Australian Government
Department of Defence
Defence Science and
Technology Organisation

DSTO

Proposed Framework for a Risk-Based Approach for the Environmental Certification of Adhesively Bonded Repairs

Andrew Rider and Roger Vodicka

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Air Vehicles Division
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ABSTRACT

Bonded composite repairs have been successfully applied to damaged aircraft structure since the early 70s. One of the major restrictions preventing widespread usage of the technology on primary aircraft structure is the lack of any defined statistical processes to guarantee the environmental durability of the bonded repair for periods that may approach the service life of the aircraft. This paper describes a proposed framework for a risk-based approach to certify the environmental durability of bonded repairs. The proposed approach is based on both laboratory-based performance data of a variety of surface treatments and the durability of repairs that have been in service for a period of time. The approach provides flexibility in repair application choices that are tailored to the criticality of the repair task. The expected outcome is to gain a quantitative understanding of environmental durability issues which will provide a sound basis for making engineering decisions.

Approved for public release

RELEASE LIMITATION

AQ F05-05-1019

Published by

DSTO Platforms Sciences Laboratory
506 Lorimer St
Fishermans Bend, Victoria 3207 Australia

Telephone: (03) 9626 7000
Fax: (03) 9626 7999

AR-013-224
October 2004

APPROVED FOR PUBLIC RELEASE

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Executive Summary

The current status of bonded repair technology in the context of RAAF usage has been reviewed and limitations assessed. Presently, RAAF provide no credit for bonded repairs to primary aircraft structure and the aircraft is managed as it would be in the absence of the patch. The major concern with adhesive bonding technology is the potential for the repair to degrade unpredictably to a zero strength condition due to exposure to a humid environment. If bonded repairs are to be given structural credit for application to primary aircraft structure, then the strength and toughness of bonded joints with time and exposure to adverse environment must be either predictable or measurable with non-destructive systems. By developing a certification path for bonded repairs the full benefit of the technology can be realised and major cost savings in the management of aging aircraft fleets will result.

The RAAF have implemented a Quality Management System to introduce reliability in adhesive bonding conducted on ADF aircraft. The approach involves the regular qualification of personnel involved in bonding operations. Strict management of materials and a highly trained workforce are seen as essential ingredients in reliable application of bonded repairs. The RAAF approach is based on the absence of any reliable or mature NDI technique that can accurately assess the quality of an adhesive bond or its long-term durability in the service environment.

The RAAF approach provides the basis for developing a Risk and Reliability (R+R) system for the certification of bonded repairs. It is proposed that establishment of an acceptance test to qualify environmental durability of bonded repairs be established. Correlation of the test with known service performance would provide the basis of establishing a R+R model and consequently a strategy for certification. The Boeing Wedge Test (BWT) is an industry standard and is currently employed by RAAF to qualify bonding technicians and monitor material and process quality. The BWT provides a rigorous assessment of the surface treatment process applied to the bonding substrate and an analogue for the most critical steps in the bonded repair application process. The type and quality of surface treatment applied in the bonded repair is the most critical factor determining bond strength and long-term environmental durability. As the BWT is an extreme representation of a loaded bonded joint in an adverse environment, a quantitative model of the BWT for the current RAAF surface treatment would provide an initial basis for a risk model for the bonded repair process. Identifying critical parameters affecting wedge test performance would establish factors influencing the quality of bonded repairs applied in depot or field level maintenance. Correlating the BWT results with known service performance would establish the validity of the acceptance test and the risk approach in certifying environmental durability of adhesive bonded repairs.

It is clear the proposed risk based certification strategy would be heavily reliant on data, for both the BWT and repairs. Efforts are currently underway to collect data from RAAF and DSTO sources and this information may provide the basis for the initial model. The

model would continually evolve as improvements in processes were implemented and monitored. International collaboration is critical to the success of the certification strategy. An initial survey of international effort in bonded repairs indicates that a substantial database is available. If the database can be efficiently managed, then there will be a substantially reduced effort in the development of a robust model for assessing the environmental durability of bonded repairs.

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Contents

1. Introduction

Bonded composite repairs have been successfully applied to damaged aircraft structure since the early 70s [1]. In a typical configuration boron composite patches are adhesively bonded to cracked metallic aircraft structure using structural epoxy adhesive (Figure 1). One of the advantages of the technology is the ready application in field or depot level repairs. Successful application of the technology has relied on the skills of the engineering design and more critically on the skills of the technicians applying the repairs. Despite a range of successful applications that have provided huge cost savings for the Royal Australian Air Force (RAAF), the technology is still considered niche and may not be included in the available options for aircraft repair by ADF maintenance engineers. One of the major restrictions preventing widespread usage of the technology on primary aircraft structure is the lack of any defined processes to guarantee the environmental durability of the bonded repair for periods that may approach the service life of the aircraft. Whilst bonded repairs can be applied readily to secondary and tertiary structure, the real advantage and full economic benefit of the technology will only be realised when structural credit for primary aircraft structure can be provided. In recent years DSTO has begun to consider the issues relevant to environmental certification of adhesive bonds in order to enable the development of a strategy that would provide structural credit for the bonded repairs [2].

The main concern with bonded repairs to metallic structure is the potential for moisture ingress into the adhesive bond to degrade the repair to a zero strength condition if the surface treatment procedure is inadequate. Whilst this potential has never been realised in DSTO repair applications, it is a risk that RAAF and certification authorities around the world are not prepared to accept. As such, it is imperative that strategies and processes are implemented to achieve environmental certification of adhesively bonded repairs.

Service failures of bonded repairs in the RAAF are rare but there have been cases where surface treatment procedures have been inadequate which has led to poor bond durability. In addition, the failure rate of test specimens used to qualify RAAF technicians is in excess of 10% at times which indicates the possibility of high variability in the surface treatment process and hence a high degree of risk for application in the field. Expectations for the acceptable risk for surface treatment failures has not been defined to date but is expected to be very stringent, especially in cases where repairs are applied to primary structure. In any case, the acceptable risk level will be more stringent than that which is currently being achieved in practice.

This report details a proposed framework to improve the management of bonded composite repairs by using a risk and reliability based approach. This entails collecting data on the prior performance of bonded repair durability and ensuring that adequate data is collected to allow future data analysis to be performed. Data is used to model the likelihood of repair failure due to poor environmental durability of the bond, which is most often associated with poor surface treatment application. The approach also calls for existing and future repairs to be monitored. Success of this approach may lead to the certification of bonded repairs and more widespread use within the ADF. This report provides guidelines for the development and implementation of such an approach. The development of the risk and reliability models and the associated management tools and data collection will need to be the focus of future efforts towards this goal.

The following report details: 1) Historical applications of bonded repairs by RAAF, 2) the current status of bonded repairs in terms of RAAF usage of the technology, 3) the proposal for a preferred status for bonded repairs in the RAAF environment and 4) proposed solutions for the environmental certification of bonded repairs. Finally, a recommended research program is defined to implement the proposed approach.

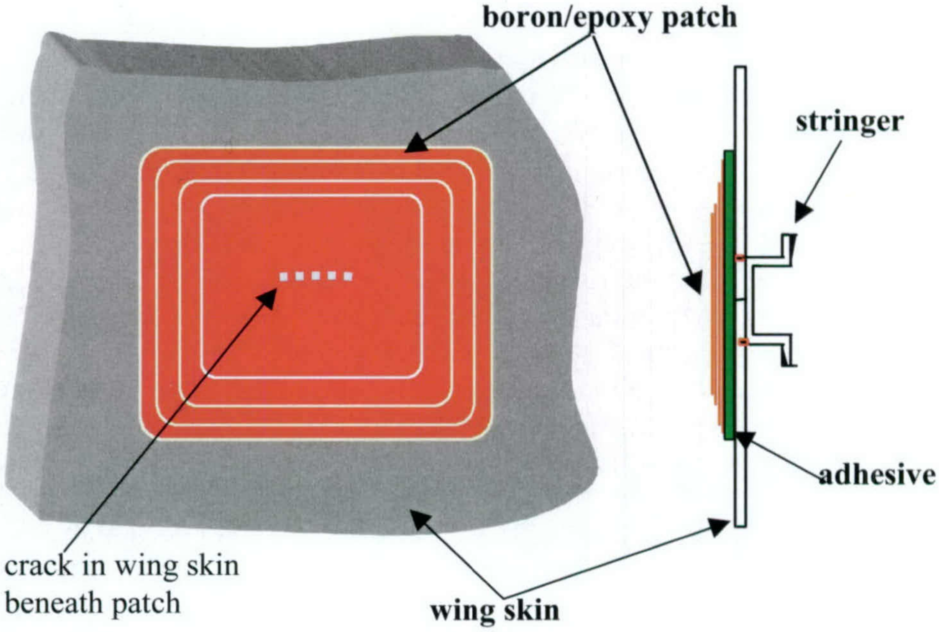


Figure 1 Typical configuration for a boron-epoxy patch bonded to cracked aluminium skin of an aircraft.

2. RAAF use of bonded repairs

Table 1 indicates a range of bonded repair applications to RAAF aircraft carried out over the past 25 years. In this time bonded repairs have been performed to restore structural stiffness and strength in regions where corrosion or flaws have been blended out, reduce stress intensity in regions with fatigue and stress corrosion cracking and stiffen under-designed regions enabling an increase in static strength or a reduction in fatigue strain.

Table 1 Examples of bonded repair applications to RAAF aircraft carried out since the mid 70s. from [3]

Aircraft	Problem	Surface Treatment	Remarks on Environmental Durability
C-130E	Stress corrosion cracked stiffeners in wing, aluminium alloy 7075.	GB* initially GB+S# later (+b/ep + AF-126, FM73)	Over 20 years of service. No bond durability problems where bonding carried out as specified
Mirage III	Fatigue cracking in lower wing skin, aluminium alloy AU4SG.	$PANTA (b/ep+ AF-126)	180 wings repaired or reinforced. Eight bond durability problems over around 8 years. Failures were associated with adhesive voiding caused by extreme humidity in the tropical repair station.
F-111C	Secondary bending in wing pivot fittings leading to a fatigue problem. Steel D6ac fastened to aluminium alloy wing skin.	GB+S (b/ep + FM73)	No bond durability failures to steel or aluminium surface over 10 years.
F-111C	Stress corrosion cracking in weapon bay longeron flange, aluminium alloy 7075T6.	GB+S (&gr/ep cloth + ep)	Over 10 aircraft repaired. No bond durability problems over around 8 years.
F-111C	Stress corrosion cracking in longeron adjacent to refuel receptacle, 7049-T6.	GB+S (b/ep + EA 9321)	Over ten aircraft repaired. No bond durability problems in 8 years.
F-111C	Metal-to-metal and sandwich structure repairs. RAAF adopted GB+S and changed to FM 300 adhesive in 1992.	GB+S FM300 FM 73, EA 9321	No bond durability failures in over 7 years.
F-111C	Pork-chop panel (lower fuselage). Panels rebuilt after repeated in-service failures.	GB+S FM 300	Repeat rebuild rate reduced from 95% to zero. No bond durability failures in 7 years.
P-3C	Full depth corrosion damage in horizontal tail, aluminium alloy 7075 T6.	GB+S (al alloy + FM73)	No bond durability problems over around 10 years
F-111C	Fatigue cracking in lower wing skin at fuel flow hole under forward auxiliary spar.	GB+S b/ep	No bond durability problems in over 2.5 years service.

* GB: grit-blast, # S: epoxy-silane, $PANTA: Phosphoric acid anodise, non-tank application, +b/ep: boron-epoxy composite patch, &gr/ep: graphite epoxy composite patch.

One of the most successful RAAF applications has been on C-130E, where wing riser stress-corrosion cracking out of rivet holes was prevented through application of small boron-epoxy patches, initially using a simple grit-blasting treatment and a structural epoxy adhesive (Figure 2). These simple repairs enabled RAAF to fly the C-130E aircraft through to retirement without the need to replace the outer wing skins. The estimated savings from this work were $130 million dollars.

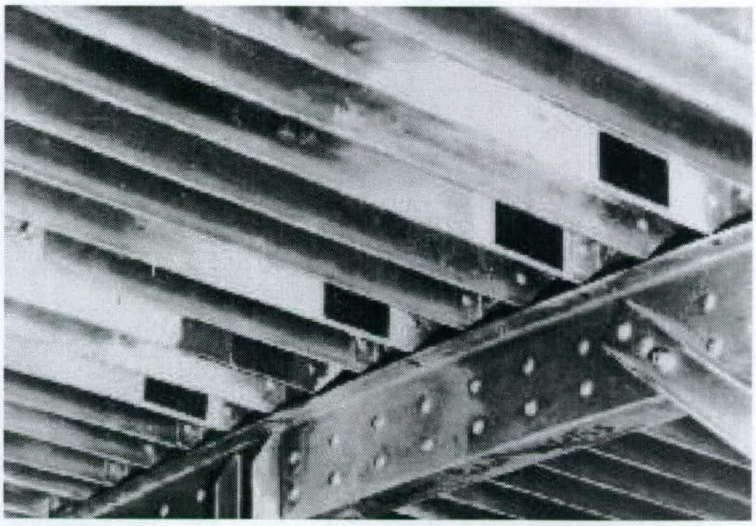


Figure 2 Boron-epoxy patches applied to C-130E wing risers (Al-7075 T6) to prevent stress-corrosion cracking out of the rivet holes. Over 25 years of successful service enabled RAAF to obviate the need to replace the outer wing skins during the aircraft service life.

