THE DEVELOPMENT OF AN ENGINEERING STANDARD FOR COMPOSITE REPAIRS.

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SUMMARY

The RAAF has used bonded composite patches for structural repairs to aircraft for nearly twenty years, and they are now seen as a reliable alternative to mechanically fastened repairs. To control the implementation of the repair technology, RAAF propose to adopt Engineering Standard C5033 on Composite Materials and Adhesive Bonded Repairs. The Standard addresses repair authorisation and design, as well as repair methodology and quality control.

This paper will describe the philosophy of repair design contained in the standard, and outline the materials and process controls necessary for performance of repairs which comply with ISO 9001.

1. INTRODUCTION

Bonded composite repairs have been used by RAAF to repair defective metallic structures since May 1975 [1,2,3]. These repairs have achieved significant cost savings for RAAF. Some benefit is derived from the reduced application time (up to a factor of six) and the longer fatigue life of the repairs, compared to mechanically fastened repair. However, other savings have been identified which are more significant than the short term advantages provided by the method. For example, the use of simple bonded boron/epoxy patches on C-130-E aircraft has enabled the RAAF fleet to achieve life-of-type without wing plank replacement programs, which have been forced on many other operators.

The RAAF now sees bonded repair technology as a viable alternative to mechanically fastened repairs. To control the use of the technology, RAAF will adopt an Engineering Standard on Composite Materials and Adhesive Bonded Repairs (Eng. Std. C5033). The purpose of this Standard is to formalise procedures in such a way that repair designs are addressed in a manner appropriate to their criticality, and application procedures are standardised to specific processes which have been validated by scientific testing.

A long term objective is to refer *all* bonded repair procedures for all aircraft types to this Standard. Such a practice will eliminate variations in procedures between aircraft types, and eliminate erroneous procedures contained in existing repair manuals. Common training in procedures which are not aircraft specific will provide greater flexibility in service postings, and by use of modular training, personnel will be trained only to the level appropriate for each aircraft type.

Rapid incorporation of advances in processes developed by DSTO laboratories is also facilitated by the use of a single publication. Any amendment would automatically apply to all aircraft types which use the specific procedure being changed.

2. APPLICATION OF THE STANDARD

Repairs are to be considered as a total package, with the design engineer having responsibility for

- Defect Assessment.
- Repair Design.
- Materials Selection.
- Application Processes.
- Quality Management.
- Aircraft Restoration.
- NDI Requirements.

This level of control recognises the deficiencies experienced by RAAF in bonding techniques in approved Original Equipment Manufacturer (OEM) manuals for repair of sandwich panel and composite structure [4].

3. REPAIR DESIGN

Repairs are designed as bonded joints, using an analytical approach which is a combination of AMRL "crack patching" technology [5,6] and John Hart-Smith's bonded joint analysis [7,8,9]. This method is permitted for secondary and tertiary structural elements. The method may be used for preliminary design for primary structure, however validation by Finite Element methods and/or experimental methods is mandatory.

Design is a multi-stage process (see Fig. 1) which involves:

- Checking Rapid Repairability Criterion (adhesive load capacity).
- Calculating required overlap length and patch dimensions.
- Verification of integrity of repaired structure.
- Verification of repair durability.
- Calculation of tolerable bond defect size.

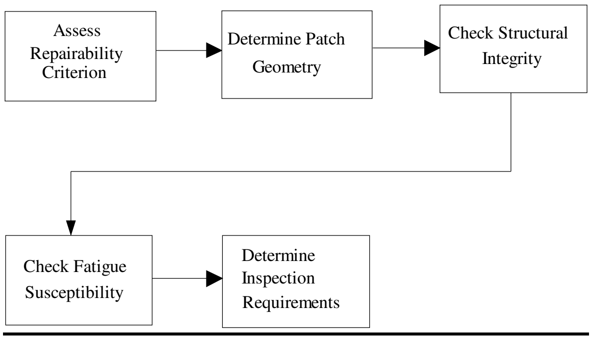


Figure 1. Process flow for repair design.

3.1. Patch Thickness

Patch thickness is determined from stiffness requirements. As a minimum requirement, the patch stiffness ***Et*** should match the stiffness of the parent structure, in order to restore load intensity capacity.

3.2. Rapid Repairability Criterion

A major advantage of adhesive bonding is that the load capacity of an adhesive bond can be designed to be GREATER than the unnotched yield strength of the parent material (see Fig. 2). (Note; not just design ultimate) [9]. This provides a simple test to determine if simple design methods may be used by field engineers, i.e. a Rapid Repairability Criterion. If the load capacity of the adhesive is greater than the unnotched yield strength of the parent material, together with a reasonable safety factor, then the repair can be designed using simple methods.

If this requirement can not be met, or if any of the remaining design requirements can not be satisfied, then the repair is directed to a design authority for comprehensive repair design. Note that a failure to meet the Rapid Repairability Criterion does not mean that the structure is unrepairable. It simply means that a higher level design is required.

