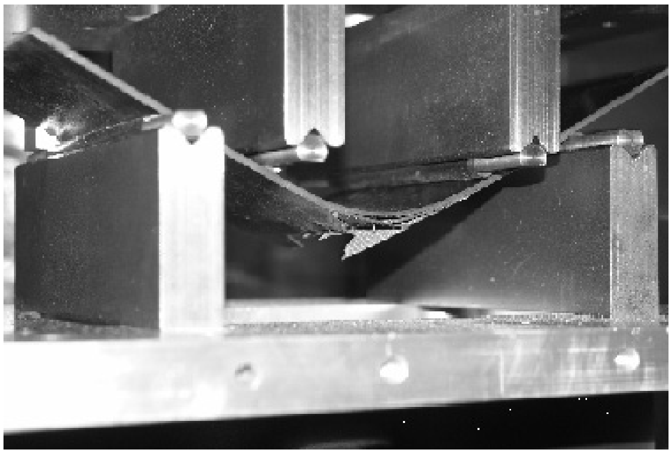


Figure 14. Residual stiffness and strength test. Prior to the test, the specimen shown was shot with a 20mm projectile with no structural load.

During the process to support development of a battle damage repair manual, the importance of the residual properties was further recognised, as they relate to how to specify and interpret the damage limits for a composite structure when it has many possible damage modes (skin in-plane damage including delamination, core damage or skin-core debonding in sandwich structure, etc.). A series of tests is currently being conducted to determine residual tensile, compression and shear properties of composite skins, honeycomb sandwich structures and frame components for a particular aircraft material system. This in conjunction with empirical formulae from the literature and computational modelling, hopefully should provide sufficient knowledge for practical use.

3.0 REPAIR MATERIAL SYSTEMS AND TECHNIQUES

Given the nature of a battle environment, the need for battle damage repair gives rise to two primary types of aircraft repair, namely a field repair and depot repair. The field repair must be completed within a short time frame (typically within two hours) with minimum portable tools and materials. The depot repair may take a longer time (24 to 48 hours$^{(1)}$) and utilise a greater level of tooling and materials which are likely to be available at a war time facility.

3.1 Repair material systems

Besides the requirement of high mechanical performance, the material systems for BDR applications require long shelf life, easy storage, portability, and the ability to be processed rapidly using minimum equipment. An important requirement for temporary repairs is that the repair process should create minimum damage to the parent structure to minimise the size and complexity of the permanent repair; hence the requirement for fastener holes for mechanically fastened repairs is a disadvantage compared with adhesive bonded repairs.

A number of material systems potentially suitable for rapid patch repair applications have been assessed. These include:

- Metal sheet or procured composite sheet/rivet
- Pre-cured composite sheet/two-part paste adhesive
- Wet-layup using dry reinforcement fabric and two part-resin
- Low temperature curing prepreg/film-adhesive
- Room temperature storage prepreg/film-adhesive
- UV curable prepreg/film-adhesive

The assessment included a series of standard coupon tests to characterise the stiffness and strength properties of the patch materials and bonding strength of the adhesive materials under room and elevated temperature conditions, applications of these material systems to repair aircraft components, and structural testing to verify the repair effectiveness with these materials under aircraft structural loading conditions.

Repairs based on riveted metallic patches are a traditional approach for aircraft battle damage repair. Patches may be applied rapidly to a flat surface or curved surface with single curvature. Note that whilst the thin and relatively brittle laminated polymer composite panels extensively used on composite aircraft structures make riveted patch repairs less effective, this repair method could still be effective for rapid repair of thick composite frame aircraft structures in BDR scenarios. This was demonstrated in a helicopter frame repair program where an aluminium patch was bolted to a thick CFRP frame structure with simulated ballistic damage. The repair was completed within an hour and repair strength was validated to be satisfactory in the subsequent structure testing.

The repair may alternatively be conducted using pre-cured composite patches bonded to the damaged structure with paste adhesives. This repair may be applied to a flat surface or slightly curved surface with single curvature. The pre-cured composite patch has the advantages of high strength and stiffness, low density, relatively easy surface treatment and is chemically compatible with the aircraft parent material in terms of adhesive bonding, over a metallic patch material. The paste adhesive material in two-part form may be stored at room temperature. The evaluation conducted in this study indicated that repairs using pre-cured composite patches with epoxy-based paste adhesives cured at elevated temperature were satisfactory.

The epoxy adhesive could be cured at room temperature, however, this would require extended curing time (one to five days depending on the adhesive used and repair strength requirement), that may not be available in a battle damage scenario. As an alternative to epoxies, acrylic paste adhesives can be cured rapidly at room temperature. This advantage makes them attractive for battle damage applications. Several acrylic adhesive materials were selected in this study and the testing so far showed that with rapid surface treatment, the adhesives achieved high bonding strength between metallic adherends, but only medium bonding strength between epoxy polymer composite adherends. Efforts are still being devoted to achieve high bonding strength between composite adherends by using improved surface treatment and other types of acrylic adhesive materials.