Repairs to cracking on Mirage III were also successful in extending the last remaining years of the aircraft (Figure 3). Patch design lowered stresses sufficiently to slow the growth of cracks that emanated from the fuel decant hole in the lower wing skin. The process used a modified version of the phosphoric acid anodise surface treatment and combined with a structural epoxy adhesive (AF-126) provided environmentally durable adhesive bonds, as determined by service records and laboratory testing.

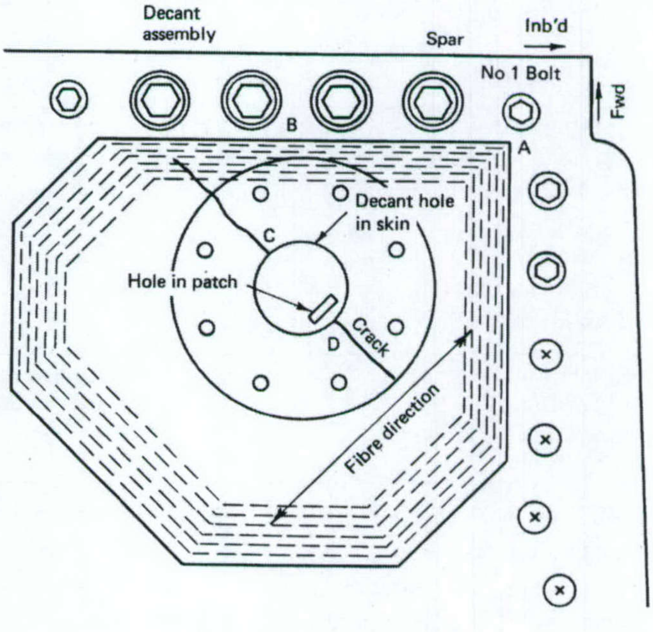


Figure 3 Boron-epoxy patch reinforcement to the lower wing skin fuel decant hole cracking.

By far the greatest number of routine bonded repairs carried out by RAAF has been to F-111C honeycomb panels used throughout the fuselage and flight control surfaces of the aircraft (Figure 4). Metallic skins bonded to predominantly metallic honeycomb core requires regular repair due to the susceptibility of the structure to mechanical damage during service and maintenance operations. Repairs at a rate of almost 30 per month across the fleet are not unusual. Since 1995 the surface treatment of the aluminium skins prior to bonding has used the DSTO developed grit-blast and epoxy-silane method [2]. Since 1995 there have only been two reported failures of these repairs that were traced to technicians deliberately avoiding using the prescribed engineering procedures. Prior to this date the failure rate of repairs was much higher.

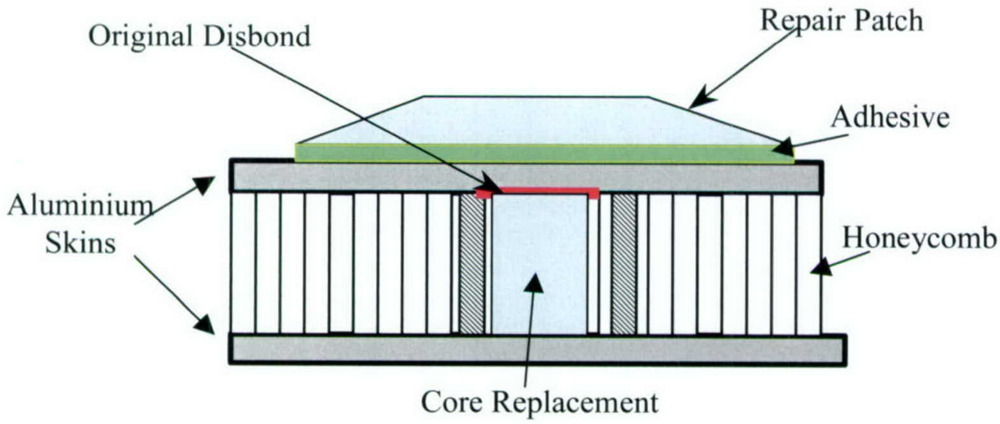


Figure 4 *Typical metal-to-metal repairs carried out on F-111C*

3. Estimated reliability of bonded repairs

The durability of bonded repairs applied by the RAAF has improved, particularly with the introduction of the grit-blast silane surface treatment and the RAAF standard [5]. Much of the evidence regarding the bond durability of repairs is from anecdotal evidence. Two failures have been reported in connection with repairs conducted on F-111, both of which were due to operator error during application. Repairs conducted on the Mirage using the PANTA process were less reliable with 8 from 180 bonded repairs showing some form of durability problems associated with adhesive voiding due to curing in a tropical environment (Table 1). Recent teardown of Hercules C-130E repairs has also indicated that durability issues may be a concern. To date, 17 out of 42 repairs applied to the C-130E aircraft during the period from 1978 to 1984 showed evidence of substantial bond degradation. Although the surface treatment applied to the C-130E was inferior to the current process, it highlights the fact that it may take many years before the true service durability of a given surface treatment may be adequately evaluated. The evaluation and teardown of existing bonded repairs is the critical requirement for reliably evaluating the environmental resistance in service.

Current surface treatment processes applied in the RAAF are significantly more durable, but there are indications that test specimens used to qualify technicians for the surface treatment process can provide crack growth rates which are greater than expected. In excess of 10% of all RAAF qualification tests failed to approach expected performance, based on recent data (see section 7.3). The risk of surface treatment process failure should be quantified and used as one measure to estimate the risk of in-service bonded repair failure.

Selecting an appropriate acceptance test, defining limits for the test and then establishing the relationship between the acceptance test failure rate and in service failure rate are the major obstacles facing bonded repair certification. For example, should a failure rate of 1 in 10 million be required, the level of testing and subsequent monitoring and recording of repair performance may be unrealistic. The ability to co-ordinate data gathering and monitoring activities amongst users of bonded repair technology is the key to establishing a sufficiently robust database. Once data recording and monitoring protocols are defined, appropriate models to reliably assess the risk of failure, based on the repair system and service environment, can be produced.

4. Current status of bonded repair usage in RAAF

The RAAF currently apply bonded composite patches to primary aircraft structure, but provide no structural credit to the repair. The aircraft structure is maintained as it would be in the absence of the patch. In strict terms, the repair should be described as a reinforcement or fatigue enhancement.

In terms of static strength, the bonded reinforcement can only be applied if, as a result of its loss, the structure will not exceed material yield allowable stresses at design limit load (DLL) and material ultimate allowable stresses at design ultimate load (DUL). DLL is the maximum load the aircraft is likely to experience and DUL is determined by applying a margin of safety to DLL, often 1.5.

In terms of fatigue life, the aircraft structure may be managed using a Fail-Safe approach [3]. In this case, the component that has only a single load path should have sufficient strength to withstand DLL times a safety factor and the crack growth inspection intervals are managed as they would be on the basis of the unpatched structure. This approach is suitable for preventative patching or if the initial crack is small or crack growth is slow. Alternatively, in multiple load path designed components, it is sufficient if the structure can withstand DLL times a safety factor should a single load path fail. The structure in this case is managed as it would be without the patch present and the only guarantee required is that the patch doesn't impede normal inspection procedures. Clearly, these conditions enable bonded repairs to be applied, but their benefit is limited. Substantial benefits would be provided if structural credit could be given to the bonded repair, particularly, in examples where the patch could be shown to substantially reduce crack-growth rates for structure with critical crack sizes. In such cases, substantial cost savings would be associated with reduced inspection intervals and postponement of costly component replacement programs.

5. Preferred status of bonded repairs for ADF

The preferred status for bonded repairs is the case where full structural credit can be provided. Certification of the repair would involve:

1) credit for the restoration of the original static strength of the structure for DUL condition

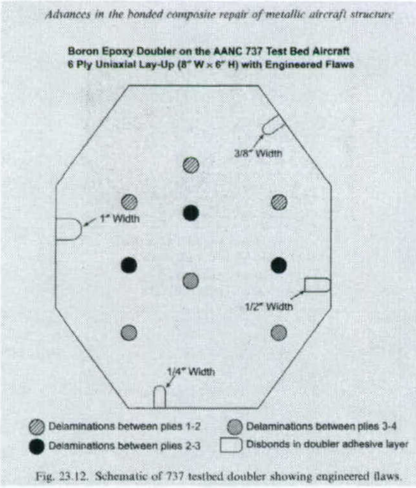
2) credit for the restoration of the fatigue life of the structure (involving a damage tolerant approach to manage structure and define inspection intervals) and
3) credit for the environmental durability of the patch for the required service life of the structure.

Clearly, the above requirements imply that any reduction in design capability of the bonded repair will be identified by a management strategy prior to any compromise in air worthiness. Initially, credit for restoration of DUL condition would be directly applicable for RAAF's current fleet management philosophy, in which all damage is removed prior to repair. Re-establishing the static strength of a component may provide substantial cost savings by extending the limits of removal for corrosion or fatigue damage and, thereby, extending the life of the structure.

The provision of credit for restoration of fatigue life of the structure would enable repairs to be applied to cracked structure and managed on the basis of the reduced crack growth rates offered by the patch.

The main limitation on the certification and continuing airworthiness of adhesively bonded repairs is the inability to ensure environmental durability of the adhesive bond, by either NDI or fatigue acceleration testing. Here the term environmental durability refers to the possibility of time-dependent degradation of adhesive bond strength due to hydration induced failure that may result from inadequate surface treatment. Service data accumulated over the past few decades have confirmed that, provided adhesive bonding is performed by qualified personnel in accordance with approved processes, the likelihood of rapid failures due to insufficient environmental durability is extremely rare. In fact, no evidence of this rapid separation has been discovered in repairs performed in accordance with an approved quality system. Nevertheless, limited disbonding has occurred in a small number of repairs. Even in these cases, bonded repairs have been found to be able to sustain the design load, because the localised disbond exhibited a slow and stable propagation behaviour. This suggests that the structural integrity of bonded repairs could be managed with a safety-by-inspection approach.

NDI research[4] has confirmed that standard ultrasonic techniques, such as the Pulse-Echo C-scan ultrasonics, and thermography are able to reliably detect disbonds and delaminations of the order of 12.7 mm in diameter (Figure 5). The impact of a localised disbond on the structural integrity of a repair is far less than that of a full width disbond in a one-dimensional bonded joint that is single load-path only. Therefore, a bonded repair would be inherently tolerant to some localised damage, even at the highly-stressed perimeter of the repair. In conclusion, the integrity of bonded repairs could be adequately managed by a combination of the damage tolerance methodology and a risk/reliability approach to ensure that the risk of repair failure would not compromise airworthiness.



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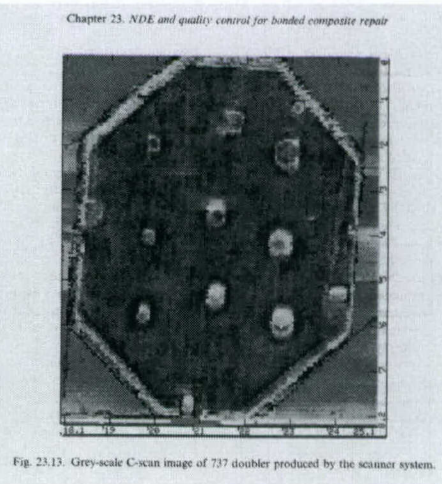

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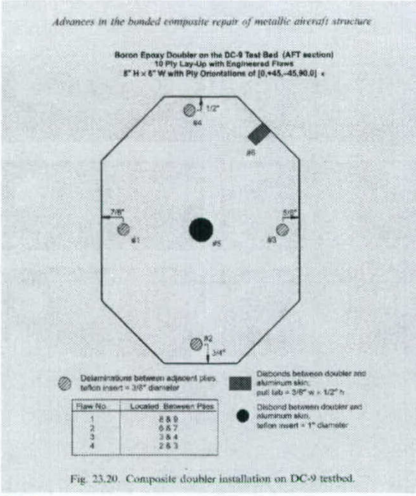

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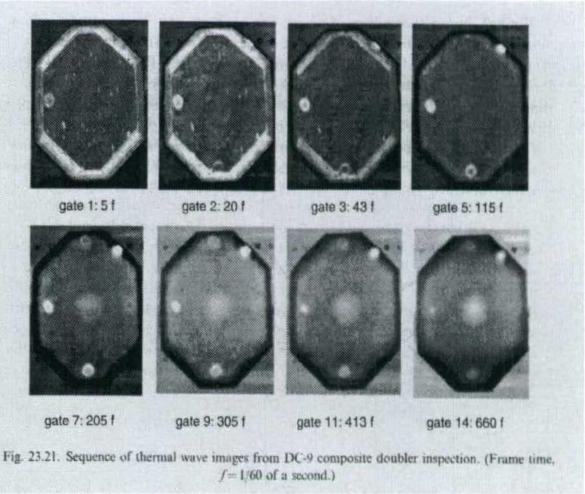

[D]

Figure 5 *[A] Embedded flaws in a Boron repair and [B] ultrasonics images*
[C] Embedded flaws in a Boron repair and [D] thermography images[4].

Figure 6 shows the certification pyramid for bonded repairs. This shows that certification is a multi-layer requirement. In order to certify the repair, the design of the repair must be based on sound engineering standards and provide its intended function over the service life. In addition, the repair can only remain durable for its service life if the environmental durability of the adhesive bonded repair can be adequately certified. The environmental durability is dependent on the surface treatment, substrate, adhesive, repair application process and service operating environment. Environmental certification is discussed in detail in Section 8. Design certification requirements are not addressed in this document but are outlined in the RAAF Engineering Standard [5] and Bonded Repair Software (BRS), which is being developed by RAAF, ASI section and Aerostructures Australia.