The load capacity is calculated using Hart-Smith's equations for double overlap joints [8]. Single overlap repairs which have restraint against out-of-plane bending are analysed as a double overlap joint on a structure twice as thick as the actual structure. The load capacity is given by the lesser value of:

$$P = (\alpha_o - \alpha_i)\Delta T E_i t_i + \sqrt{2\eta\tau_p\left(\frac{1}{2}\gamma_e + \gamma_p\right)2E_i t_i\left(1 + \frac{E_i t_i}{2E_o t_o}\right)}$$

and

$$P = (\alpha_i - \alpha_o)\Delta T\, 2E_o t_o + \sqrt{2\eta\tau_p\left(\frac{1}{2}\gamma_e + \gamma_p\right)4E_o t_o\left(1 + \frac{2E_o t_o}{E_i t_i}\right)}$$

The variables are shown in Fig. 3. If the adhesive load capacity is greater than the unnotched strength of the parent structure, knowledge of actual loads is unnecessary for assessment of the adhesive strength, as such designs automatically satisfy all other load cases.

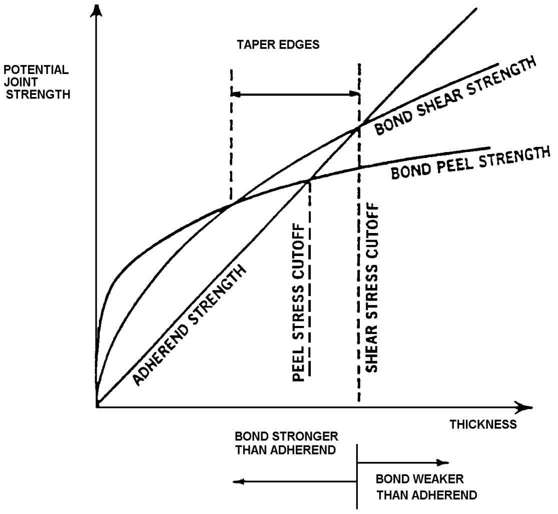


Figure 2. Load capacity of bonded joints, showing that adhesives may be designed for a load capacity greater than the strength of the parent structure [9].

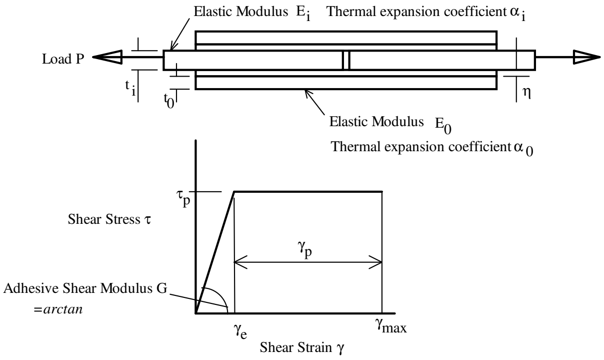


Figure 3. Variables used in load capacity calculation for double overlap repair.

The standard requires the adhesive load capacity to be greater than 1.2 times the unnotched yield strength of the parent material.

$$P > 1.2 \times t_i \sigma_y$$

For non-critical structure, any repair design which meets this requirement is repairable, provided the remaining structural integrity and durability checks are acceptable. Where this requirement can not be met, the repair is referred to a Design Authority, possibly for a full Finite Element analysis at Design Ultimate Load. (Note that FE methods which replace the patched area with equivalent stiffness elements are not recommended. FE analysis must correctly represent the behaviour of the adhesive layer.)

For repairs designed to this requirement, the adhesive will never be the critical element in the repair. The structural integrity is then limited by the strength of the patch, or the strength of the repaired structure. Note that this design procedure results in very conservative designs, as shown in Fig. 4.

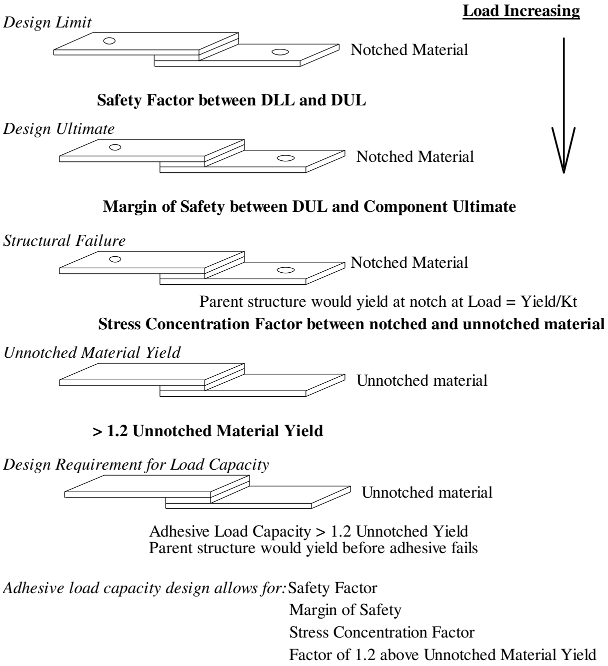


Figure 4. Design requirements for aircraft repair. By designing the adhesive load capacity above material yield, the adhesive is never the critical element in the repair. There is a significant margin of safety between Design Limit or Design Ultimate and the required load capacity for the adhesive.