A wet-layup material system using two-part epoxy resins and dry reinforcement fabric also meets the long shelf life and easy storage criteria. It may be applied to contoured surfaces with double curvature. Compared with the pre-cured patch/paste adhesive system, it is also more versatile in tailoring the patch layup and edge taper to achieve the optimum repair design. The assessment conducted in this study indicated that the wet-layup material system has adequate laminate stiffness and strength and bonding strength for battle damage repair applications.

Low temperature curing prepreg/film adhesive, room temperature storage prepreg/film adhesive and UV curable prepreg/adhesive systems have also been assessed in this study. The low temperature curing prepreg system has the advantage of low temperature curing, low voids and low spring-in. Since these materials still need to be stored in a freezer, they are more suitable for depot repair applications. Prepregs/film adhesives generally need to be stored at low temperatures and thus do not meet the material storage requirement for field BDR applications. However, recent literature indicates that some prepregs and film adhesives may be stored at room temperature for an extended time(10). Thus these have good potential to be used for BDR applications. UV curable glass-fibre prepreg/adhesive may have a long shelf life at room temperature and the curing can be completed under UV light within a few minutes at room temperature. Thus this material system also has potential to be used for rapid battle damage repairs. The assessment conducted in this study so far has indicated these material systems are promising for BDR applications.

Central adherend material	Doubler and adhesive material	Width (mm)	Overlap length (mm)	Maximum load (KN)
8 layer of M18/G939 carbon epoxy prepreg(16) cured in autoclave	Dry carbon fabric/two-part resin wet layup*	25	13	13·9
			60	18·4
	Pre-cured CFRP laminate EA9395 paste adhesive(13)		13	11·6
			60	15·5
	UV curable fibre-glass prepreg and adhesive(15)		35	13·2

* RC200P dry fabric(11) and Hysol EA 9396C-2 epoxy paste(12)

Tables 1 and 2 list measured properties of selected materials discussed above.

Table 1
Selected test results of patch material properties

Patch material	Layup	Strength σ_{11} (MPa)	Stiffness, E11 (GPa)
Dry carbon fabric /two-part resin wet layup*	$(0/90)_8$	390	52·2
Low temperature curing carbon epoxy prepreg and film adhesive**	$(0/90)_8$	458	58·5
UV curable E-glass fabric prepreg(15)	$(0/90)_4$	475	25·6

* RC200P carbon fabric(11) and Hysol EA 9396C-2 paste(12)

** LTM45-1/CF0300 plain-weave fabric/epoxy prepreg and XVTA(13-14)

Table 2
Selected double-lap joint test results

3.2 Repair techniques

A series of repair techniques suitable for BDR applications were assessed in this study, including:

- Means of heating other than autoclave or oven
- Approaches to provide pressure during curing
- Rapid surface treatment methods
- Pre-manufacturing techniques
- Tools for rapid bonding quality validation

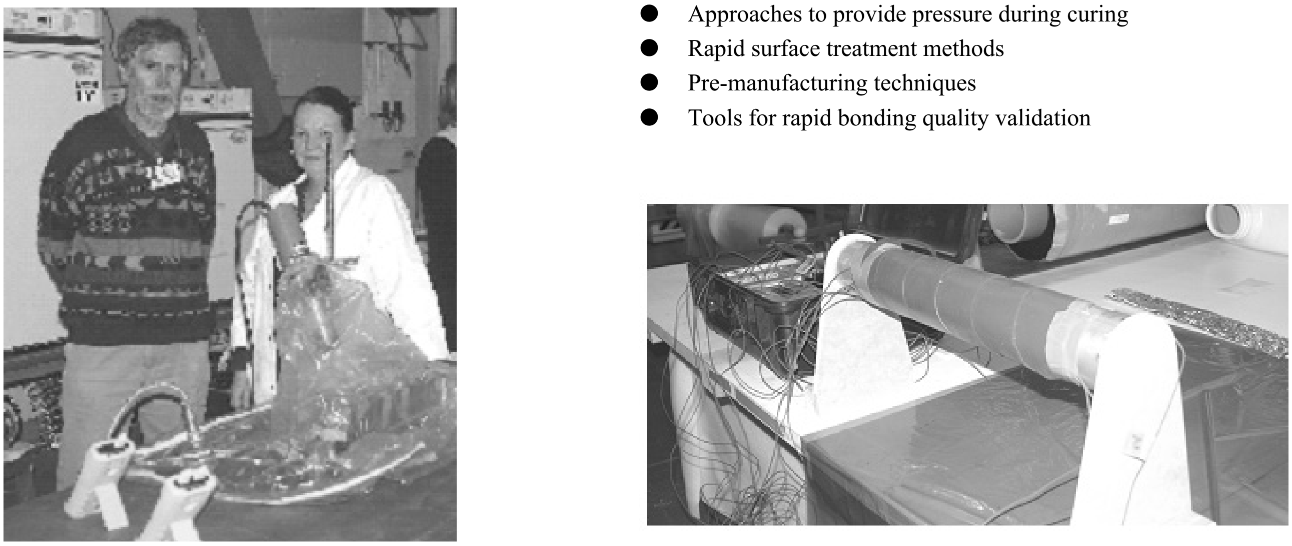


Figure 15. Bonded repairs cured under a hot air gun (left) and electrical blanket (right).