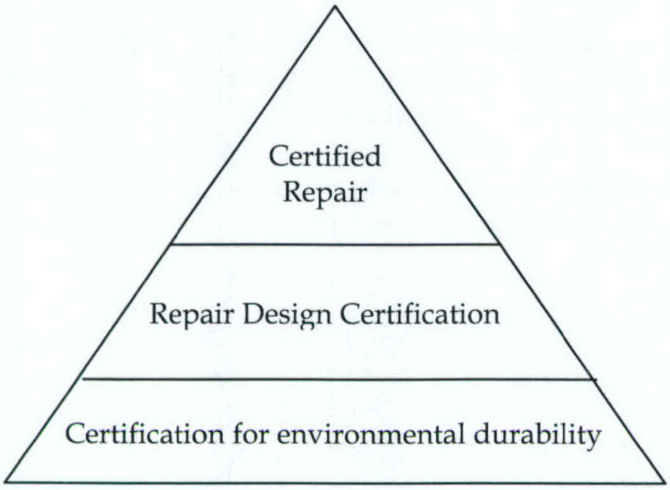

Figure 6 Certification pyramid for bonded repairs

Clearly, the first issue that should be considered in bonded repair certification is the environmental durability issue. No current mature NDI process can reliably assess the strength of an adhesive bond and predict its long-term environmental durability. Therefore, the best repair design and most rigorously conducted testing to validate the design for fatigue durability and static strength is insufficient if the environmental durability of the patch system cannot be guaranteed. As indicated, critical to the success of any adhesive joint is the quality of the surface treatment and accelerated laboratory testing indicates that this parameter is also critical in determining environmental durability. Environmental certification, therefore, relies on establishing the quality and reproducibility of the repair application process. Whilst materials are a critical parameter in any repair, the high labour content of bonded repair application means the success of the process is highly reliant on operator skill. However, even in the best-trained workforce, human error and process variability is always a potential risk that needs to be assessed and, if possible, engineered out of the production process.

The application of Risk and Reliability (R+R) engineering to such a problem offers a number of clear benefits. The risks in the bonding process can be identified and improvements can be introduced to mitigate them. In cases where variability cannot be controlled, a quantitative assessment of the risk can be made and the consequence on repair durability established. The benefit of the R+R approach is its flexibility to assess repair requirements on a case-by-case basis. The level of control required for a primary structure repair for a crack of critical length may be unnecessary and economically infeasible for the majority of repairs required in routine maintenance. Risk modelling can also establish the cost of implementing repairs and provide a measure of the benefit of a given repair option relative to traditional technology.

6. Environmental durability problem statement

A repair must guarantee that it will remain durable for a known period and will not degrade beyond the limits of a damage tolerant design when exposed to service conditions. Service conditions may include humidity, high and low temperature excursions, exposure to a range of fluids including water, hydraulic fluid and fuel. The residual strength of an adhesive bond cannot be measured non-destructively at present, thus, the question of the integrity of a given bonded repair is always an unknown. Only a destructive teardown of a patch can reveal its residual strength. Clearly, however, NDI will play a critical role in the damage tolerant management of the bonded repair, as indicated in Figure 5.

Adhesive bonding operations must rely on strict adherence to processes and standards. Quality systems may be introduced to ensure that processes are followed in a consistent manner and that all materials are of acceptable standard. Once the bonding process is complete, the confidence in the ability of the bonded repair to carry out its function is based solely on these assurances.

A critical element determining adhesive bonding performance is the quality of the surface treatment. Surface treatment processes should aim for:

- a high degree of reproducibility with low variability
- insensitivity to processing conditions and environmental exposure
- insensitive to operator skill levels
- a high degree of in-service durability

Surface treatment procedures for bonded repairs are often conducted in a non-factory environment and thus are subject to less strict controls. Surface treatment is very sensitive to contamination and to the environmental conditions under which it is conducted. Even very small traces of contaminants can seriously affect the strength and durability of a bonded repair. The surface treatment process is conducted by human operators and relies on experience, training and judgement to create the best quality. The surface treatment process favoured by RAAF is the grit-blast and epoxy silane treatment [6], which consists of the following general steps:

- Degreasing the surface with solvent
- Mechanically abrading the surface
- Grit blasting the surface
- Applying chemical coupling agent
- Drying the surface
- Applying film adhesive and the composite patch to the repair area
- Curing the adhesive/patch combination

The Boeing Wedge Test (BWT) has been used as a means of evaluating both the durability of a given surface treatment under laboratory conditions and as a training tool. The test uses two plates of alloy bonded together from which five strips of one-inch width are cut. A wedge is driven between the mating aluminium strips forcing adhesive fracture. Once crack growth has equilibrated at room temperature the coupon is placed in a hot and humid environment, typically 50°C and close to 100%RH (Figure 7). The growth of the crack generated by the wedge is measured at equilibrium and after 24 and

48 hours exposure to the hot and humid environment. Details of the test are provided in ASTM D3762-03 and is adopted as part of the RAAF Standard [6]. Even though the BWT test is defined in a standard it is sensitive to test conditions and environment and requires strict control of the test temperature, humidity and specimen orientation.

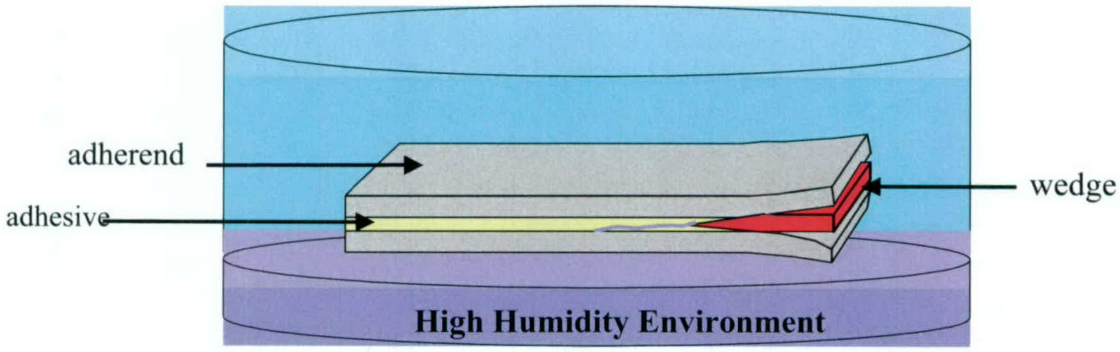

Figure 7 Boeing wedge test

The RAAF uses the BWT to train and re-qualify technicians before allowing them to conduct bonded repair operations. The BWT does have limitations in that it measures environmental resistance over a period of only 48 hours of exposure to a humid environment at 50°C. The results of a BWT and its relation to long-term environmental durability are difficult to gauge and one of the challenges is in determining a relevant BWT acceptance criteria. The BWT does provide a basis for monitoring the quality of the bonded repair process and improvements to the process can be measured.

Quality systems to control the process and a training system have been implemented successfully by the RAAF. In addition, extra quality measures are always sought and the process continues to be the focus of improvement efforts. Recent examples of this are detailed in Section 7.5.

The correlation between a BWT and service durability can be determined from historical data. A number of bonded repairs have been flying in the RAAF for a long period and the surface treatment used is known. The BWT performance of these legacy repairs can be determined or reproduced and linked to both anecdotal reports of environmental durability as well as by employing a tear-down program to determine residual bond strength. This approach may be a first step in moving towards using the BWT as a tool to certify bonded repairs. This approach alone would not be sufficient for certification since the bonding process is still subject to human factors and material variations and there is a finite risk that the process will be compromised resulting in poor durability. Understanding the risk of these occurrences may be a key part of certifying the environmental durability of bonded repairs.

7. Current efforts to improve bonded repair technology

7.1 FAA workshop initiatives

The U.S Federal Aviation Authority (FAA), through Larry Ilcewicz, sponsored a Bonded Structures Workshop to benchmark adhesively bonded structures. The workshop was conducted as a part of MILHDBK-17 conference from June 16-18, 2004. The primary objective of the conference was to document the technical details that need to be addressed for bonded structures and focussed on critical safety issues and certification considerations. Examples of proven engineering practices will also be documented in forthcoming FAA publications. By providing a benchmark for the existing technology it is hoped directions for future research and development will also be identified. Participants came from a wide cross-section including industry, government and academia. It is anticipated as a result of the conference the FAA will update the Technical Centre Bulletin on Bonded Structures and will draft a paper on the FAA Certification Policy for Bonded Structure by October 2004. DSTO and RAAF, ASI had representatives at the workshop.

RAAF indicated the following outcomes from the workshop would be desirable in advancing efforts to certify bonded repairs[1]:

- Consensus that environmental durability is a form of degradation that needs to be certified.
- Consensus that certification on the basis of process qualification is acceptable (i.e. recognising that interrogation of the bond is not feasible and that establishing bond durability deterministically is a viable alternative).
    - consideration of the role of 'companion testing' and NDT to support the process-based certification approach. Whilst a companion test may not guarantee a surface treatment application, it may provide certainty about some of the key process variables such as material quality and operator skill.
- Consensus that the key process step is surface preparation (SP) and, if a good process is used and performed adequately, that the final bond should be environmentally durable (all other factors appropriately managed).
- Consensus on how to qualify the process i.e.
    - is the BWT an acceptable and sufficient test?
    - should the test be accompanied by a minimum level of in-service repair evidence or environmental durability testing for each SP process?
- Determination of process qualification test acceptance criteria.
- Consensus on how to assess the risk that is inherent in the above approach (e.g. probabilistic/statistical approach).
- Determination of acceptable risk level.
- Determination of data necessary to support the risk assessment.

[1] Email from SQNLDR Adrian McKenzie, 2/6/2004 to Andrew Rider, DSTO, and Max Davis, ASI-4D.

RAAF aims were consistent with those of the workshop organisers. The FAA indicated a strategy will be established, providing a clear direction for achieving certification objectives. DSTO canvassed options and introduced a potential methodology for certifying the environmental durability of adhesive bonded repairs for consideration by the workshop attendees. Attendees present at the workshop also saw merit in the approach proposed and some have registered interest in entering into potential data sharing arrangements, particularly, for wedge test and service data. Data collection and analysis, as indicated later in the report, will be the basis on which a successful outcome can be achieved. The process of developing the risk and reliability model using the collected data may further encourage international participation in the development of an environmental durability certification strategy for bonded repairs. A report on this overseas visit is now available and details of the outcomes and FAA technical initiatives are provided [7].

7.2 Analysis of historic Boeing wedge test (BWT) results

A program of work was conducted to analyse historical data based on Boeing Wedge Tests generated by a wide variety of sources including DSTO and RAAF. This data indicated that trained and experienced personnel conducting these tests could provide a surface treatment quality which was conducive to consistently good BWT results. These were characterised by a low initial cracklength with a low standard deviation and minimal crack growth after 48 hours exposure to hot and humid conditions. The data also showed that groups that did not conduct surface treatment processes on a regular basis produced BWT results with much greater scatter, larger initial cracklengths and much higher growth rates under environmental exposure. This result highlights the human factors that affect the process and can have a significant impact on the quality of the surface treatment performance [8].

Further analysis of the BWT data provided a regression model which highlighted the significance of a range of variables including adherend alloy, adhesive type, grit blasting and chemical treatment type. The significance of some of these factors is expected, but their effect on BWT performance can only be determined using a model such as the multiple regression model developed [9]. The report highlighted the need for additional data in order to build a more robust model. Such data may appear in the future as it is continually gathered and may be sought from DSTO, RAAF and external sources (see section 7.1). A data trawl of BWT and service data is vital in developing a risk model of the bonding process and establishing requirements for additional testing, given gaps in the present data exist.

To date, DSTO has examined more than 130 wedge tests produced by the RAAF Bonded Structures and Testing Team (BSTT) during qualification of technicians required to perform bonded repairs on ADF aircraft. More than 650 individual pieces were examined and all available variables recorded during manufacture were consolidated in a spreadsheet for the data analysis described above. Details of the recorded variables are provided in Appendix A: . The development of such a database enables important parameters to be identified that can affect wedge test performance. Inclusion of failure analysis inspections within the database is a critical link in establishing relationships between performance and each of the variables.

An exercise is currently underway to gain data from international sources. A questionnaire was provided to gain knowledge about international experience with bonded repairs and the type of hard data that may be available (Appendix B:). Gathering this data and relating it to service experience could provide a means to generate a detailed model of the durability of the adhesively bonded repair process. A system to gather future wedge test data from RAAF sources such as the Bonded Structures Testing Team (BSTT) and a means to analyse it in a consistent manner has been provided by Aerostructures [9]. A defined process to test and analyse service teardown and performance data also needs to be established.

7.3 Redefining the BWT pass/fail criteria

The pass/fail criteria for wedge tests has been defined in the Australian Air Publication 7021.016-2 [6] as:

- 42 mm maximum initial crack growth
- No more than 6.5 mm of growth over 48hrs while exposed to 95%RH at 50°C.

An examination of Bonded Structures Testing Team[2] (BSTT) data for over 130 wedge tests conducted between September 2002 and March 2004 shows that the average initial cracklength is 39 mm and only an average of 4.3 mm of growth occurred after 48 hours. These tests were performed using FM300 adhesive and aluminium alloy plates (2024 T3 clad). These results highlight the fact that the pass/fail criteria as it currently stands may be too generous and may allow some poorer quality surface preparations to be classed as satisfactory. It should be noted, however, that the standard also requires that no more than 10% of the cracked region of the wedge test should exhibit adhesion failure. Typically, in the larger crack growth samples, adhesion failure is 100% and these tests fail using the second criteria established in the standard. Revising the allowable cracklengths should, however, be considered.