3.3. Overlap Length

Shear stresses in bonded joints and repairs peak at the ends of the overlap. At higher loads, the adhesive becomes plastic at the ends. For the analysis, the adhesive is assumed to be ideally elastic-plastic, so a plastic zone exists at the ends of the joint at high loads (see Fig. 5). The fact that the adhesive is allowed to exceed the plastic limit does not have the same connotations as for normal structural designs. For adhesive bonds, a very significant proportion of the load capacity is achieved due to plastic behaviour in the adhesive [9].

If the plastic zones are designed to be large enough to carry ALL the load at material yield (see Fig. 6) the joint will always have a load capacity greater than the parent material [9]. An elastic zone is essential for creep resistance and damage tolerance.

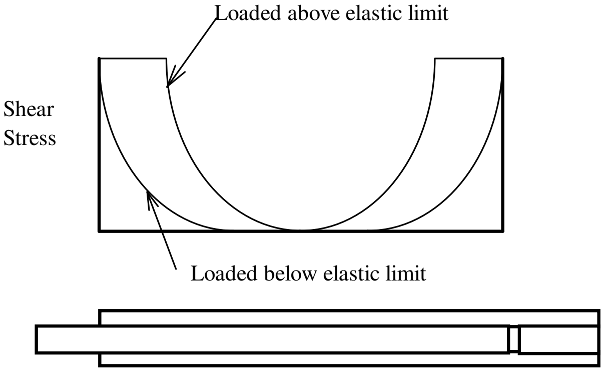


Figure 5. Assumed shear stress distribution in adhesive in bonded joints showing the plastic zones developed at the ends of the joint at higher loads.

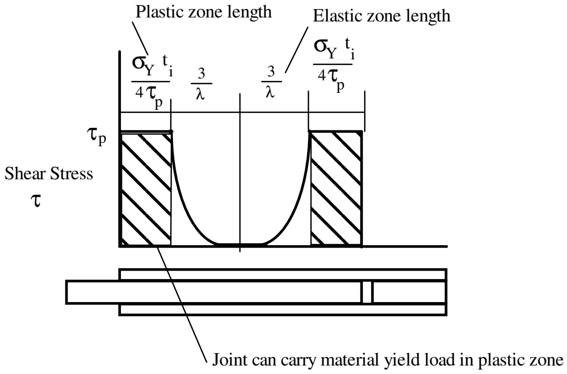


Figure 6. Repair overlap lengths for elastic and plastic zones, such that the load capacity will be greater than the parent structure [9].

In bonded repairs designed this way, the adhesive is never the critical element. The adhesive is therefore damage tolerant, provided the calculated length of the plastic zone always exists in the bond line. Although this design philosophy requires larger overlaps than crack restraint designs or designs based on actual ultimate load values, the simplification of the design process inherent in this approach greatly facilitates repair management. It is also conservative, and the reserve factors built into the designs will readily accommodate variations in material properties and repair geometry experienced in practical repairs.

This method of repair management provides a clear delineation between a conservative design method suited for less critical repairs, and repairs to critical components, where a more exacting analysis is appropriate.

4. STRUCTURAL INTEGRITY ASSESSMENT

Integrity of the repair depends on:

- Integrity of the adhesive.
- Patch strength.
- Strength of the repaired structure.

A structural integrity assessment must address all of these factors.

4.1. Integrity of adhesive

The fact that the Standard requires adhesive load capacity at least 1.2 times material yield strength, or twice design limit load automatically establishes the integrity of the adhesive. However, the Standard also requires verification that the maximum shear strain at Design Ultimate is below the maximum shear strain for the adhesive.

4.2. Integrity of structure

Integrity of the repaired structure is assessed at Design Ultimate Load (DUL). Where DUL is not known, structural integrity is assessed using Material Yield divided by a known stress concentration in the original structure. The result is multiplied by a factor of 1.2 for safety.

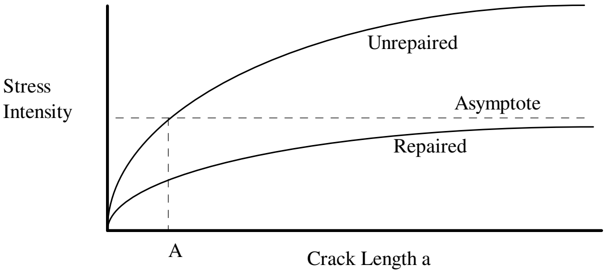
The design process used for assessment of structural integrity depends on the defect type remaining under the repair patch: Essentially, two cases exist:

- Structure with a crack remaining.
- Structure with a defect removed.

4.2.1. Cracked Metallic Structure

For cracked structure, the design is based on the stress intensity after repair at DUL, using AMRL's "Crack Patching" analysis [4,5]. This analysis shows that stress intensity after repair approaches an asymptote for increasing crack length (see Fig. 7) [5]. Crack repair design using this method is therefore independent of the original crack length, as the design is based on the asymptotic value of stress intensity. Since the stress intensity never exceeds the asymptotic value, the method is conservative.

The value of the asymptotic stress intensity is checked against reference values of fracture toughness of the structural material.



Crack behaves like unrepaired crack of length 'A'

Figure 7. Stress intensity variation with crack length for repaired and unrepaired structure [6].