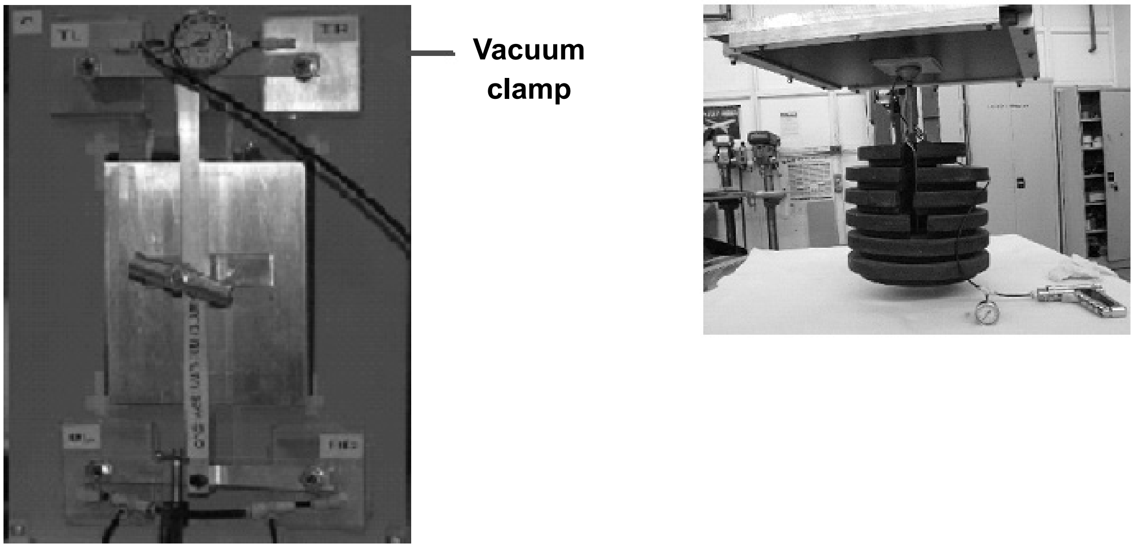


Figure 16. Left: a mechanical clamping jig to apply pressure to a repair patch. The pressure is applied by clamping an aluminium plate onto a layer of silicone rubber that covers the patch. The jig is attached to the structure by using vacuum pressure through four 'vacuum clamps'; Right: a pull out test to examine the loading capacity of the vacuum clamp.

Hot air guns and electrical blankets are portable and effective for curing adhesives at elevated temperature. Figure 15 shows some trials conducted at DSTO.

The application of a bonded patch repair to an airframe component requires the use of bonding pressure. The use of the standard vacuum bags is a simple and very effective means for developing (atmospheric) pressure for forming and bonding patches and thus is widely used.

The success of vacuum bags relies on the vacuum integrity of the prospective repair region. Sometimes sealing is difficult to achieve due to leaks for example through the damage or fastener holes in the region. In some particular circumstances, vacuum may also cause expansion of entrapped solvents and air, resulting in porosity in the adhesive and, if co-cured, the patch as well. These problems do not arise with positive pressure. Riveting is an effective way to provide positive pressure(17), which is applicable when a pre-cured laminate patch is used and the relevant surface of the aircraft component is flat or of low single curvature. Hand clamps, straps, magnetic stones and other simple devices, are effective in producing modest pressures under a limited range of conditions, for example to small components or where internal access is available.

A mechanical clamping jig is a very effective means of pressurising prepreg and wet-layup composite patches as well as adhesives. By using a rubber pad or better a gas bladder this approach can apply pressure to double curvature surfaces. However, the use of mechanical clamping jig requires existing attachment points on the airframe that are often not available at a required or specific location. Research was carried to develop a versatile approach to attach a clamping jig to aircraft external surfaces using a vacuum clamp. A jig system is shown in Fig. 16. Pull-out tests conducted indicate that the vacuum clamp can provide high and durable clamping force at environmental temperatures tested up to 55°C under vacuum provided by a hand pump. The vacuum pressure did not cause any damage to the thin-skin honeycomb sandwich panel.

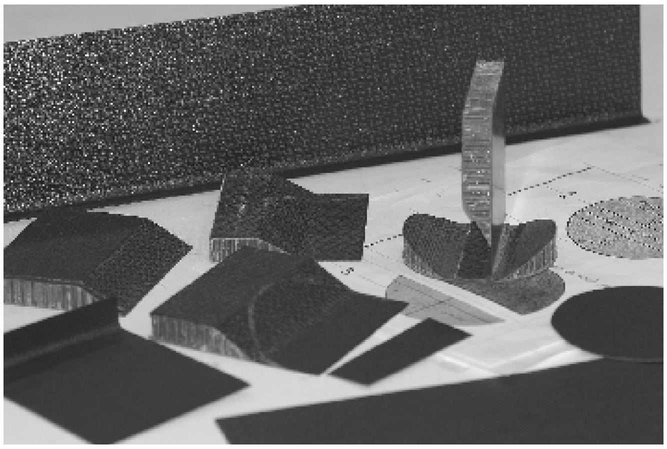


Figure 17. Pre-manufactured materials and rapid insert manufacture.