Using the BSTT data with criteria 39 mm initial cracklength and 4.3 mm of growth:

- 92% of BWT samples passed the initial cracklength criteria
- 84% passed the growth criteria

Altering the initial cracklength criteria showed that the percentage of pass/fail dropped to 85% when the value was set to 41 mm. The growth criteria was less sensitive and it was found that it could be reduced to 4 mm while still maintaining a 77% pass rate. The data shows that a growth of less than 3 mm in 48 hours can be readily achieved reproducibly by a skilled technician. Tightening the 48 hours growth criteria to this level would provide a more stringent pass/fail requirement. Leaving the initial cracklength criteria at 42 mm would pass high quality surface treatments using FM300 adhesive.

A report provided by Aerostructures [9] shows that setting the total cracklength criteria after 48 hours to 45.4 mm provides a 1% false alarm rate. The revised criteria described above provides a total cracklength of 45 mm (42 mm initial plus 3 mm growth) after 48hours. This would be acceptable since only 1 in 100 tests are expected to fail the test due to conditions outside of the operator control. Clearly, however, it is unreasonable to fail a technician unless the causes of failure can be identified and processes implemented

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[2] BSTT are the RAAF unit tasked with qualifying all technicians required to perform bonded repairs on ADF aircraft. The pass/fail criteria is based on technician adherence to process rather than the result of the wedge test as, presently, there are variables in the bonding process that are not addressed in the RAAF Standard that can lead to result variation.

to identify the deficiencies and rectify them. Quality control tools, described in the following section, can make a contribution in achieving this aim.

7.4 Surface treatment process optimisation

A model of the environmental durability of the surface treatment process provides the potential to gain an improved understanding of the variables and parameters that are most significant. The sensitivity factors can be examined in an analytical manner through carefully designed experiments and procedures to assess or control their influence on the bonding process can be developed. A parametric model should be able to provide a level of optimisation for a given process. The regression model developed by Aerostructures may be used to optimise the variables in the BWT process [9]. Changes to the process would need to be tracked in order to evaluate their impact on BWT performance and process variability.

7.5 QA tool development

A number of quality assurance tools may be employed to improve the quality of the bonding process.

7.5.1 Gloss meter for grit blast

Failure analysis of the BSTT wedge test samples between September 2002 and March 2004 revealed that 50% of the failed samples exhibited poor quality grit-blasting. Review of existing equipment to measure surface reflectivity or colour revealed a unit produced by BYK Gardner [10], called the Hand Held Micro TRI Gloss®, which was suitable for discriminating between different levels of grit-blasting. The unit, which retails at $5,390.00 (excl. GST), can take gloss measurements at three angles (20°, 65° and 80°), is self-calibrating and can download measurements to a spreadsheet application. Measurements comply with ISO, DIN and ASTM standards. It is expected after brief development the unit will be used to measure surfaces prepared during wedge qualification and a correlation with performance will be established along with an accurate assessment of the ability to model the grit-blasting effect on the wedge result. The grit blast process is often conducted manually and will therefore be subject to variation across the surface. A number of gloss measurements would need to be taken to ensure some measure of consistency.

7.5.2 Pre-packaged chemical kits

Selected analysis of failed BSTT wedge samples using X-ray photoelectron spectroscopy (XPS) revealed very low levels of silicon on the metallic surface. Typically, 3-5 atomic percent of silicon would be expected on the surface from the epoxy-silane. This indicates a potential problem with the application of the epoxy-silane solution. Additionally, pH measurement of the epoxy-silane solution used by technicians during qualification were neutral. Previous studies have revealed that a pH around 4-5 is required for optimal performance. Clearly, a significant variable in the surface treatment is the epoxy silane solution. It was decided that packaging the epoxy silane into kits, which contained measured quantities of epoxy silane, distilled water and acetic acid, for pH control, would provide greater reliability in the process. Each chemical is provided in separate vials and mixed prior to use. This avoids possible errors in measuring quantities and reduces health risks in decanting from large volumes of chemicals. Additionally, the kits could be traced back to batch numbers and problems associated with bonding would be able to be more readily traced to the source materials if required.

7.5.3 Fourier Transform Infrared (FT-IR) Analysis of epoxy silane

In addition to provision of epoxy silane kits, a procedure to evaluate the quality of the epoxy silane source material was developed. Previously, the epoxy silane was sourced from a single supplier and its quality and shelf life were established simply on manufacturer's data. Infrared spectroscopy was employed to measure the transmission spectrum of the neat epoxy silane and reflection-absorption infrared (RAIR) spectroscopy was used to measure the film deposited on a model aluminium surface from a 1% aqueous epoxy-silane solution. Transmission spectra can identify aging and deterioration of the epoxy-silane material through the presence of carboxyl and hydroxyl impurities. RAIR spectra can identify impurities and film thickness, both of which increase through epoxy silane aging [11].

7.5.4 Quality Surface Monitor

The water break test is typically used to identify surface contamination through the surface treatment steps of the wedge test. Controlled experiments suggested that silicone can be present at levels that can degrade the adhesive bond durability, but will not be identified with the water-break test. Alternative and more sensitive quality control tools are, therefore, required to analyse the bonding surface. Presently, infrared spectroscopic techniques have potential in this area, however, their application relies to some extent on the skill of the operator employing the technique. The equipment used to measure the infrared spectrum of a metallic surface is also, generally, restricted to laboratory environments. Modifications to standard equipment would be required to adapt the process to field or production environments similar to those experienced at BSTT, Amberley [12].

Work at DSTO identified a unit called the SQM-200 from Photoemission Technologies [13] for measuring surface contaminant [14]. The unit works on the basis of shining ultraviolet light at a metal surface and detecting the electrons stimulated by the radiation. The flux of optically stimulated electrons relies on the metal surface's work function and is affected by monolayer levels of contaminant. Previous research has indicated the high sensitivity of the equipment and efforts to implement it for quality control monitoring in wedge test fabrication are being examined. The surface quality monitor technology is not sufficiently mature at this stage for certification of surface treatment processes and more work would be required to identify the relationship between surface quality monitor indications and contamination.

7.5.5 Failure analysis

Failure analysis of the wedge test samples produced from either qualification testing or controlled experiments is the cornerstone of developing a robust system. It is only through the reliable detection of faults in the process that failure can be correctly described and potential process improvements implemented. XPS, as described in section 7.5.2, provides a valuable tool for identifying the locus of failure in the bonded joint, however, additional tools are also required. Time of Flight Secondary Ion Mass Spectroscopy (ToF-SIMS) is capable of identifying elements and molecular structures on surfaces at sub-monolayer levels and is presently being employed on BSTT failure samples that have not revealed obvious failure mechanisms. Other analytical equipment will also need to be examined to develop a reliable capability to identify all sources of failure from defective BWT and service repairs.

7.5.6 QA tool (Cusum Plot) to monitor BWT requalification data

The Bonded Structures Testing Team (BSTT) provides operator training and evaluation based on the BWT. The BWT is used for qualification of technicians and new BWT data is generated frequently. Changes in the trends in BWT results may indicate problems with the surface treatment process or materials. Understanding the current state of process quality for both training and repair purposes is essential for quality management. BWT data from BSTT should be analysed on a continuous basis and compared to past results. Process variations will become visible if a tool is used to graph BWT data as it is produced.

Aerostructures [9] devised a statistical cumulative sum or 'cusum' plot which tracks BWT data as it is gathered and entered into an EXCEL spreadsheet. Variations in the process (both positive and negative) can be immediately deduced. This then provides an opportunity to provide a rapid response to any changes in the processing environment, raw materials and operator application. This approach reduces the lag between such events and potential corrective measures. An additional benefit is provided in the form of a standard to which operators can aim.

The cusum plot is a relatively simple tool which monitors the average crack growth from the initial wedge test where monitoring begins and cumulatively adds the difference from the mean value with subsequent testing. In Figure 8 two of three possible states are represented i.e. No change in the first 50 tests followed by a continuous deterioration in BWT performance, indicated by increasing gradient of the trend line.

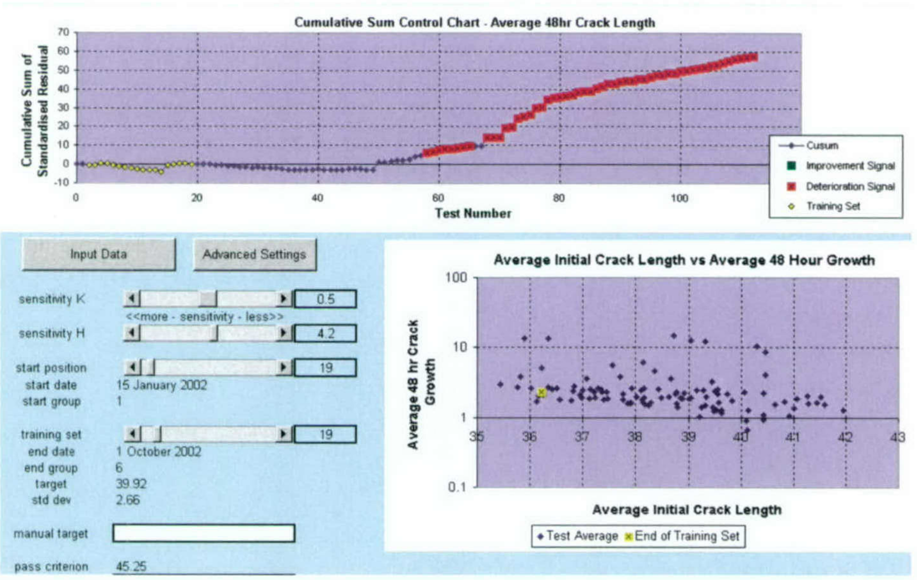

Figure 8 CUSUM plot used to indicate variations in Boeing Wedge Test (BWT) performance.

7.6 Conclusions

The range of measures described above provides an initial assessment of the status of processes involved in manufacturing bonded repairs. The initial status of the quality of BWT samples being produced under the current RAAF Quality Management System has been established and efforts to measure, monitor and improve that quality and reliability have been initiated or implemented. Whilst these efforts go towards improving the existing processes in RAAF they are only one component of a larger effort to enable certification for environmental durability of bonded repairs. Correlation between the wedge test result and service performance, as well as determining the influence of the environment of repair application and service need to be considered. The development of a risk and reliability approach to quantify these effects and develop a process of environmental certification are considered in the following sections.

8. Environmental certification of bonded repairs

8.1 Requirements

A certification approach for bonded repairs should be able to demonstrate:

- Required design performance over its entire service life
- A management approach which can evaluate the integrity of the repair over its service life
- A level of failure risk below that which is acceptable for air worthiness

The application of a bonded repair is designed to provide a predetermined level of intended performance over its entire service life. Given the uncertainty in bonding processes a certification path should provide an estimate of the level of risk of the bond failing over its intended life. The intended life may differ depending on application and may include short-term needs such as battle damage repairs or long-term requirements covering the life of the air platform. A model which provides the level of risk for a given bonding operation and its associated durability needs can provide a basis for decision making when considering bonded repairs as an option. These factors are influenced by the criticality of the repair, its location, the repair task and the processes used to conduct the repair and assess its ongoing integrity.

8.2 Bonding process certification

The certification of the bonded repair process requires a number of factors to be addressed. Both the design and application of the repair need to be certified to provide a satisfactory end result. Figure 9 shows a pyramid of factors required to successfully certify the environmental durability of a bonded repair process.

At the base level, the entire repair durability is underpinned by the materials and their allowables. At the next level, the surface treatment process and its inherent robustness and performance determines another factor in service durability. Repair application techniques must be then successfully applied to the desired repair location. On top of all this comes the operator qualification which allows all the processes beneath to be applied in a consistent and correct manner. All these factors provide the basis to certify a repair for environmental durability.

The pyramid of factors highlights the need to get each step correct before moving up to the next level of the pyramid. Failures in any of the layers that underpin a certified repair may compromise the service durability. The risk approach takes into account these factors and assesses the risk of each step, leading to a final consolidated risk level for the bond failing during its service life.

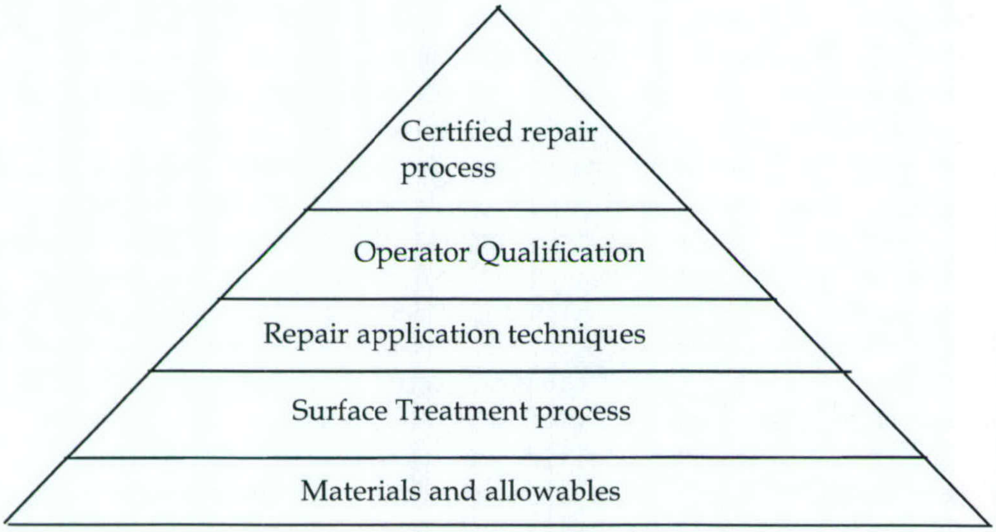

Figure 9: Pyramid for certification of bonded repair process

Improving training is a way of minimising process risk. The use of operator qualification and periodic testing provides some measure of assurance that the repair will be applied to the platform as per the required process. Any process is subject to human error or variation in repair conditions and materials. Training only provides one level of assurance in the overall scheme of repair certification. Means of mitigating risks at the other levels within the risk pyramid also need to be addressed.