Note that the Standard does not permit "stop" drilling before repair. Fatigue tests [10], have shown that drilling the crack tip produces no improvement in fatigue life of bonded repairs, and may in some cases reduce the fatigue performance. This is because drilling removes the existing crack tip plastic zone, which is known to provide some crack retardation [5].

Routing out cracks before repair results in a significantly lower fatigue life of the repair, and therefore this practice is also prohibited.

4.2.2. Non-Cracked Structure

For non-cracked structure, such as structures where damage has been cut out or for bonded doublers applied to uncracked structure to reduce stress, the procedure relies on estimation of the maximum stress in the structure under the patch, taking into account the reduced stress due to patching. This is conservative, as the displacement modification at the defect is ignored. (Any displacements which occur at the edge of the defect will result in a displacement difference between the structure and the patch, causing shear in the adhesive. The resultant load transfer will reduce the total displacement which would have occurred at the defect.)

A damage tolerant design using conventional methods is possible by assuming that the repaired structure has a crack equal to the asymptotic crack size determined in Section 4.2.1, and performing a conventional damage tolerance assessment. Note that even if a crack is assumed to initiate at a dimension larger than the asymptotic crack length, it will grow as if it is that characteristic length.

For composite structures, assessment of structural integrity relies on use of the maximum strains (derived from maximum stresses) combined with the application of a failure criterion. The Standard specifies the use of Hart-Smith's Maximum Shear Strain Failure Criterion or the Truncated Maximum Strain Criterion [11]. Sufficient doubt [12] has been cast on the validity of distortion energy methods to justify exclusion of common failure theories such as the Tsai-Hill and Tsai-Wu methods.

4.3. Peel Stresses

Peel stresses are assessed using Hart-Smith equations for double overlap joints [9]. All edges of patches are always tapered to reduce peel stresses. Composite patch ends are tapered by cutting layers during lamination. Australian convention is to use the longest layer on the outside of the patch, with the smallest layer on bonding surface. This reduces air flow disturbance and minimises accidental delamination and fibre damage.

4.4. Calculation of Tolerable Bond Defect Size

Following from the design philosophy on which the Standard is based, a critical defect is defined as one which causes the adhesive to be the critical element in the repair [9]. A critical defect will cause the adhesive to become fully plastic at yield stress in the parent material (see Fig. 8). The overlap length necessary to stop the adhesive becoming fully plastic is factored by 1.5 and then subtracted from the actual design overlap length. The result is the tolerable defect size. Any defect smaller than this will not cause the adhesive in the repair to be fully plastic, and therefore the joint will still have the capacity to carry load at material yield.

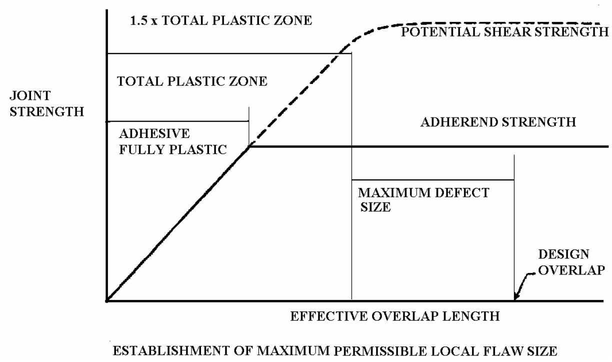


Figure 8. Estimation of tolerable defect size on the basis of load capacity being above the strength of the parent material. [Adapted from Ref. 9]

Note that this approach applies only to defects which occur during repair application. In-service defects are discussed in the Section 5.3 under "Interfacial Adhesive Failures".

5. REPAIR DURABILITY

Four possible durability aspects must be addressed:

- Fatigue of the parent structure.
- Fatigue of the patch.
- Fatigue of the adhesive bond.
- Interfacial adhesive failures.

Fatigue related elements are assessed at loads which are assumed to be 60% of Design Limit Load. If DLL is not known, the Standard allows the use of 0.533 times material yield.

5.1. Fatigue of the Parent Structure and Patch

For uncracked structure, the maximum stress is estimated on the basis of the stress concentration factor, and is checked against fatigue threshold stress values from MIL HANDBOOK 5F or other references. The calculated patch stress is checked for fatigue susceptibility in a similar manner.

In a similar manner to the structural integrity check, a damage tolerant approach may be undertaken by assuming that a crack exists of a size equal to the asymptotic crack size using the AMRL "crack patching" approach.

For cracked structure, the stress intensity after repair is calculated using AMRL's "crack patching" technology. The value estimated is used to check the crack growth reduction. MIL HANDBOOK 5F or other reference data may then be used to estimate the anticipated crack growth rate at the repaired stress intensity range. Note that this estimate is usually conservative, particularly for repair to longer cracks, as the approach ignores crack closure effects which frequently result in zero crack growth for a considerable period.

5.2. Fatigue of the Adhesive Bond

Adhesive bonds are strongly resistant to fatigue, if designed and applied correctly. Although the static strength design allows for the adhesive to yield, the fatigue design analysis allows for only limited adhesive yielding. Fatigue testing of bonded joints at AMRL has shown that joints may be subjected to repeated fatigue cycles at loads above the plastic limit for the adhesive [5]. The opening displacement of an overlap joint was measured at loads which caused the adhesive to yield (see Fig. 9).