To form a strong bond, the surface of the adherend is generally treated before application of the adhesive. For BDR applications it is desirable to develop a relatively simple surface treatment procedure that may be rapidly applied, without significant compromise of the bonding strength compared with a standard surface treatment procedure. Considerable efforts have been made in this area, including, particularly for metal surfaces, establishment of the situations (combination of adherend material type, degree of contamination, adhesive material type and environment condition), where grit blast may be omitted or replaced with manual abrasion. Other surface treatment techniques, such as silane or the more recently Boeing Sol-Gel, have also been assessed(18). Further research in this area is still progressing.

To speed up BDR a rapid fabrication technique was developed in this study. The idea was to make use of pre-manufactured parts as much as possible so that operating units would have the necessary repair items on hand to allow a rapid application during times of conflict. It is general practice to store pre-cured composite panels with suitable thicknesses and core materials for BDR applications. For a particular aircraft, as the structures in many areas are standard, more pre-manufactured components could be made. Figure 17 shows pre-manufactured honeycomb cores, CFRP flat plates and angles. Figure 17 also shows an insert, to be used for BDR of a frame-skin juncture, that was rapidly made using these pre-manufactured materials bonded using a fast curing adhesive. The honeycomb core was pre-bonded with a thin layer of CFRP at both surfaces. The bonding surface becomes a smooth, porosity free surface significantly reducing the efforts in the subsequent bonding process.

Another project in progress is the development of a bond quality tester, to provide a portable simple tool that may rapidly test bond strength after applications of bonded BDRs and, in the case of more permanent repairs, check long-term durability. This may also be a useful tool for BDR technician training.

4.0 BDR DESIGN, IMPLEMENTATION AND VALIDATION OF HELICOPTER COMPONENTS

A generic BDR design approach was applied, which involved:

- Use of a reverse engineering approach to determine the load requirements, in case (as is often the situation) that there is no design information from the Original Equipment Manufacturer (OEM);
- Application of a rapid repair design approach; and
- Validation of the design using finite element analyses and experimental testing.

In this section, the reverse engineering approach will be briefly described firstly, then BDR design, implementation and validation of several helicopter components will be presented.

4.1 Reverse engineering approach for BDR applications

With known geometry and material property information, the stiffness and load capabilities of the undamaged structure under various load conditions may be determined analytically or experimentally.

With the above information known, design and validation of a repair to restore the stiffness and loading capacities of a damaged structure becomes feasible without requiring the design data from the OEM. This approach may be used to define prescribed procedures for both depot and field repairs with pre-defined damage limits. With sufficient development on helicopter technical information database and repair design software, this approach may also be feasible for rapid depot-level repair design without the consideration of pre-defined damage limits.

The procedure to determine the load requirements includes the following steps:

- Fully understand the geometry and material specification/properties of the aircraft structure concerned;
- Consider various possible loading conditions that a structure may experience during aircraft service;
- Calculate stiffness of the structure under these loading conditions;

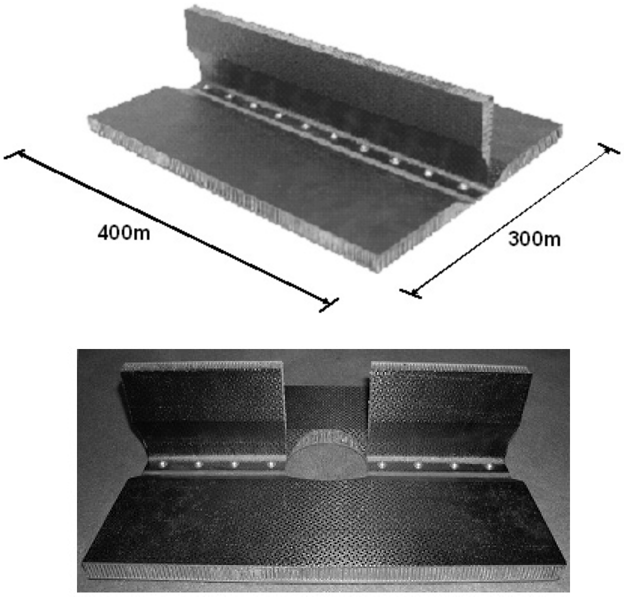


Figure 18. FSJ specimens manufactured by DSTO. (a) Pristine specimen; and (b) Specimen with simulated battle damage.

- Determine the critical sub-components that limit the maximum loadings the structure can undertake under these loading conditions. These loadings are the possible maximum loadings the structure may experience;
- To avoid an over-conservative repair design, various knock-down factors may be considered. For example, the design ultimate load during wartime may be reduced by a certain amount depending on the acceptable increase of the risk level, and the factor of the specified ballistic tolerance of the structure.

At a minimum, a repair must restore sufficient structural stiffness and strength to provide for flight under restricted conditions, such as a ferry flight back to a maintenance base. However, a repair may restore stiffness and strength such that the aircraft has full mission capability.