8.3 Possible certification approaches

A number of approaches to utilising bonded repair technology for ADF use are possible. These vary based on their approach and the perceived risk of failing to provide a repair that will be durable for the life of the repair.

8.3.1 No credit

Providing no credit for the patch in terms of strength restoration is the current approach followed by RAAF (Section 3). However, this limits the range of potential applications and confines it to remaining as a niche technology. The method still relies on good engineering design and depends on the skills of the operators applying the repairs since collateral damage from a failed patch is always a possibility.

8.3.2 NDI (pre-bond chemical assessment and post bond inspection)

The use of NDI can be used to verify the quality of the repair process at two levels. Pre-bond NDI techniques can be used to determine whether the surface has been adequately prepared and is chemically amenable to producing a high degree of service durability (Section 7.5.4). Post NDI inspection, in its current state, can be used to determine whether the repair has been applied successfully in terms of being free from large voids or disbonds.

Currently the scope of NDI to provide a means to certify a repair is limited. Pre-bond NDI for identifying chemical species on surfaces has limited availability, but research is continuing to improve its maturity [12]. As indicated in section 7.5.4, the Surface Quality Monitor can be used on metallic surfaces to detect changes in work function that may be related to surface contamination levels, but will not specifically identify the contaminant species as an infrared or similar spectroscopic procedure would. This technology is unlikely to become readily available at economic prices in the short term. Traditional post bonding NDI has many limitations, mainly due to the fact that it only determines physical contact of the patch and cannot determine the strength of a bond or its expected life in a service environment. For these reasons, traditional NDI is not proposed as a path for certification. It should be noted that Dr. Robert L. Crane, a scientist in the USAFRL Materials and Manufacturing Directorate, indicates it is now possible to detect "kissing bonds" using a process based on laser shock peening, typically employed for altering the surface properties of metals to improve fatigue resistance[3]. Shock waves induced in the structure from the laser can be tailored to produce stresses of different levels in the adhesive bond and can, therefore, detect weak or non-existent bonds that cannot be identified with traditional NDI approaches. The approach has been patented by Boeing and may provide substantial benefit in ensuring production quality. The process would not be able to predict the rate of degradation of an adhesive bond after long-term exposure to a service environment and would therefore have limited benefit in providing a basis for certification of environmental durability.

8.3.3 Smart patch

DSTO is currently developing a method to monitor stress in the "safe-life" and "damage tolerant" zones (Figure 5). A ratio of strains from these two areas is expected to detect any deterioration in patch condition due to damage or environmental degradation. This approach will work well as a Safety-by-Inspection approach once the patch has received full structural credit. The smart patch will log any change in strain ratio from the base condition and the information would be downloaded automatically with a wireless link. This would provide reduced inspection effort and would be beneficial in inaccessible areas of the aircraft. Despite these benefits, the technology is still in an immature state and will rely on patch certification to provide its full benefit, additionally, the smart patch system will require certification itself.

8.3.4 Coupon test programme with full service environmental validation

The certification of environmental durability may be approached using a coupon test programme. This programme would determine all sources of potential effects on environmental durability and their impact on the service life. These coupon tests may

[3] http://www.afrl.af.mil/successstories/2003/emerging_technologies/03-ml-16.pdf

utilise the BWT and examine all sensitive factors such as humidity, temperature, level of voiding, adhesive age and operator experience. However, many of these factors such as operator experience may be difficult to quantify. Coupon tests may be subjected to accelerated environmental conditioning designed to replicate the effects of long term service. The results of the coupon tests may then be used to determine the average durability of the bonding process over the long term.

This approach can be prohibitively expensive and there may be poor correlation between the accelerated conditioning regime and real service. The range of factors that would need to be examined could be very large and any changes to the process would require a large number of the coupon tests to be repeated. Such an approach could impede efforts designed to provide continuous process improvement.

8.3.5 Risk and reliability based approach

As indicated previously, the lack of any mature NDI technique to determine the long-term environmental durability of an adhesive bond means that the processes employed to apply a bonded repair must be highly reliable. Adhesive bonding is inherently reliant on human effort and material quality and, therefore, is susceptible to substantial variation. Additionally, in moving from a specifically designed manufacturing facility to a maintenance depot, the impact of the working environment on repair application needs to be assessed. The risk and reliability approach provides a basis with which to estimate the likelihood of a bonded repair process being applied in a manner that provides sufficient environmental durability for a given repair application. The risk tolerance of the repair may depend on its location, criticality and other factors. Risk mitigating steps can be designed to reduce any risks and may be tailored to the given application.

In a coupon test programme, described above, the number of variables and their potential impact on the bonding procedure soon becomes a huge undertaking, in which only one repair system is validated. The benefit of a risk and reliability approach to the certification of environmental durability has the potential to more rapidly identify the critical parameters in the process that need to be addressed. Intangible contributions to the bonding process such as human error are also more economically assessed in the risk-based approach. Despite the best systems, the chance of failure will always exist and the risk and reliability approach can determine the likelihood of such occurrences and provide a basis for certification.

9. Preferred certification approach

A mature technology must be able to be characterised on the basis of understanding the rate of technology failure and the associated causes. The maturity of bonded repair technology needs to be increased before certification is possible. Certification is required to expand bonded repair use beyond the current niche applications. Determining the rates of failure for both bonded repairs and BWT specimens under a range of conditions and the identification of the causes is an essential step in providing a mature technological capability. The approach outlined below provides a means to improve the bonded repair maturity by providing quantitative assessment of bonded repair performance, a means to identify ways to optimise the technology and a mechanism to continually assess its improvement. The combination of these elements and the tools to provide an assessment of the risk of a given approach are seen to be a means to certification and maturity.

9.1 Proposed risk and reliability (R+R) based system

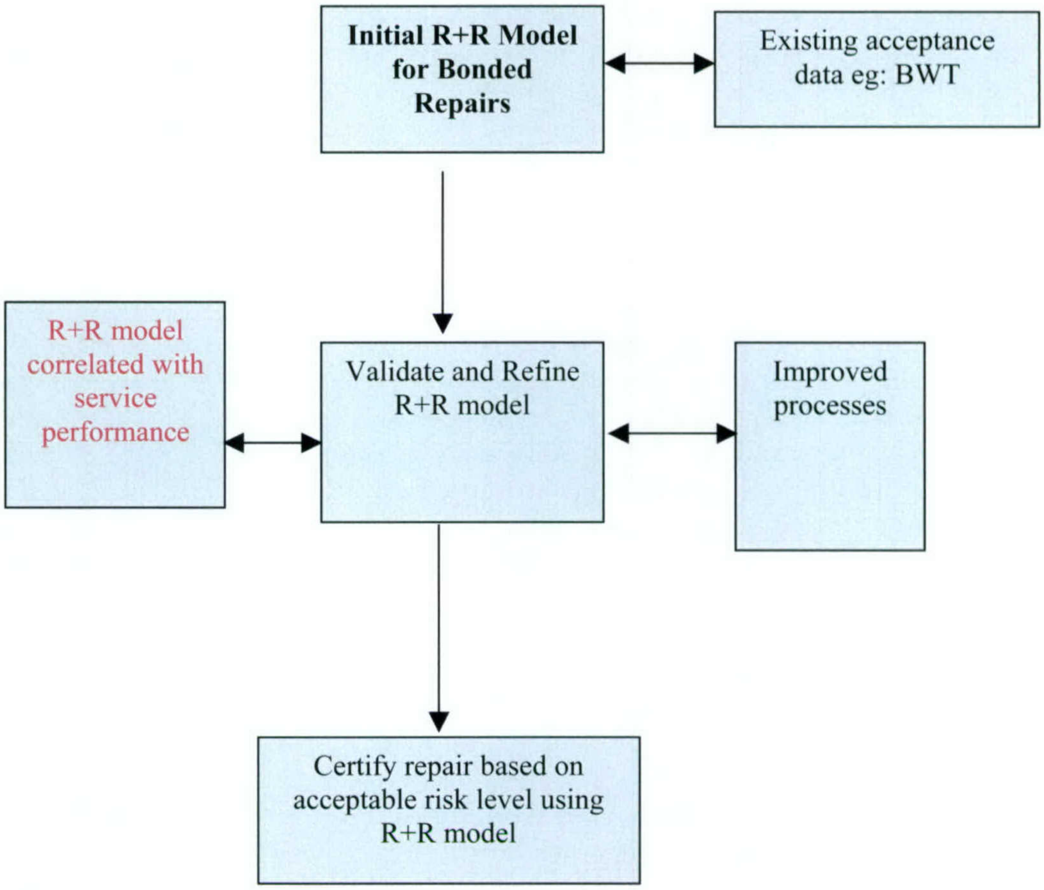

Figure 10: System to model and improve bonded repair performance

Figure 10 describes a system for developing a robust approach to modelling and optimising the performance of bonded repairs in service. A description of how this model may be developed is provided below.

An initial model of the reliability of a bonded repair is conducted based on existing acceptance data such as the BWT. This may be used to provide a parametric model which relates BWT results to a range of critical and sensitive factors which define the performance of a given surface treatment. This model would provide a baseline risk model of a given surface treatment process performed in the laboratory.

In order to improve the process, sensitive steps may be improved, NDI techniques and QA tools may be employed and extra training or supervision may be implemented to improve the operator skill and reliability level. In some cases, highly sensitive process steps may be susceptible to large variations and cannot be effectively controlled. All such factors must be taken into account in the R+R model and provide the end-user with an assessment of the resulting risk.

The correlation between service performance and BWT data must be examined since laboratory implementations of bonded repairs under ideal conditions rarely represent the situation for in-field repairs. Initially, variations in the repair application environment would need to be measured and the influence on BWT results determined. In addition, understanding the effect of long-term environmental effects on bond durability must be determined. Such data can be gained by keeping track of existing bonded repairs and examining their integrity over their service life. This may be done as a tear-down of old repairs and by using NDI on existing in-service repairs. This correlation may not be readily determined but some inferences may be made about the correlation of legacy repairs and their corresponding Boeing Wedge Test performance. It has been shown that modern surface treatment procedures have superior BWT performance compared to those employed in early bonded repair efforts. If it can be determined that legacy repairs using early surface treatments have been durable, it can be inferred that surface treatments with superior BWT performance will be even more durable.

A model that provides a prediction of service durability based on processing parameters and repair conditions can be used to provide a measure of the likelihood that the process will produce a durable bond over its intended service life. This risk can be calculated and used by an engineer to make a judgement on whether to employ a given repair process. Combined with the potential consequence of repair failure, the engineer can provide an informed decision on certifying the repair for a given application.

9.2 Risk modelling approach

Determining the risk of a process is not a straightforward task. A number of approaches can be employed:

- Estimate the risk based on anecdotal experience (soft data approach) (refer Appendix C:)
- Calculate the risk based on a large data set (hard data approach)
- A combination of the two (both soft and hard data)

In reality, it is unlikely that a complete or sufficiently large data set will be available to provide the basis for a detailed mathematical analysis in order to provide probability distributions for each part of the repair process and all factors relating to service environments. The probability of success of the complete process is a combination of the probability of successful completion of each of the required steps. For example, the repair process may have faulty materials, faulty equipment, faulty processes or poor application. The probability of each of these must be known in advance, or estimated.

9.2.1 Baseline condition of bonded repairs

As a start, the probability of in-service repair failure across all processes and surface treatments should be estimated or data gathered to provide a baseline value. Essentially, this provides the engineer with an estimate of the reliability of the technology in its present state and encompasses all the variations that contribute to its reliability.

9.2.2 Risk tolerance

Risk tolerance is a subjective engineering assessment. For this reason, the baseline reliability of bonded repairs may not be acceptable for a number of reasons. The engineer may demand a higher or lower level of risk than the base technology offers. The level of acceptable risk demanded may depend on the following factors:

- Repair location in terms of primary, secondary, tertiary
- Whether repaired component is flight critical
- Whether loss of repair will cause collateral damage
- Whether credit is given to the repair to restore component strength
- The expected life of the repair, temporary or permanent

The engineer can then decide whether the level of risk is acceptable for the given application and whether the consequence of repair failure warrants the risk taken.

9.2.3 Risk assessment

The R+R model is designed to provide a risk level associated with a given repair process. The parameters for a repair are many and varied but the main impacts on the environmental durability may include:

- process type
- process application quality
- operator training level
- repair location
- application environment
- service environment
- repair substrate (composite, metal etc.)

The R+R model must include all major drivers associated with the risks involved in using bonded repair technology. Gathering data and anecdotal evidence is vital in identifying all major factors.

9.2.4 Risk mitigation

In practice, a number of steps may be taken to mitigate the risk factors associated with a given repair. These may include:

- using repair technicians with current experience
- controlling all process steps using NDI or quality assurances
- controlling the application environment (humidity, temperature)
- using robust surface treatment systems compatible with the substrate
- implement inspection intervals dependent on the criticality of the crack growth rate

The model should provide flexibility for the engineer to choose which factors are important in a given repair and tailor the risk mitigation steps to provide an acceptable level of risk. Risk mitigation steps may involve extra overhead and cost and may not be warranted for every repair scenario. Mitigating all risk factors may be either too restrictive or too costly. Understanding the trade-off in terms of the cost of risk mitigating steps and the actual risk is vital in making decisions on providing repairs which provide the greatest cost-benefit. The model should provide flexibility in determining the risk that will remain controlled and the resulting probability of in-service failure.