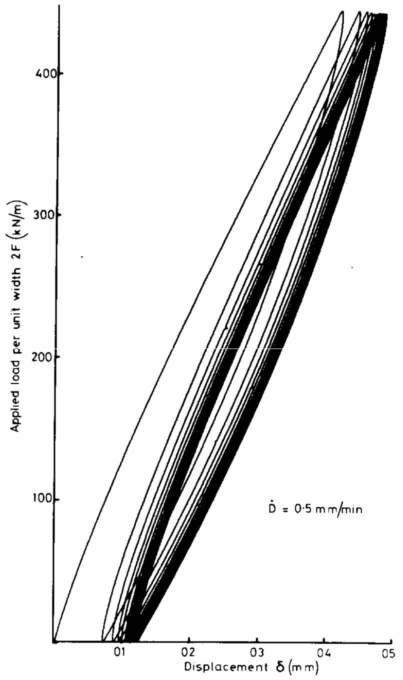


Figure 9. Joint opening displacement for a bonded joint subjected to cyclic loading [5].

The results of these tests show that creep effects due to loading above the elastic limit for the adhesive are only significant for the first few cycles. Repeated load application does not result in an accumulation of damage in the adhesive.

The Standard calls for the maximum shear strain in the adhesive to be less than $2\gamma_e$, the elastic shear strain limit for the adhesive when loaded to the maximum fatigue stress. Recent AMRL work enables prediction of debond growth under fatigue, and prediction of the changed stress intensity behaviour [13]. The Standard does not currently address this aspect.

5.3. Interfacial Adhesive Failures

Past experience with repairs applied using processes specified by OEMs has shown that very poor procedures are common [4]. Many repair failures result from debonding due to interfacial failure between the adhesive and one of the bonding surfaces.

Interfacial failures are invariably the result of poor surface preparation during application, or the incorrect cure of the bond. There is no mechanism for prediction of growth of interfacial failures, and therefore design for interfacial failure growth is intractable and dangerous.

Injection "repairs" are commonly used to correct interfacial failures. These methods are prohibited by the Standard. Resin or adhesive is injected under vacuum or pressure to fill the void created by the debond. Such attempts at re-bonding the defective area are futile, as no surface preparation is possible. An interface which has degraded to the extent that the adhesive debonds will not be corrected by the simple addition of more adhesive. Similarly, if the debond is due to accidental inclusion of a release layer, injection of more adhesive will not result in re-bonding of the defective area.

Interfacial failures must be repaired by removal of defective areas and repair using better surface preparation processes. The Standard permits the use of injection repairs only as a temporary measure, and only if a secondary patch is applied, to reduce out-of-plane displacement of the debonded region. Permanent repair measures are stipulated at the next aircraft servicing. Potted repairs for sandwich panels are only approved if a secondary patch is applied over the region.

(Note: Some benefit in static strength restoration by injection of delaminations in composites has been reported [14] using a low viscosity modified adhesive. Other tests [15] have shown that drastic reductions in fatigue lives have resulted from injection of delaminations in composites, when compared to no repair at all.)

6. MATERIAL PROPERTIES DATA

Reliable material properties required for repair design have proven difficult to obtain. Data used by the original equipment designer [16] has proven to be ultra-conservative, and may result in a repair load capacity lower than that calculated from the adhesive manufacturer's data [17] by a factor of three. Many repair designs which would be acceptable using the adhesive manufacturer's data would be rejected using the aircraft manufacturer's data.

Most adhesive manufacturers provide data which shows compliance with standards MMM 132 or MIL A 25463B. The standard of data provided is typical of that obtained from short overlap shear tests, which provide an acceptable comparative measure, but the strength measured is unrelated to that achieved in a practical bonded joint. This data may set a bench mark for repair design, but there is no specification of, or design data for:

- Shear Modulus.
- Elastic Strength.
- Elastic Strain Limit.
- Plastic Strain Limit.
- Peel Strength.

Without reliable data, design must be based on conservative values, with a consequent loss of efficiency of the repair procedure. Recent data has been derived by CYTEC Corporation which provides some of the above variables, but the values differ widely from the aircraft manufacturer. Given that this data is essential for proper design of bonded structural joints formed during aircraft construction, the paucity of reliable data must bring even original structural designs into question.

RAAF would support efforts to establish adequate testing methods and standards to allow generation of reliable repair design data for adhesives in common use for repair, and for environments expected in service.

7. MATERIALS AND PROCESSES

Design must be seen as only *part* of the repair development. The repair design procedure is tolerant to geometric and materials variations, since the adhesive is designed never to be the critical element. However, even small changes in processing methods can lead to a significant reduction in repair durability. The static strength of an adhesive bond is usually not strongly influenced by processing variables. Unless a bond is very poorly formed, the strength will not change significantly, provided the joint is tested soon after manufacture. For this reason, the traditional lap-shear test is a poor quality control test. It is even worse as a research tool to validate surface preparation techniques.