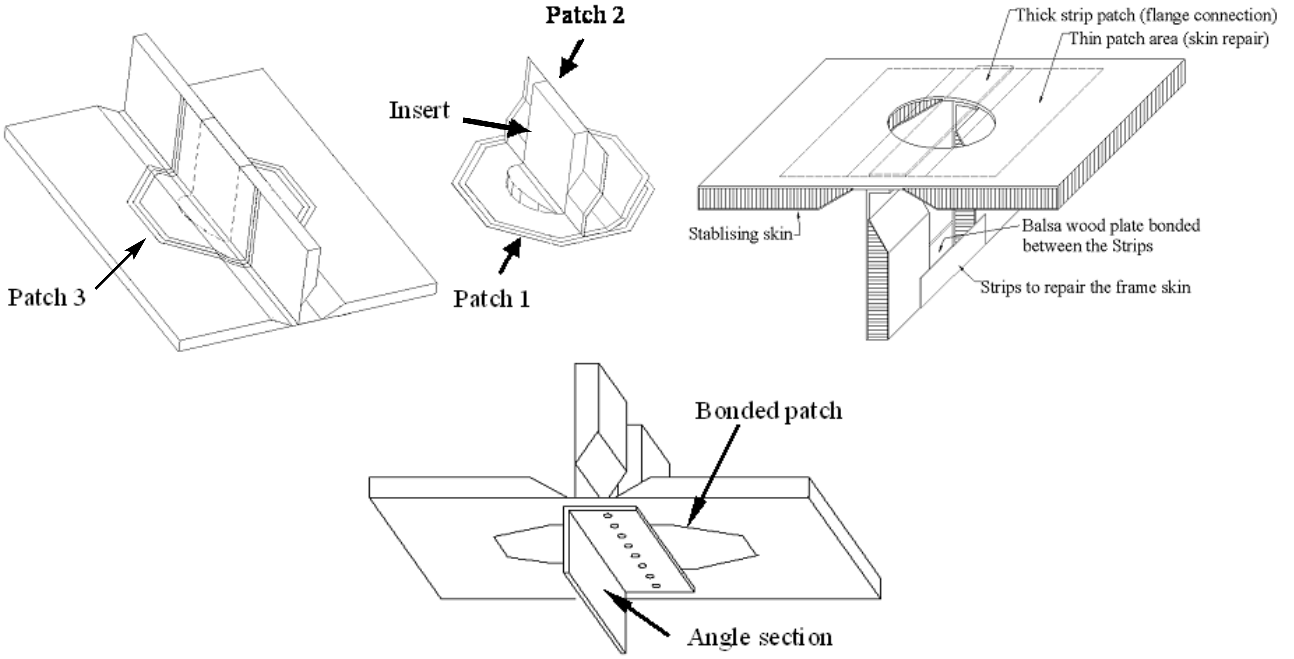


Figure 19. Layout of repair configurations. (a) Full internal access; (b) Limited internal access (only through damage hole); and (c) External repair.

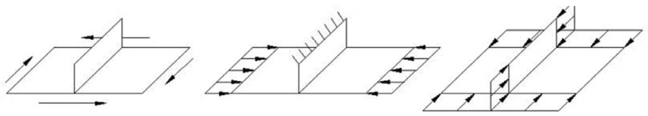


Figure 20. Major Loading conditions considered.
(a) Fuselage skin shear;
(b) Axial (from nose to tail) compression; and
(c) Transverse (frame axial) compression.

The reverse engineering approach has been successfully applied for BDR of a number of helicopter components, including a helicopter frame-skin junction (FSJ) that will be further described in Section 4.2 below.

4.2 Battle damage repair of a composite helicopter frame-skin\junction

The FSJ considered is made up of CFRP skins and Nomex honeycomb cores bonded together with structural adhesives (Fig. 18). Rivets were used along the frame-skin junction bondline to provide pressure during bonding and provide residual strength during service should debonding occur.

Battle damage was simulated using a 90mm diameter circular cut-out through the skin and frame (Fig. 18(b)). The size of the hole is considered to be representative of damage from penetration of a typical armour-piercing projectile including any area surrounding the impact site which is likely to contain delamination. The basis for using a machined hole to represent the damage zone rather than an actual ballistic impact zone was to ensure that the damage zone would be consistent amongst all of the damaged specimens. This was considered important for assessment of repair effectiveness, which is based on relative comparison of strength among the undamaged, damaged and repaired specimens.

Figure 19 shows the repair configurations. In the full internal access case (Fig. 19(a)), the repair consisted of three CFRP patches and an insert bonded to the damaged FSJ to provide a full repair. It assumes the full helicopter internal access is available, suitable for a depot repair, or in a field repair scenario, a FSJ near an accessing door or window. The sole external repair configuration (Fig. 19(c)) was made of a patch and a length of aluminium angle externally bonded and riveted respectively to structure, suitable for a field repair. Figure 19(b) shows the novel technique developed for repairing the internal structure where access is only available through the relatively large hole caused by the damage. The approach was to put pre-cured skin strips and core material through the hole and bond them to the undamaged part of the internal structure. An external patch repair was then applied to complete the repair. More information can be found in References(19,20).