10. Risk model development

It is anticipated that the risk model will evolve over time and will begin as a series of simple relationships between risk and factors affecting the repair durability. As data accumulates a simple model may be derived which provides a coarse estimate of repair failure risk. As data gathering processes are put in place to support the modelling efforts, the quality and completeness of data should improve and allow a more complex and robust model to be developed. It is envisaged that there will be a number of steps required in building the R+R model. These may include:

- Data gathering, sorting and filtering
- BWT modelling
- Expand R+R model to repair scenario
- Determine service durability to BWT performance correlation
- Produce complete R+R model
- Optimise
- Validation by future teardown/inspection or additional laboratory testing

A number of data modelling techniques may be employed in developing the risk-based model. These may include:

- Regression analysis
- Monte Carlo probabilistic
- Bayesian network approach (A diagram indicating the variables and their interaction for the surface treatment quality in Appendix D: shows the initial approach that would be employed in developing a Bayesian network model)

These methods are not discussed here in detail but the general methodology for gathering data and modelling service durability are detailed in the following sections. The type of data reduction method or methods used will evolve as data is gathered and the certification concept matures.

The complete R+R model is expected to provide a range of tools to support engineering decision-making. It is envisaged that these tools will be initially available as stand-alone modules to perform risk assessment functions but will be included in the future as an integral part of the RAAF Bonded Repair Software.

The following sections describe some of the steps required to provide a risk-based model for the certification of bonded repairs. This is not complete and will be developed as data are gathered and the model grows in scope. Two important areas of risk modelling, data gathering and service durability modelling are covered in detail below.

10.1 Data requirements for developing a risk and reliability model

Data gathering is one of the most important functions in providing a R+R model. The correlation between current BWT performance for a given surface treatment and the service environmental durability is vital. Since service data on durability may be required for decades it is important to provide this data in a form that will become useful to future RAAF and ADF needs. The data requirements to provide a robust and accurate R+R model will in fact define the requirements for future information gathering.

The limitations of building a risk model of the bonded repair process is that potentially large amounts of quality data are needed. Large data sets are required to produce statistically meaningful results. If the model is comprehensive and extends to cover a wide range of factors then the data requirements become even more onerous. This limitation can be overcome by:

- gathering large data sets from external sources
- limiting the problem to provide a model of lower complexity
- setting up a system to gather data for future modelling needs
- establishing causal relationships and thereby designing efficient test matrices

BSTT, through continual requalification of technicians provides a regular source of BWT data that can be assessed and the effects of process modifications monitored. The monitoring and feedback allows continual improvement in the bonding process. A mechanism to continually assess the performance of in-service repairs is also needed. This may include basic knowledge such as the rates of repair failures or using NDI methods to inspect repairs on a periodic basis. This information then needs to be correlated with processes and conditions used during repair application. The accuracy of the R+R model depends on clean and high quality data. Incorporating processes in the RAAF system to provide this data will in turn improve the confidence in understanding the durability of bonded repairs.

Currently, RAAF-ASI and Aerostructures are involved in the inspection of bonded repairs applied to F-111 honeycomb panels. An estimated 500 repairs are present across the fleet for the 2 year period from 1997 to 1999 in which good details of the repair procedures and environments are available. Results from NDI and teardown inspection will provide initial correlation between BWT and service performance.

Constructing the model will utilise data based on the performance of legacy repairs as well as current repairs inspected non-destructively in service. In many cases, the data will not be complete. However, the data will enable a basic model to be constructed and this will enable identification of the current limitations in the data gathering and recording. Improved quality data will result in an improved R+R model and future efforts must include rigorous data gathering and management procedures. Current RAAF standards manage the information well but it is presented in a paper-based form that is not easily evaluated by a computer-based model. Implementing an electronic-based system to collect this data would pave the way for future efforts. Similarly, the data concerning the performance of legacy repairs must be collected in a consistent and complete manner. Retrospective examination of existing repairs can provide an initial step in understanding the true environmental durability of bonded repairs. All future repairs need to be tracked and the failure of repairs must be noted and the cause assessed.

Gathering data from other organisations involved in adhesive bonding and the application of bonded repairs can provide a short cut in creating a robust model (Appendix B:). This is especially important in relating the performance of a BWT and in-service durability. The correlation between these two parameters is vital in understanding the R+R modelling needs as well as being able to draft a suitable standard to assess the effectiveness of a given surface treatment.

A number of organisations have recently expressed interest in collaborating on the base lining of bonded structure environmental durability. Mr Jim Mazza from USAF Research Laboratories and Dr Andrew Johnson from the NRC in Canada have both indicated a willingness to exchange data on bonded repair and structure service performance. Mr Mazza is currently tearing down several hundred patches from retired C-141 aircraft which were repaired in the early 90's. Dr Johnson has access to the civilian aircraft grave yards and will be able to recover bonded structure from retired aircraft. It is anticipated that exchange of data through a TTCP operating assignment will be achieved. Dr Nigel St John from MPD, DSTO is the coordinating an operating assignment in MAT-TP7 that will facilitate international cooperation in the development of a teardown database on bonded structure and repairs. Other partners in the operating assignment are also being canvassed and interest from USN, NAVAIR has been provided from Doug Perl.

10.2 Service durability modelling

Service data is required in the form of the number of repairs that have failed and the residual bond strength attained after being taken from service. This information will inform the model as to the correlation between BWT data and service durability. Such a model can inform the identification of a suitable standard to which a BWT should perform for a given service durability need.

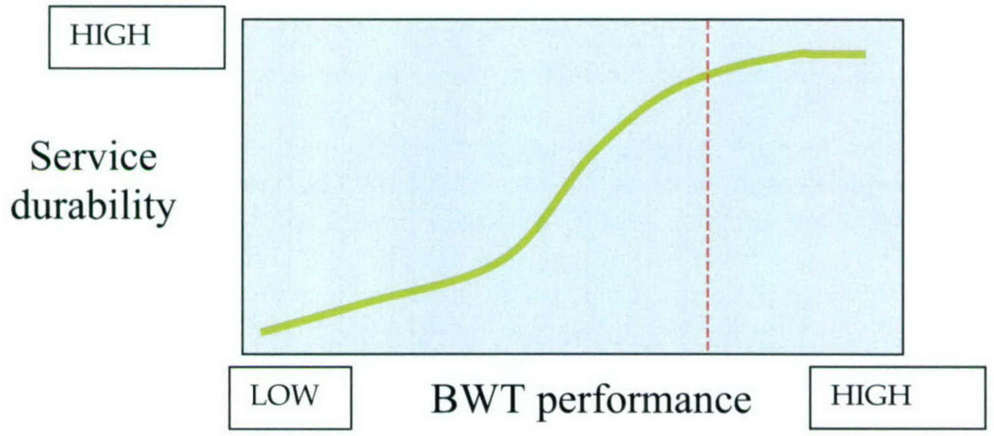

Figure 11: Correlation of service data to BWT

Figure 11 shows an example in correlating service performance with BWT performance. This is an arbitrary example of a correlation function. On the horizontal axis is represented the performance of a wedge test for a given surface treatment.

Corresponding to this wedge test performance is the service durability. A correlation of this type will apply to each combination of surface treatment process. The correlation shows that for low BWT performance (i.e. large crack growth under environmental exposure) the durability will be low. As BWT performance improves the durability also improves. The function shown assumes that BWT correlates with service durability and that past a particular BWT performance (shown by the dashed red line) the service durability is essentially assured for the expected life of the repair. The actual function describing this correlation would need to be generated by analysing actual service and BWT data.

11. Risk based certification - examples

The risk based certification approach should provide flexibility to the designer and not dictate a preconceived risk level. For example, the acceptable risk level for repair to primary structures, and the controls required to guarantee the risk level, may be far too costly when applied to a non-critical repair designed for tertiary structures. The risk tolerance of a given repair should drive the needs with regards to bond process control and inspection intervals. This section provides three case studies that highlight the benefits of the risk and reliability based approach under differing application conditions and requirements.

11.1 Battle damage repair

In this type of repair the following conditions and requirements are typical:

- Low need for bond durability, typically less than 100 hours
- Design is the major driver to restore temporary capability to original level or to a level to provide a safe ferry flight
- Repair may need to be conducted by technicians with limited expertise
- Materials allowables may be less than expected due to lack of guarantee over material storage
- Repair timeframe must often be short
- Repair environment is uncontrolled (no humidity or temperature control)

Under these requirements the risk model will receive the inputs described above and will provide an estimate of the risk of bond failure. The estimate will be accompanied by a confidence level in this assessment. These estimates will be based on service data, BWT data and the amount and quality of data which supports them. The engineer can then choose to accept the repair based on the risk level provided or may choose to mitigate some risks and re-calculate the results. For example, the engineer may wish to stipulate that an experienced and qualified technician undertake the repair. This may lower the risk to an acceptable level. Other controls may include insisting on repair materials that have a known history and have been recently tested or by conducting a "companion" BWT which is analysed prior to certifying the repair.

11.2 Secondary structure repair

In this type of repair the following conditions and requirements are typical:

- Need for long-term durability of up to 25 years

- Can be conducted at a depot level or in the field
- Repair needs to be inspected to ensure it is providing adequate performance
- Expert technicians can be made available
- Materials are adequately controlled
- Environmental controls are available if needed
- Timeframe is often not short and specialist training particular to the repair is an option
- Quality assurance tools may be implemented as required.

In this case, the engineer has a wide range of options in carrying out the repair. Quality assurance tools and expert technicians can be made available if the repair is critical. For example, a technician with a known ability to perform high quality BWT samples may be preferentially selected to apply the repair. The QA tool of the 'cusum' plot (Section 7.5.6) can provide an indication of the level of competency of a bonded repair team over time. This can influence the team selected for a given repair. In non-critical repairs, new trainees may be allowed to perform repairs based on minimal supervision. Other QA tools such as those listed in Section 7.5 may be utilised, but these may increase the repair cost and complexity. The associated risks with implementing tools may be reflected in lower durability risks. The risk approach is designed to provide a wide range of repair options that are suited for the intended purpose. For example, inspection intervals for crack-growth under the patch may initially be conducted on the basis of major service intervals or in accord with normal maintenance in the absence of the patch. Based on successful initial performance of the patch the intervals could be extended or inspection requirements removed i.e. the risk model would establish a weighting system based on prior successful history.

11.3 Primary structure repair

In this case the maximum assurance for bond durability may be an overriding factor. Low risk tolerance or risk aversion is characteristic of this type of repair. In this case, the repair may be accompanied by inspection intervals in order to provide confidence in continuing performance. The engineer may elect to choose a repair method with a long and well-known history in order to provide the greatest confidence in the risk evaluation. Selection of all risk mitigation factors may be necessary and an inspection interval based on historic data will improve confidence in the repair approach. The risk and reliability model will provide a standardised method to evaluate risk that is not subject to engineering bias such as previous experience with bonding repair. Risk assessments will be provided on the basis that they are underpinned by quality data. An example of the flexible approach of the risk assessment methodology would involve determining the consequence of patch failure on airworthiness. This approach would have a significant influence on inspection intervals and consequently the economic benefits of repairs in fleet-wide applications.

12. Conclusions

The current status of bonded repair technology in the context of RAAF usage has been reviewed and limitations assessed. Presently, RAAF provide no credit to bonded repairs to primary aircraft structure and the aircraft is managed as it would be in the absence of the patch. The major concern with adhesive bonding technology is the potential for the adhesive bond strength to degrade unpredictably to a zero strength condition due to exposure to a humid environment if the surface treatment procedure is inadequate. It is apparent that for bonded repairs to be given structural credit for application to primary aircraft structure environmental durability issues must be addressed. By developing a certification path for bonded repairs the full benefit of the technology can be realised and major cost savings in the management of aging aircraft fleets will result.

The RAAF have implemented a Quality Management System to ensure the quality of adhesive bonding conducted on ADF aircraft. Involved in this approach, is the regular qualification of personnel involved in bonding operations. Strict management of materials and a highly skilled workforce are seen as essential ingredients in reliable application of bonded repairs. The RAAF approach is based on the absence of any reliable or mature NDI technique which can reliably assess the quality of an adhesive bond or its long term durability in the service environment.

The RAAF approach provides the basis for developing a Risk and Reliability (R+R) system for the certification of bonded repairs. It is proposed that establishment of an acceptance test to qualify environmental durability of bonded repairs be established Correlation of the test with known service performance will provide the basis of establishing a R+R model and consequently a strategy for certification. The Boeing Wedge Test (BWT) is an industry standard and is currently employed by RAAF to qualify bonding technicians and monitor material and process quality. The BWT provides a rigorous assessment of the surface treatment process applied to the bonding substrate and an analogue for the most critical steps in the bonded repair application process. The surface treatment applied in the bonded repair will be the most critical factor determining bond strength and long-term environmental durability. Initially, developing a risk model of the BWT for the current RAAF surface treatment will provide a basis for a risk model of the bonded repair process. Identifying critical parameters affecting wedge test performance will establish factors influencing the quality of bonded repairs applied in depot or field level maintenance. Correlating the BWT results with known service performance will establish the validity of the acceptance test and the risk approach in certifying environmental durability of adhesive bonded repairs.

It is clear the risk based certification strategy will be heavily reliant on data, for both the BWT and repairs. Efforts are underway to collect data from RAAF and DSTO sources and this will provide the basis of the initial model. The model will continually evolve as improvements in processes are implemented and monitored. Critical to the success of the certification strategy will be international collaboration. An initial survey of international effort in bonded repairs indicates, potentially, a substantial database is available. If the database is efficiently managed, then there will be a substantially reduced effort in the development of a robust model for assessing the environmental durability of bonded repairs. Efforts through TTCP MAT TP7 operating assignments should assist in these endeavours.