Processing deficiencies have most effect on the longer term durability of a repair. The usual mechanism is degradation by hydration of the interface between the adhesive and one of the materials being bonded. The frequent use of inadequate processes or the poor performance of good processes has led to the widely held lack of confidence in adhesive bonding for aircraft repair.

Aspects which must be considered in the development of a repair include:

- Materials selection and processing.
- Application processes.

***Even the best design can not make allowances for poor processing**.*

7.1. Patch Material

The success of bonded patches depends primarily on the adhesive bond; patch materials are a secondary factor. Patches may be made of most structural materials such as metals or composites, provided stiffness requirements are met.

Composite patches have the advantages of:

- Formability.
- Better NDI.
- Lighter repairs.
- Thinner repairs.
- Better fatigue performance.
- Better corrosion resistance.

Boron composite patches are thinner and smaller due to high stiffness, which is why they are preferred for repairs in Australia. The advantages of boron composites include:

- Better aerodynamics.
- Reduced bending effects.
- Reduced interference between adjacent moving components.
- May be applicable for repairs with limited bond overlap length.

For general stress fields, such as may be required for corrosion repairs, use of metallic or quasi-isotropic laminates is required.

7.2. Application Processes

The current authority for repairs in RAAF is the applicable aircraft Structural Repair Manual (SRM). This practice will continue. To implement the standard, amendments to the SRMs are proposed, which will replace specific bonding procedures with a referral to the appropriate Process Specification in the Standard. For example, a solvent cleaning step would be replaced with the instruction:

> "Perform solvent cleaning IAW Engineering Standard C5033 Volume II, Process Specification 6.1."

For repairs outside the SRM limits, the design engineer can specify repair processes by direct reference to the standard. Application process control is fundamental to successful repair. This area has led to most in-service failures of bonded repairs. The Engineering Standard addresses many aspects of bonded repair processes including:

- Approved Materials.
- Adhesive Off-Optimum Cure Cycles.
- Adhesive Quality Control.
- Patch Fabrication and Cure.
- Surface Preparation.
- Temperature Measurement and Control.
- Vacuum Bagging.

Processes currently specified in aircraft repair manuals for repairs to sandwich panels and composite structures are grossly inadequate. The main areas of deficiency are:

- Surface preparation.
- Distribution of heat sources.
- Temperature control.

7.3. Surface Preparation

Given the susceptibility of bonded repairs to process variations, the Standard closely controls surface preparation by providing detailed Process Specifications for all aspects of the tasks. The Standard emphasises the importance of the fundamental requirements of a proper surface preparation. These are:

- Removal of soluble surface contamination by solvent cleaning.
- Exposure of a fresh, chemically active surface by abrasion, preferably grit blasting.
- Chemical modification of the active surface.

These steps are fundamental to bond durability. For metallic surfaces, all of the above steps must be performed, but for composite materials, the chemical modification process may be omitted. Process steps must follow the above sequence exactly, as steps can not be interchanged. Each step must be performed to exacting standards which far exceed those commonly described in repair manuals. Any short cuts will result in inferior bond performance.

The Standard has adopted the AMRL silane process for the standard chemical modification process for metallic structures. The absence of acidic materials and ease of performance are the main reasons for this selection. If properly performed, the performance approaches that for more complex acidic methods, such as phosphoric acid anodising or chromic acid etching.

7.4. Distribution of Heat Sources

Almost every repair manual which provides instructions for application of heat to structures relies on the use of a single heater blanket. Even on uniform structures, single heater blankets exhibit significant temperature variations. If used on complex structural elements, there is a high probability of either undercure of adhesive in regions which do not achieve the cure temperature or overheating of the parent structure. RAAF has experienced repairs departing aircraft in flight due to adhesive undercure, and has also had panels destroyed by heat damage during repair.

The Standard calls for the use of multiple heat sources, with the configuration determined to suit the distribution of thermal masses within the repair zone. Each zone is heated by a separate heater blanket controlled by a thermocouple located within that zone. Using this approach, areas with a low thermal mass receive only sufficient heat to reach the control temperature, while thicker structure will be supplied with more heat to raise the temperature to the control temperature. Using this method, a more adequate temperature distribution is achieved.

The Standard prohibits the use of "multi zone" heater blankets which are fabricated with concentric heated zones, as these systems do not allow correct configuration of the heat sources. Use of these systems on complex structure carries a real danger of cure deficiencies or structural damage.

7.5. Temperature Control

The Standard requires that temperature control is performed by use of thermocouples *located on the surface being heated*. Thermocouples located within the heater blanket are not permitted. Control of heat by a thermocouple not within the heated zone is also prohibited.

Thermocouples perform two functions in bonded repairs:

- Control of temperatures to ensure the structure is not overheated.
- Assurance of adhesive or composite cure.

Both of these functions are essential to successful repair implementation. To achieve these requirements on repairs, thermocouples must be located in a specific manner:

- For control of heat sources, thermocouples must be *located in the heated zone* at the location where the ***highest*** temperature occurs.
- For cure assurance, thermocouples must be located *adjacent to the repair* such that the ***lowest*** temperature is measured.