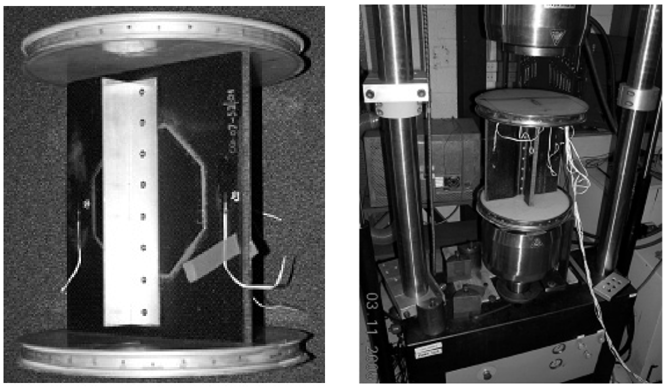


Figure 21. FSJ Specimen and compression test. The specimen ends were encapsulated in a resin casting. The encapsulation provides reinforcement to avoid premature failure of the specimen ends and helps smooth the load application.

- Fuselage skin shear (Fig. 20(a));
- Axial (from nose to tail) compression/tension (Fig. 20(b)); and
- Transverse (frame axial) compression/tension (Fig. 20(c)).

Since the fuselage skins are supported by honeycomb or frame, the sandwich structure should withstand shear and compression loadings. Furthermore, between the compression and tensile loadings, only the compression loading was considered as the compression loading provides a measure of the stability (buckling load) of the structure, whereas a tensile load generally does not.

A FE modelling was conducted to determine the load requirement following the procedure detailed in Section 4.1. The modified Hart-Smith approach(21-22) was used in the bonded repair design. For the riveted repair, the aluminium angle material properties and rivet bearing strength were considered.

Finite element analyses were further conducted to evaluate the repair designs under the various load conditions. The analyses included: linear static, linear buckling, material non-linear and geometric non-linear analyses. The results showed that the damage would cause significant strength reduction. The full-access repair could fully restore the static strengths and buckling stability; the sole external repair could sufficiently restore the strengths as required for a temporary repair; and the limited access repair achieved a strength in between those of the other two repairs as expected.

The repair was further validated experimentally (Fig. 21) in the selected load case (worst case scenario as determined from the FEM modelling).

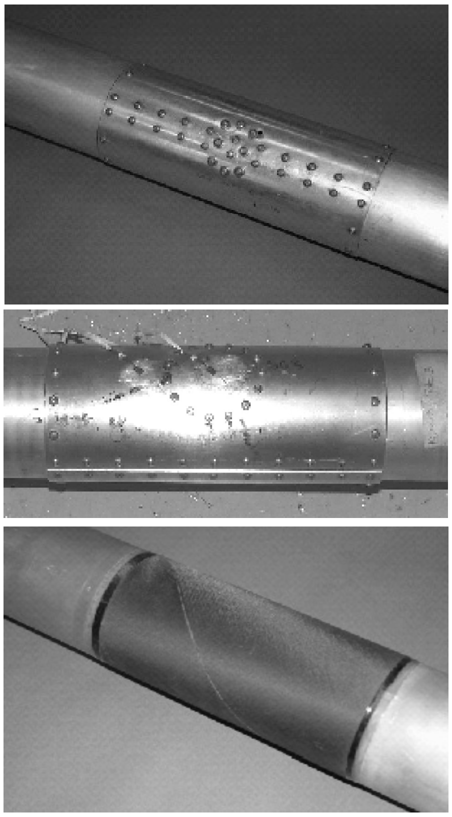


Figure 22. TDS Specimens with repairs.
Top: riveted repair using a single riveted aluminium sheet;
Middle: riveted repair using two pre-rolled halves of aluminium sheets;
Bottom: bonded repair using a composite patch.

Further research is now planned to explore the optimal end tapering of the repair angle and the possibility of achieving a better load path by replacing the angle with a C-channel for frame repair.

4.3 Battle damage repair of a tail drive shaft

The tail drive shaft (TDS) of a helicopter is both primary structure and a dynamic component. The TDS of a military helicopter is designed to have a relatively large ballistic damage tolerance. Provided that the ballistic damage is within this tolerance, the shaft would not fail catastrophically upon receiving the ballistic impact. However, the damage could seriously compromise the performance of the helicopter. Depending on the degree of the damage, the helicopter may not achieve its full mission capability, or in the worst case, might even be at risk for a return-to-base flight. Ideally, the damaged shaft would be replaced as soon as the helicopter is landed. However, a replacement shaft may not always be available.