13. Recent initiatives to improve bonded repair management and certification

A number of initiatives have been recently raised to begin to implement the risk-based methodology for the management and certification of bonded repairs. Initially, the current quality of wedge tests being produced by RAAF bonded technicians during requalification testing has been reviewed. This process has established a number of controls that need to be implemented to optimise the process and improve reliability. These controls include the use of pre-measured epoxy silane kits, gloss measurement of the grit-blasted surface after treatment and recording of process and materials details during wedge manufacture for inclusion in a consolidated database. Implementation of these controls is underway with purchase of a reflectometer by ASI, trialling of the epoxy silane pre-measured kits and consolidation of the BSTT database with new quality control software generated by Aerostructures to monitor wedge performance. Strong ASI support has resulted in employment of an Aerostructures statistician to model the RAAF wedge data and establish the significance of the control variables being monitored. Development of an initial regression based model has also occurred. Significant variables include grit-blast quality, operator experience, location and adhesive age. Efforts to collect comprehensive wedge test data are underway. Jim Mazza from USAFRL has been contacted and an extensive wedge test database on the FM 73 and grit-blast and epoxy silane system is likely to be made available for statistical analysis. A new SOR has also been developed for Aerostructures to further develop the regression model incorporating the Mazza data and to design experiments to develop sufficient statistical data to improve the robustness and reliability of the model.

Efforts are also underway to coordinate and collect data from current or retired repairs. ASI has provided support in employing Aerostructures to non-destructively examine all repairs applied to F-111 between 1997 and 1999. To date around 60 repairs have been examined on the fleet and only two that have defects have been identified, neither due to bonding durability problems. A number of unserviceable panels are also available for inspection and ASI and Aerostructures are providing support to deliver repairs from these panels to DSTO for inspection. In parallel with these efforts, the regression model being developed with Aerostructures will include the results from the F-111 bonded panel repairs. The model will include all recorded variables available during repair application and correlate this data with service performance. Additionally, data recording requirements during repair application will be specified. Procedures will be implemented to insure that repairs are continually monitored and information consolidated into a database in a form that can be analysed with the regression model. International contacts have also been made regarding collection and consolidation of data on repair performance. Jim Mazza is presently tearing down a large number of patches from C-141 and it is hoped, through a TTCP-MAT TP7 working assignment, this information and the Australian data from F-111, Mirage III and C-130E can be shared. Dr Andrew Johnson from NRC also indicated that data on bonded structure from retired civil aircraft may also be available and a collaborative program through TTCP could also be organised.

Further details of progress and development of the R+R model are planned in a future DSTO technical report.

14. Recommendations

The preceding document provides a position paper for developing a research program that can develop and implement processes to enable the environmental durability of adhesive bonds to be certified for use by the ADF. The following section provides recommendations on a potential program which could be implemented to establish the viability of the Risk and Reliability Engineering approach that has been described.

14.1 Major objectives

The major objectives of the program would be to undertake the following activities:

- Analysis of current BWT data
- Creation of R&R model for BWT
- BWT process re-engineering
- QA system for BWT requalification
- Correlation between BWT and real-world exposure
- Software tool to assess R&R for bonded repair application
- Certification of bonded repairs using risk basis engineering

Each of these activities would involve the following tasks:

14.1.1 Analysis of current BWT data

- Sort and filter the current data set
- Add new BSTT data
- Assess use of historical data from various sources
- Statistical analysis
- Suggest revised pass/fail criteria for RAAF STD
- Identify major predictor variables

14.1.2 Creation of R&R model for BWT

- Create R&R model to predict BWT
- Examine model sensitivity
- Suggest optimal parameters for desired BWT result
- Design suitable test matrix to establish multiplicative effects of predictor variables
- Assess need for fresh data (testing) to improve confidence in model
- Perform tests as necessary

14.1.3 BWT process re-engineering

- Examine impact of human factors
- Recommend process controls
- Assess tools to provide QA control
- Recommend changes to RAAF STD

14.1.4 *QA system for BWT requalification*

- Identify data required for ongoing collection
- Provide tool to assess data trends (cusum 'worm'/other)
- Develop system to provide rapid response to process deviations beyond prescribed tolerances
- Implement system and amend RAAF STD

14.1.5 *Correlation between BWT and real-world exposure*

- Review bonded repair survey from domestic and international sources
- Review Amberley bonded panel records from 1997-1999
- Examine repairs for integrity
- Teardown legacy repairs (Mirage, C130, F-111, PABST)
- Co-ordinate teardown research results with international collaborators through TTCP
- Correlate BWT data and field performance
- Identify suitable process for implementing BWT companion test and ongoing monitoring of repair performance in service by coordinating activities with Boeing

14.1.6 *Software tool to assess R&R for bonded repair application*

- Design software to predict BWT result based on a selection of input parameters and controls
- Predict BWT failure risk
- Predict repair durability based on risk and service data
- Certify tool and incorporate into RAAF STD

14.1.7 *Certification of bonded repairs using risk basis*

- Examine R&R issues related to design
- Expand R&R certification methodology to include all aspects of bonded repair design and application
- Develop complete tool and incorporate into BR-S for insertion into RAAF STD

15. Acknowledgements

The authors would like to acknowledge the strong support provided by RAAF, ASI during initiation and development of the certification research, in particular, Dr Madabhushi Janardhana, Squadron Leader Adrian MacKenzie and Mr Max Davis. Support from Dr Alan Baker in providing contacts for the repair survey is also acknowledged. Finally, comments from Dr David Arnott were of considerable value and efforts provided in reviewing the report are greatly appreciated. Contributions from Dr Chun Wang in the section on damage tolerant management of bonded repairs for environmental durability are also acknowledged.

16. References

1. A.A. Baker and R. Jones, Bonded Repair of Aircraft Structures, Martinius Nijhoff Publishers, Dordrecht, The Netherlands, 1988.

2. D. R. Arnott, A. N. Rider and J. Mazza, in "Advances in Bonded Composite Repair of Metallic Aircraft Structure", Ed. A.A Baker, L. R. F. Rose, R. Jones, Vol 1, Chapter 3, pp. 41-86, Elsevier, United Kingdom, 2002.

3. A.A. Baker, in "Advances in Bonded Composite Repair of Metallic Aircraft Structure", Ed. A.A. Baker, L.R.F. Rose, R.Jones, Vol 2, Chapter 22, page 643-657, Elsevier, United Kingdom, 2002.

4. D.P. Roach and C.M. Scala, in "Advances in the Bonded Composite Repair of Metallic Aircraft Structure", Ed. A.A Baker, L. R. F. Rose, R. Jones, Vol 1, Chapter 22, pp. 659-724, Elsevier, United Kingdom, 2002..

5. DEF(AUST)9005 Issue A, "Composite Materials and Adhesive Bonded Repairs", Australian Defence Standard, Australian Department of Defence, Commonwealth of Australia.

6. Australian Air Publication 7021.016-2, "Composite and Adhesive Bonded Repairs, Repair Fabrication and Application Procedures", Royal Australian Air Force, 9 April, 2003

7. A. Rider, "Report on FAA Bonded Structures Workshop and Mil-Hdbk-17 Meeting in Seattle, USA, June 2004". DSTO Overseas Visit Report DSTO-OR-0589, 2004.

8. P. Livingstone, "Bonded Repair Data Audit", Aerostructures Document Ref: 4-13-27-3.14GR1475, 2003.

9. P. Livingstone, "Statistical Analysis of Boeing Wedge Test Data", Aerostructures Document No. ER-RISK-ASM403, 18/5/2004.

10. BYK Gardner, Lausitzer Strasse 8, 82538 Geretsried, Germany. Phone 49-8171-3493-0. Fax 49-8171-3493140. www.micro-gloss.com

11. A. Rider, R. Vodicka and G. Mathys. "Review of RAAF Procedures Employed for Qualifying Bonded Repair Technicians". DSTO Technical Report - in review.

12. H. Bley, S. Behrning, "Methods for Qualitative and Quantitative Analysis of Lubricants and Contamination Formed on Surfaces", Proceedings of the 6th Conference on Sheet Metal, Vol. 1, Enschede, The Netherlands,1998, S343-353.

13. http://www.photoemission.com/downloads/sqm200.pdf, Photo Emission Tech. Inc., 3255 Grande Vista Drive, Newbury Park, CA 91320

14. C. L. Olsson-Jacques, D. R. Arnott, L. T. Lambrianidis, A. R. Wilson, M. R. Kindermann, and G. Theodossiou "Toward Quality Monitoring of Adherend Surfaces Prior to Adhesive Bonding in Aircraft Repairs", The International Aerospace Congress 1997, 7th Australian Aeronautical Conference, pp. 511-520.

Appendix A: BSTT Wedge Data

Table A 1 Data recorded as a part of the BSTT wedge test audit, including manufacturing variables and fracture analysis inspections

Data Description	**Mode of Collection**	**Significance**
Sample No	Data from BSTT	Identification of sample by technician name
Adhesive	Data from BSTT and wedge inspection	Adhesive type
Adherends	RAAF Standard and wedge inspection	Metal and alloy type
Exposure	RAAF Standard	Environment used for wedge testing (50°C and 100% R.H.)
Surface Prep	RAAF Standard	Details exact steps used in surface preparation of adherend and if any deviations from standard have occurred
Test Date (ddd/mmm/yy)	Recorded by DSTO during wedge test	Date when test starts and finshes
Initial crack-length (mm)	Recorded by DSTO during wedge test	Provides initial crack-length of each wedge test specimen from number 1 to 5 after 1 hour of crack-growth in the laboratory environment
24 hour crack-length (mm)	Recorded by DSTO during wedge test	Provides 24 hour crack-length of each wedge test specimen from number 1 to 5 after 24 hours of crack-growth in the humid environment
48 hour crack-length (mm)	Recorded by DSTO during wedge test	Provides 48 hour crack-length of each wedge test specimen from number 1 to 5 after 48 hours of crack-growth in the humid environment
Mean initial crack-length (mm)	Recorded by DSTO during wedge test	Provides mean initial crack-length
Mean 24 hour crack-length (mm)	Recorded by DSTO during wedge test	Provides mean 24 hour crack-length
Mean 48 hour crack-length (mm)	Recorded by DSTO during wedge test	Provides mean 48 hour crack-length

Data Description	Mode of Collection	Significance
Requalification date (ddd/mmm/yy)	Data from BSTT	Date when wedge samples made and requalification testing was carried out
Batch No./ Roll No.	Data from BSTT	Batch and roll number of adhesive used for testing
Adhesive arrival date (ddd/mmm/yy)	Data from BSTT	Date adhesive batch arrives at Amberley
Adhesive requalification date (ddd/mmm/yy)	Data from BSTT	Date adhesive batch is relifed to extend manufacturer's use by date by 6 months
Adhesive expiry date (ddd/mmm/yy)	Data from BSTT	Date adhesive batch exceeds use by date
Silane Batch No.	Data from BSTT	Epoxy silane coupling agent batch number from manufacturer
Water break drying temperature	Data from BSTT	Temperature metal plates dried at after water break testing
Silane Drying Temperature	Data from BSTT	Temperature metal plates dried at after being treated with the 1% epoxy silane solution
Temperature (°C)	Data from BSTT	Temperature in Bonding facility during wedge test manufacturing
Humidity (%)	Data from BSTT	Relative Humidity in Bonding facility during wedge test manufacturing
Cohesive (%)	Recorded by DSTO during wedge test	Percentage of cohesive failure observed visually on the fracture surfaces of the wedge test specimens from number 1 to 5 by technician examining failure surfaces
Grouping	Recorded by DSTO during wedge test	The group number based on the date of receipt and testing of wedge samples from BSTT at DSTO.
Supervisor	Data from BSTT	Name of the BSTT Supervisor examining the technicians during wedge test requalification
Unit	Data from BSTT	Location of company or unit of technician being tested
Organisation	Data from BSTT	Affiliation of technician
Course	Data from BSTT	Course number attended by technician for training prior to wedge qualification

Data Description	Mode of Collection	Significance
Service No.	Data from BSTT	Service number of technician being tested
Test Site	Data from BSTT	Location at which the testing occurred
Name	Data from BSTT	Full name and rank (if applicable) of technician being tested
Pass/Fail	Recorded by DSTO during wedge test	Pass or fail of the wedge samples as determined by the technician testing BSTT specimens
Grit-blast level	Recorded by DSTO during wedge test	Assessment of the quality of the grit-blast based on 10X digital image acquired from non-bonded area of wedge sample
Large Void (%)	Recorded by DSTO during wedge test	Provides visual assessment of area of each wedge test specimen from number 1 to 5 containing largely voided regions
Small Voids (%)	Recorded by DSTO during wedge test	Provides visual assessment of area of each wedge test specimen from number 1 to 5 containing sub-millimetre voided regions
Adhesion Failure (%)	Recorded by DSTO during wedge test	Percentage visual of adhesive failure observed visually on the fracture surfaces of the wedge test specimens from number 1 to 5 by DSTO scientist examining failure surfaces
Comments	Recorded by DSTO during wedge test	Unique elements of wedge test sample or group that distinguish or clarify results

Appendix B: DSTO Bonded Repair Survey

Table A 2 Summary of responses from a survey on bonded repairs world-wide conducted by DSTO from 2001-2003