This practice requires equipment capable of supporting multiple heat sources, and capable of reading sufficient thermocouples to meet the above requirements. RAAF could not identify a suitable commercially available temperature control unit to meet these requirements, and which gave adequate data presentation to enable high level control of heating processes. Hard copy of all measured temperatures was also considered essential for quality control.

RAAF engaged an Australian company to develop a high quality temperature controller for hot bonding. The Novatech HBC-43 unit has the following features:

- Six controlled power outlets, each with core balanced relay protection.
- Maximum power capability is 14.4 kW on 3 phase 415 Volt power. Similar capabilities can be achieved on 3 phase US power systems.
- Sixteen thermocouples, optically isolated from the control unit.
- Computer control using a PC.
- Software which presents data in graphical or digital form.
- All measured parameters can be displayed on one screen in digital form.
- Data is in color, enhancing operator perception.
- Control is based on zones corresponding to thermocouples located under each controlled heat source. The system automatically controls by the hottest temperature in the particular zone.
- Cure cycle duration is automatically determined, based on specified acceptance thermocouples located around the repair. Cure cycles are determined by pre-programmed cure cycle envelopes to suit the specific adhesive. The system automatically determines the coldest temperature form the specified thermocouples.
- Faults are recorded and indicated in plain language.
- Non-critical faults initiate audible and visual alarms, as well as hard copy output.
- Critical faults result in automatic shut down with conditions recorded on hard copy.
- The process can be re-started after power failure.
- Process variables can be changed while the system is running.
- Hard copy of all measured parameters is provided at programmed intervals, and at the end of the cycle.

This system has been adopted as the standard control unit for repairs in RAAF, and has been in service for approximately fifteen months. It has proven reliable, and with limited training, operators find the units easy to use. Identification of problems and performance of corrective actions has been substantially improved when compared to other hot bonding units.

8. QUALITY CONTROL

Because bonded repairs are a single fastener system which is susceptible to processing variations, a vigorous quality plan is essential to success. Measures are required before repair to assure materials quality and adequate recording of repair details. After repair, testing is needed to ensure adequate bond strength and durability has been provided by the repair.

8.1. Quality Before Repair

Quality assurance of adhesives and pre-pregs is essential. Cure cycle data and pre-application NDI on pre-cured composite patches is required. Detailed and accurate NDI records are required of the location, size and nature of the defect being repaired. Failure to record this information will lead to confusion during later inspections.

Note that stress corrosion cracks being repaired should be inspected no more than one week prior to repair, as this form of crack frequently propagates even while the aircraft is grounded. Failure to accurately record the crack details can lead to erroneous conclusions in relation to the effectiveness of the repair following later inspections.

8.2. Quality After Repair

Common practice is to use standard Lap Shear Test coupons cured with the repair as a quality control test. This test is frequently coupled with a "Coin Tap" test after bonding to give assurance of bond integrity. More sophisticated tests use ultrasonics. Some recent publications have recommended concurrently prepared Boeing Wedge Tests for validation of surface preparation.

The lap shear test is not a suitable method for assurance of adhesive cure, when formed under a heater blanket adjacent to a structural repair. The lap shear test is quite insensitive to surface preparation, and only very bad surface preparation will be detected by this test. The results in respect to the degree of cure are influenced by the location of the specimens relative to the heater system. Also, unless the specimen is cured on a flat section of the structure, the distortion of the specimens will cause erroneous results. Any specimen which gives different results depending on the location of the samples is not a reliable quality control method. Lap shear testing is really only suited to acceptance testing of adhesive supplies.

The concept of concurrent preparation of Boeing Wedge Test specimens prepared at the time of repair application appears at first to have some merit, as surface preparation is a common source of deficient repairs. However, this test is costly to perform on a regular basis and results are usually not available for several days after the completion of the repair. There is also the danger that the operator will pay more attention to the specimen than to the repair.

A further disadvantage is the time involved in preparation of the sample, and the fact that preparation of the sample will impinge on the exposure of the repair to the risk of contamination while the sample is being prepared. Given that the sample is prepared as a 150 mm (six inch) square, the probability of finding a flat area of that size near the repair is remote. The specimen will also interfere with heating of the structure.

NDI tests and coin tap tests after repair validate *necessary*, but not *sufficient* conditions for repair integrity assurance. They may indicate bond line defects, but the lack of any bond line defects is not an assurance of acceptable bonding, as they have no relevance to surface preparation.

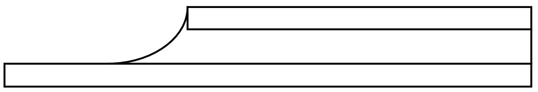
There is no test which can provide 100% assurance of bond integrity.

One significant method for detecting deficiencies in adhesive bonds is by inspection of the flash around the repair (see Fig. 10). A good bond should always exhibit a well formed fillet. Absence of adhesive flash or poor filleting may be due to poor pressurisation or cure of the adhesive with a slow heat-up rate. A frothy appearance in the adhesive flash may be due to heating at a rapid rate, causing gelation of the adhesive before voids have migrated. Frothy adhesive may also be due to moisture contamination in the adhesive, inadequate drying or excessive grit blasting during surface preparation.