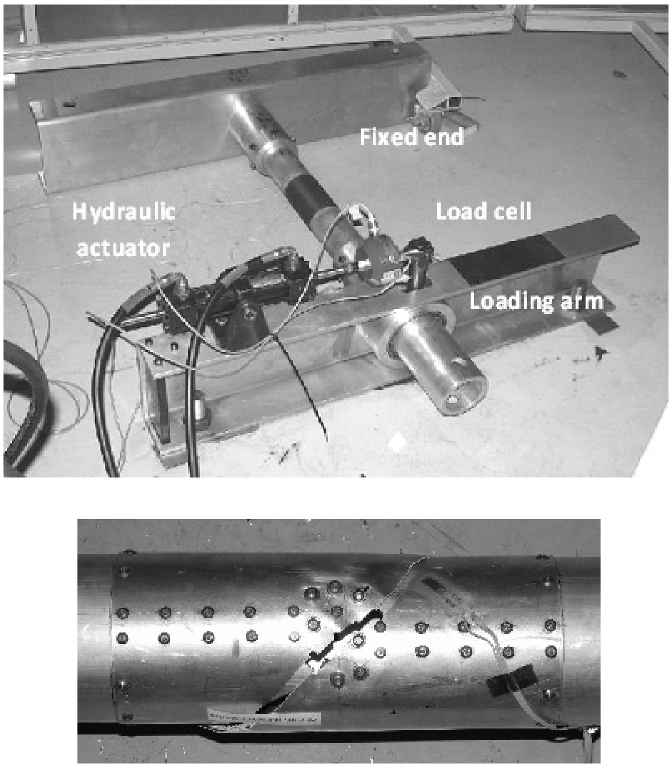


Figure 23. TDS torsion test. Top: test rig. Bottom: Failure of a single, thin aluminium sheet, riveted repair under fatigue loading.

As discussed in Section 2.1, the helicopters being considered here have three sets of tail drive shafts, namely, horizontal shafts, a pylon shaft and a tail rotor output shaft. The horizontal shafts, due to their high rotational speed and low sectional area, are the most critical component in terms of the adverse effect of the shaft unbalance and strength reduction imposed by ballistic damage and thus were the focus of this study. The horizontal TDSs are generally made of aluminium alloys.

Two factors must be considered when developing battle damage repairs for a TDS, namely the repair needs to be completed within a short timeframe, with minimum facilities and materials, and restoration of balance must be achieved by a well-defined repair procedure, assuming unbalance could not be measured under the BDR condition.

Three types of repair were assessed: a thin, single aluminium sheet, riveted repair (Fig. 22 left); an improved thick, two-half aluminium shell, riveted repair (Fig. 22 middle); and composite bonded repairs (Fig. 22 right). The first was a traditional repair method, while the second and third were developed in this study. The assessment included the time required to complete the repair, effectiveness of balance restoration and strength restoration, and other factors, such as the effect of the repair on the vibration behaviour of the shaft.

In terms of time required to complete the repair and effectiveness of balance restoration, the assessment indicated that traditional thin sheet, riveted repair method could be implemented within two hours, which is suitable for field BDR applications, and is reasonably effective in restoring the rotational balance of the shaft. The thick, two-half aluminium shell (which need to be pre-rolled and stored in BDR kits), riveted repair, can be completed in a significantly shorter time scale, with better balance recovery. The bonded repair may be implemented in approximately four hours, well suited for many BDR applications at a forward base, with excellent balance recovery.

Static and fatigue tests (Fig. 23) indicated that the damaged shaft would not immediately fail catastrophically upon receiving a ballistic impact if the damage is within the specified ballistic damage limit, however, the shaft would be under a high risk of failure for further flight if the damage is large and not repaired. The thin, single aluminium sheet, riveted repair significantly restored static strength, however, it is considered that the repaired shaft may only be used for limited time for a mission, as it's fatigue life is short. The improved thick, two-half aluminium shell, riveted repair and bonded repair had sufficient static strength and, in terms of the requirement for a battle damage repair, excellent fatigue life. The bonded repair may even be considered as a semi-permanent repair.

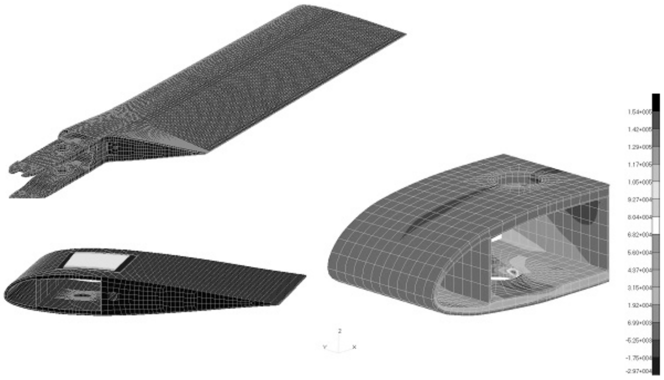


Figure 24. FE model of a helicopter main rotor blade. Upper: FEM mesh of inboard part; Lower left: a slice showing damage and patch repair; Lower right: predicted stress distribution at the damaged area, under combined tensile and bending forces.