Organ.	Contact	Platform	Repairs	Materials	Surface Treatment	Qualification	Service(h) /repair	Status
RAAF	Max Davis	F-111	3000+	metal-metal, composite - metal	Grit-blast + epoxy silane	Quality Management (wedge test)	4000h+	97-99 repairs being inspect.
		P-3	23+	composite - metal	Grit-blast + epoxy silane	Quality Management (wedge test)	unknown	In service
Belgian Defence (MRSys-V/C)	Capt. Rudi DeCrop	F-16B	1	metal-metal	Grit-blast + epoxy silane	Coupon, Component, Static &fatigue	800h+	In service
RNZAF	Ian Gatehouse	Macchi	1	metal-metal	Grit-blast + epoxy silane	Quality Management (wedge test)	150h	Voiding during cure, problems in application
		Skyhawk	2	metal-metal	Sand, solvent clean prime	Quality Management (wedge test)	830+	In service

Organ.	Contact	Platform	Repairs	Materials	Surface Treatment	Qualific-ation	Service(h) /repair	Status
FAF, Air Material Command	Ari Kivisto	Hawk MK51	8	composite - metal	Grit-blast + epoxy silane + BR-127	Lap shear	300+	In service
Israel Aircraft Industries	Arnold Nathan	F-16	1	composite - metal	Pasajell 105 + BR127	Lab scale static and fatigue, wedge test	100+	In service
		Kfir Military Aircraft	100+	composite - metal	Pasajell 105 + BR127	Lab scale static and fatigue, wedge test	1000+	In service
		IAI Galaxy Business Jet	1	composite - metal	Pasajell 105 + BR127	N/A	13000+	Out of service
NAVAIR Depot NI, Materials Eng. Lab.	Douglas Perl	F-5E	9	composite - metal	Grit-blast + epoxy silane + BR-127	Lab scale static and fatigue, wedge test	1370+	Out of service Oct '04
R-Tec	Mohan Ratwani	T-38	4	composite-metal	PAA	Wedge test	U/A	U/K
Comp-osite Technol-ogy Inc.	Terr-ance Reininger	AH-64	150	composite - metal	Grit-blast + epoxy silane	Wedge, coupon, full-scale, flight	4000	Out of Service

Organ.	Contact	Platform	Repairs	Materials	Surface Treatment	Qualific-ation	Service(h) /repair	Status
FAA, Airworth-iness assurance Center (Sandia)	Dennis Roach	Delta L1011, FedEx DC-10	7	composite - metal	PACS	Wedge, ultraso nic	3 years+	In service
Bomb-ardier, Canada	Martin Vallerand	CF18A/B	100s+	metal-metal, composite - metal	Pasajell 105 /107+ BR127	SRM or wedge and lap-shear	60-2000+	In service
DSTO	Ivan Grabovac	FFG	4	Composite-metal	Grit-blast + epoxy silane	Quality Manage ment (wedge test)	7-8 years	In service
DSTO	Andrew Rider	Mirage III	160	Composite-metal	PANTA	Quality Managem ent (wedge test) Lab scale static and fatigue,	2000	15 repairs recovered
		C130	3000	Composite-metal	Grit-blast	Lab scale static and fatigue, basic training	19 years	50+ repairs recovered

Appendix C: Risk Assessment Table

Table C1 Major risk components involved in the use of Bonded Composite Repairs:

Procedure	Elements	Sub-Elements
Design	Damage identification	
	Database	
	Tools	FE
		Analytical
		Standards
	Validation	
	Repair requirement/location	Loads
		Temperature
		Environment
Application	Materials	
	Equipment/Facilities	
	Environment	
	Repair Location	
	Operator/Personnel	
	Quality Processes	
	NDE Post Repair	
Through Life Support	NDE	
	Protection	
	Environment	

Table C 2 *Global Assessment of Risk Associated with use of Bonded Composite Repairs*

Assessment risk is based on Low: 1/1000, Medium 1/100, High: 1/10
Probability of Repair Failure is based on the specified Element failing in a worst case scenario

<table>
<tr><th>Procedure</th><th>Element</th><th>Probability of Process Failure</th><th>Justification</th><th colspan="3">Probability of Repair Failure
(if process fails)</th><th>justification</th></tr>
<tr><td>Design</td><td>Damage ID</td><td>Low</td><td>NDI procedures reliable</td><td colspan="3">Low</td><td>NDI unlikely to be drastically wrong</td></tr>
<tr><td></td><td>Database</td><td>Low</td><td>Materials and design data qualified with standard testing and procedures</td><td colspan="3">High</td><td>Poor design data can lead to inaccurate safety margins</td></tr>
<tr><td></td><td>Tools</td><td>Low</td><td>Tools validated, processes cross-checked and authorised</td><td colspan="3">Med</td><td></td></tr>
<tr><td></td><td>Validation</td><td>Med</td><td>Difficult to replicate and interpret real aircraft loads in laboratory scale testing</td><td colspan="3">Med</td><td>Old eg. F-111 WPF</td></tr>
<tr><td rowspan="3"></td><td rowspan="3">Repair requirement/ location</td><td rowspan="3">N/A</td><td rowspan="3"></td><td></td><td colspan="2">Location</td><td rowspan="3">Good locations easy to design eg. Flat surface with support

Bad locations challenge the design limits</td></tr>
<tr><td>Type</td><td>Good</td><td>Bad</td></tr>
<tr><td>Probability of failure</td><td>Low</td><td>Med</td></tr>
</table>

Table C 2 *Global Assessment of Risk Associated with use of Bonded Composite Repairs*

Application	Materials (Adhesive, composite, Solvent, silane…)	Low	Materials are qualified and manufactured according to factory standards	High	If materials perform significantly under spec patch will fail eg. Adhesive doesn't flow or cure correctly or voids badly.
	Equipment	Low	Backup systems in place, scheduled maintenance and calibration	High	Eg. Vacuum or temperature fails to cure adhesive
	Consumables	Low	Sourcing and storage performed according to standard procedures	Medium	Risk not as high as equipment failure
	Environment	Low	Repairs have to conducted in controlled environments	Medium	Wedge testing data provides good evidence to show what effect environment can have on bond performance
	Repair Location	High	Large number of areas on aircraft are difficult to repair i.e. access etc.	Low	Service history data indicates reliable performance for repairs over wide number of areas on aircraft structure
	Operator/ Personnel	Low	Training and requalification together with processes and inspectors	High	Bonding processes are highly operator dependent
	Quality Processes	Low	Underpinned by research and engineering and regular independent review	High	Incorrect procedures lead to bad repairs eg. SRMs for adhesive bonding pretreatment
	NDE Post Repair-Bond Strength	---	No NDI can detect the presence of adhesive bonding	Low	NDE has never been used to qualify repairs, based on adherence to processes and QA.
	NDE Voids/ Delamination	Low	NDI procedures well defined and reliable	Low	Good evidence to suggest bonds and delaminations don't lead to catastrophic patch failure

Table C 2 Global Assessment of Risk Associated with use of Bonded Composite Repairs

Through Life Support	NDE Bond Strength	---	No NDI can detect the presence of adhesive bonding	Low	NDE has never been used to qualify repairs, based on adherence to processes and QA.
	NDE Voids/ Delamination	Low	NDI procedures well defined and reliable	Low	Good evidence to suggest bonds and delaminations don't lead to catastrophic patch failure
	Protection	Low	Simple procedures carried on aircraft structure routinely	Low	Failure would be picked up readily during NDI and repaired, absence of protection will not degrade bond
	Environment	High	Aircraft experiences hostile and extreme environmental conditions	Low	Whole process designed to withstand Aircraft conditions. Lots of examples of broadly varying environments and good service performance.

Table C 2 *Global Assessment of Risk Associated with use of Bonded Composite Repairs*

Appendix D: Surface Treatment Risk Factors

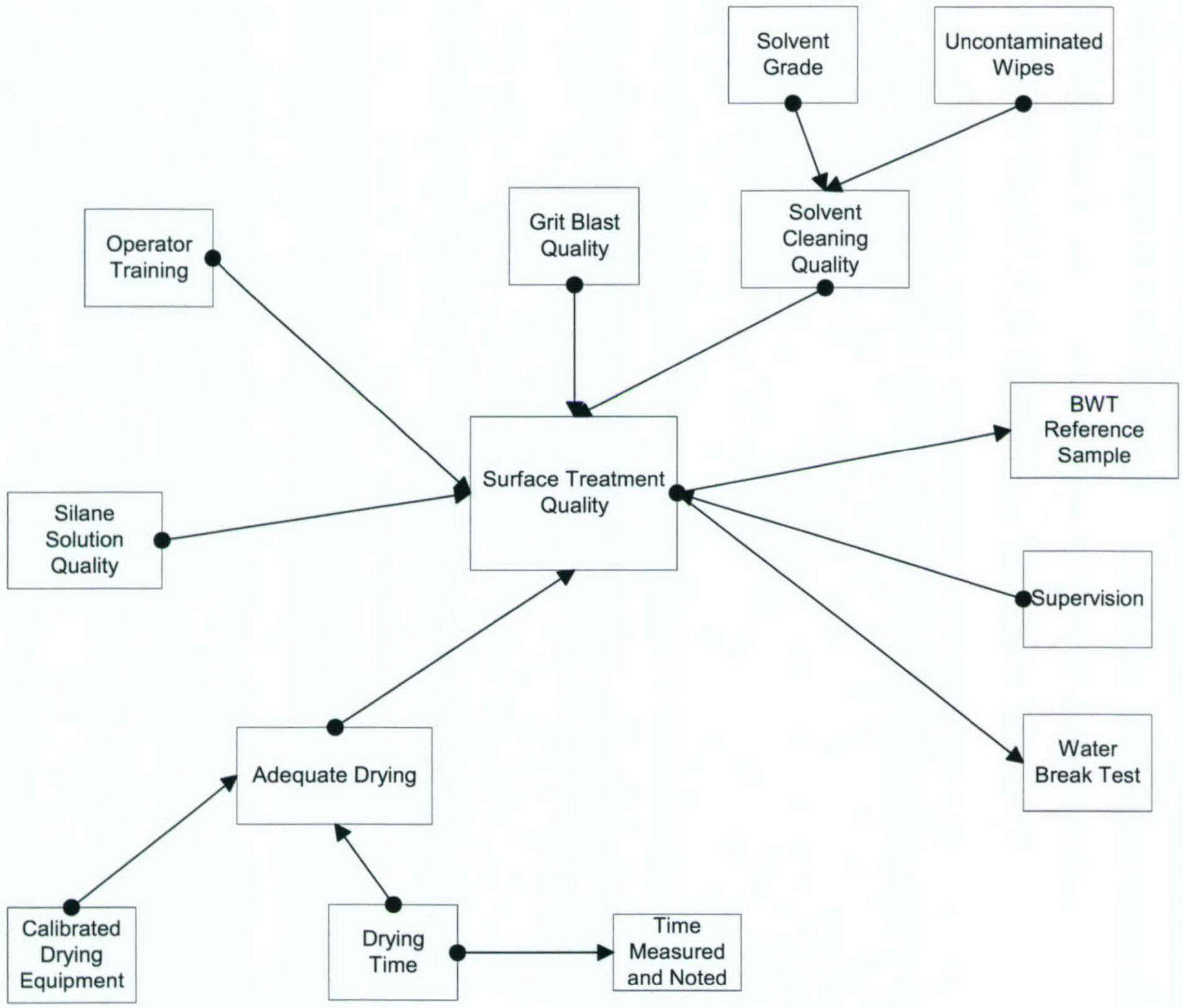

Figure D 1 List of some of the potential risk and mitigating factors affecting the DSTO grit-blast and epoxy silane surface treatment.

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Andrew Rider and Roger Vodicka

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DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION DOCUMENT CONTROL DATA	1. PRIVACY MARKING/CAVEAT (OF DOCUMENT)

2. TITLE	3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION)
Proposed Framework for a Risk-Based Approach for the Environmental Certification of Adhesively Bonded Repairs	Document (U) Title (U) Abstract (U)
4. AUTHOR(S)	5. CORPORATE AUTHOR
Andrew Rider and Roger Vodicka	Platforms Sciences Laboratory 506 Lorimer St Fishermans Bend Victoria 3207 Australia

6a. DSTO NUMBER	6b. AR NUMBER	6c. TYPE OF REPORT	7. DOCUMENT DATE
DSTO-RR-0282	AR-013-224	Research Report	October 2004

8. FILE NUMBER	9. TASK NUMBER	10. TASK SPONSOR	11. NO. OF PAGES	12. NO. OF REFERENCES
2004/1039715	AIR 03/120	DGTA	48	14

13. URL on the World Wide Web	14. RELEASE AUTHORITY
http://www.dsto.defence.gov.au/corporate/reports/DSTO-RR-0282.pdf	Chief, Air Vehicles Division

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16. DELIBERATE ANNOUNCEMENT

No Limitations

17. CITATION IN OTHER DOCUMENTS Yes

18. DEFTEST DESCRIPTORS

Bonded repairs, risk, reliability, quality management

19. ABSTRACT

Bonded composite repairs have been successfully applied to damaged aircraft structure since the early 70s. One of the major restrictions preventing widespread usage of the technology on primary aircraft structure is the lack of any defined statistical processes to guarantee the environmental durability of the bonded repair for periods that may approach the service life of the aircraft. This paper describes a proposed framework for a risk-based approach to certify the environmental durability of bonded repairs. The proposed approach is based on both laboratory-based performance data of a variety of surface treatments and the durability of repairs that have been in service for a period of time. The approach provides flexibility in repair application choices that are tailored to the criticality of the repair task. The expected outcome is to gain a quantitative understanding of environmental durability issues which will provide a sound basis for making engineering decisions.

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TECHNICAL REPORT DSTO-RR-0282 AR-013-224 OCTOBER 2004

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