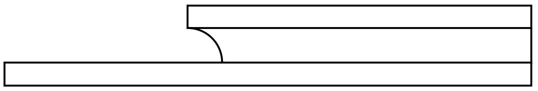
8.3. Repair Quality Standards

Repair quality management is possible in accordance with AS 3901 (ISO 9001) on Quality Systems. Para 4.9.2. of that Standard applies to "Special Procedures", those for which there is no validation test. Adhesive bonding is such a process.

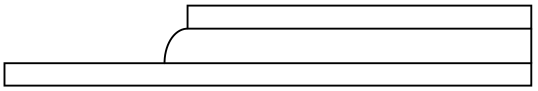
The required procedure for control of "special processes", and hence bonded repairs, is to *certify compliance* with *validated* process specifications by adequately *trained* personnel.



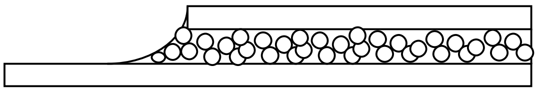
Well filleted bond



Absence of adhesive flash



Poor adhesive fillet



Porous adhesive fillet

Figure 10. Adhesive flash conditions which are indicative of adhesive bond quality.

This process requires:

- Validated procedures.
- Adequate process specification.
- Training and re-certification of technicians.

These aspects are addressed by the Standard. Processes specified in the Standard are based on experimental results from reliable sources, usually AMRL. Where possible, validating data is sought from independent sources [18].

The standard proposes to manage quality by:

- Assurance of adhesive quality before repair.
- NDI of composite patches before installation.
- Use of hard copy data produced during repair cure to verify that the adhesive has seen the full cure cycle.
- Inspection of the adhesive flash for evidence of deficiencies in cure.
- Tap testing, and/or ultrasonics NDI to verify the absence of bond line defects.

The lap shear test is not specified, nor is the use of a Boeing Wedge Test. As discussed in Section 8.2, these tests have limited value when prepared with the repair.

The Standard proposes that surface preparation quality is managed by ensuring that the technician is correctly trained, assessed and regularly re-qualified using the Boeing Wedge Test to verify that adequate standards can be achieved. The quality of performance of repair tasks is checked by recording the time between steps during the preparation process.

If the operator can demonstrate the ability to correctly perform the processes for re-qualification, then adequate specification of the processes, together with certification requirements and control of the time to perform tasks should provide adequate assurance of surface preparation.

9. TRAINING

The standard specifies the qualifications for technicians involved in repair application, as well as the design engineer. Currently RAAF conducts its own training for technicians and engineers.

Technical training is provided to tradesman level for Aircraft Structural Fitters (metalworkers). The current course is six weeks long. RAAF intention is to review the course with the objective of modularisation so that training will be provided only to the required standard for particular weapon systems. All levels will be instructed in correct methods for surface preparation, but only those who require added training will progress to the level in which elevated temperature adhesive bonding and composite fabrication procedures would be taught.

RAAF proposes to introduce twelve monthly re-qualification testing of technicians who perform bonded repairs to assure maintenance of standards after training.

Most junior RAAF engineers receive a familiarisation course in composite materials and adhesive bonded repairs. This course extends over eight days, and includes a large proportion of hands-on exposure to bonding processes. A general view of the design procedures for bonded repairs is presented.

A further course has been established in which engineers required to design bonded repairs are trained in the use and application of the Engineering Standard.

10. COMMENT

Aircraft manufacturers have in the past been seen as the paramount authority for repairs. Their expertise in structural design, component manufacture and aircraft assembly is well established.

This author suggests that reliance by airworthiness authorities on OEM support may not be the appropriate method of management of adhesive bonding technology for field applications. Repair technology for field application differs significantly from production processes. For example the tank surface preparation methods with which most manufacturers are familiar are impractical under field conditions. Manufacturers who have familiarity with autoclave bonding processes may not be competent in the performance of the same processes using localised heater blankets and vacuum bags.

Experience with OEM approved repair manuals for sandwich panels and composites indicates a poor understanding of field level repair technology by the OEM authors. As part of a review of repair practices at one RAAF facility, 367 Defect Reports were reviewed. Of these reports, 194 (53%) refer to non-impact related adhesive bond damage, i.e. debonding or corrosion. Of those 194 defects, 79 (41% of the non-impact related bond defects, or 21% of the total number of defects) are repairs to area where previous defective repairs have been applied. Those defective repairs were applied following the aircraft repair manuals approved by the OEM. Examples of deficient practices have been presented elsewhere, [4].

Australian Defence experience is that the technology must be controlled from a position of specialist expertise, using validated process specifications, focussed training programs and a design standard.

11. CONCLUSIONS

Bonded and composite repair is becoming an established technology for aircraft maintenance in Australia.

The Standard aims to check that:

- The adhesive is never the critical element in the repair.
- Static strength is acceptable at Design Ultimate.
- Fatigue behaviour is acceptable at 80% of Design Limit.
- The adhesive is damage tolerant by determination of a critical defect size.

RAAF is adopting the repair technology in-principle, with formal control by an Engineering Standard combined with appropriate training and process control measures. Bonded repairs are approached as a "whole technology". Application is based on validated processes which are compatible with ***field*** requirements, and which must be correctly specified and performed.

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