4.4 Battle damage repair of a helicopter main rotor blade

For a battle damage repair to a helicopter main rotor blade, a series of complicating factors need to be considered, including static and dynamic balance, the effect of repair on aerodynamic performance and dynamic behaviour of the blade, validation methods for structural strength, etc., in addition to the feasibility of completing a repair that can restore the local stiffness and strength at the damaged area and meet BDR time and facility requirements. A literature review was conducted to assess the state-of-the-art knowledge in these. It indicated that a battle damage repair to a helicopter main rotor blade is feasible and should play a vital role

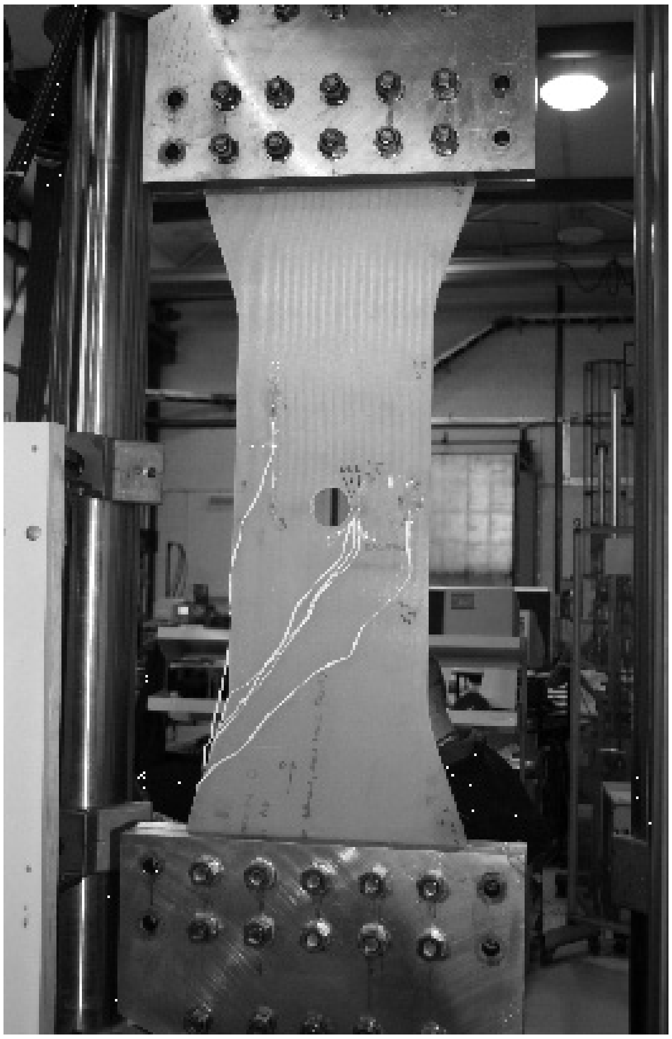


Figure 25. A large panel test. A specimen with a 50mm hole is shown.

in maximising helicopter availability during times of conflict.

Repairs to non-spar damage have been included in existing helicopter BDR manuals and thus the techniques may be considered as mature. Spar damage to blades with metallic spars is considered non-repairable due to the poor fatigue notch sensitivity of metal spars used in most operational blades. The main rotor blades with composite spars have been used in new generation helicopters. These blades have high fatigue resistance even in the presence of notches, making BDR repair to a blade with spar damage feasible.

The major objective is to examine if a rapid bonded patch repair could sufficiently restore strength of a rotor blade with ballistically damaged composite spars, with other factors, listed previously in the beginning of this subsection, taken into account.

The following repair considerations were made:

- Only externally applied lap joint repairs are feasible under field BDR conditions (scarf or other complicated repairs are not considered);
- The repair does not have to restore the full original strength of the structure (including full ballistic tolerance); rather it targets a sufficient increase of the safety factor up to what is required for full mission capability.

A main rotor blade for a typical military helicopter is considered in this study. The blade including its spars is made of S-glass reinforced polymer composite materials.

FEM modelling of pristine, ballistically damaged, and damaged and then repaired specimens was conducted (Fig. 24). The loads considered include a span wise tensile load due to the centrifugal force and bending moments due to lift and drag forces. The ballistic damage was simulated using holes with different sizes. A typical condition considered in the analysis is when the damage reaches the design ballistic tolerance. The helicopter would be under some risk of structural failure if a mission is continued without repair. The FEM results indicate that a relatively low-mass and thin patch repair could reduce the maximum stress by around 40%, effectively enabling the helicopter to continue its mission with a significantly increased safely margin, and thus warrants further experimental investigation.

The planned experimental program includes three levels of testing:

- Coupon tests
- Large panel tests
- Constant section blade specimen/full blade specimen tests

The coupon tests have been completed. The large panel testing is being conducted (Fig. 25). The tooling for the constant section blade specimens has nearly been completed. For the full-scale specimen test, it is planned to use unserviceable blades as test specimens

5.0 SUMMARY AND FUTURE WORK

This paper summarises recent research conducted at DSTO in the area of aircraft battle damage repair, covering aspects such as ballistic testing, ballistic damage prediction, non-destructive inspection of damage, structural residual strength assessment, repair design approaches, repair materials and techniques, repair implementation and demonstration. The research in some of the areas was conducted in conjunction with CRC-ACS. The research has been focused mainly on composite helicopter structures. This paper provides an overview of a wide range of research conducted and detailed information in selected areas.

In terms of future research, besides continuing work in the areas already discussed, it is also considered to develop computer software and a database for BDR applications. DSTO will also try to focus more on technology transfer to the Australian Defence Force and industry; working together more closely with them, and promoting collaboration with other defence research organisations and industries to achieve the goal.

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