ADHESIVE BONDED REPAIR TECHNOLOGY: SUPPORTING AGING AIRCRAFT

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The applicability of adhesive bonded repairs to fatigue cracking, stress corrosion cracking, corrosion damage and fatigue enhancement repairs suggests that this technology is ideally suited to the support of aging aircraft. Experiments and service history have demonstrated that adhesive bonded repair technology is a far superior method for repair of aging aircraft than the more conventional mechanically fastened repairs. Adhesive bonded repairs are lighter, usually faster to install and considerably more fatigue resistant than the more conventional mechanically fastened repairs. However, even with these significant advantages, the number of adhesive bonded repairs being performed on aircraft is limited to a few applications that are usually difficult to repair using mechanical fastening. This paper will discuss the basis of the technology as contained in the ADF engineering standard on composite and adhesive bonded repairs DEF AUST 9005, which is soon to replace RAAF STD ENG C5033. It will also outline the reasons for the reluctance of industry and defence organisations to embrace this technology. The paper will suggest methods to promote a more widespread application of adhesive bonded repairs.

1. INTRODUCTION

The use of adhesive bonded patches to repair metallic structures is a technology that was pioneered by DSTO in the mid 1970s. Numerous repairs have been performed using bonded metallic and composite patches to repair fatigue and stress corrosion cracks and corrosion damage, and to reinforce structures in areas of high stresses. The advantages of adhesive bonded repairs [1] include superior fatigue performance, elimination of stress concentrations at fasteners, reduced repair weight, better NDT and improved corrosion resistance. In most cases, adhesive bonded repairs can be performed significantly faster than mechanically fastened repairs because access is only required to one side of the component, thus eliminating the need to access both faces to install fasteners. These advantages have resulted in considerable savings in aircraft maintenance costs. One composite repair scheme applied to C-130 aircraft enabled RAAF to be the only operator in the world to achieve LOT for the C130-E aircraft without changing the wing skins, with an estimated saving of $130 million.

This paper will outline the basic elements of repair design and processing for implementation of successful bonded repairs. The principles of this system form the basis for the revision of RAAF STD ENG C5033 which is soon to be released as DEF AUST 9005. The associated design handbook AAP 7021.016-1 will also be released soon.

The paper will also discuss why so few adhesive bonded repairs are being implemented, and will outline an approach to encourage more wide-spread use of bonded repairs.

2. SCOPE OF THE TECHNOLOGY

Adhesive bonded repairs have been applied to fatigue cracking [2], stress corrosion cracking [3], corrosion damage and fatigue enhancement repairs [4]. Therefore, this technology is ideally suited to the support of aging aircraft.

In particular, the effectiveness of adhesive bonded repairs in arresting or significantly slowing the propagation of fatigue and stress corrosion cracks is directly attributable to the characteristics of the

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adhesive bond. In mechanical repairs as well as bonded repairs, the repair patch acts to share the load with the substrate, thus reducing the local stress at the defect. However, with bonded repairs there is an additional effect that significantly enhances the performance of the repair. As the crack opens under load, the adhesive adjacent to the defect transfers load away from the crack into the patch. Importantly, for larger cracks, the crack opening displacement is limited by the adhesive bond such that it never exceeds the opening displacement that would occur in a bonded butt joint. There is an upper bound on crack opening displacement and hence there is an upper limit on stress intensity of cracks repaired using adhesive bonding. The stress intensity of a repaired crack approaches and never exceeds an asymptotic limit. This is a significant factor in the applicability of the repair technology to multi-site damage because even if multiple damage sites did coalesce, they stress intensity would still not increase above the asymptotic limit.

3. LIMITATIONS ON APPLICABILITY OF BONDED REPAIRS

While adhesive bonded repairs are a very effective means of managing structural issues, there are some circumstances where the use of adhesive bonded repairs would be inappropriate. The load bearing capabilities of adhesive bonds depends directly on the properties of the adhesive, and these properties vary significantly with temperature. At high temperatures, the adhesive properties degrade significantly once the temperature exceeds the Glass Transition Temperature[1]. Therefore, c care is required to ensure that adhesives selected for repairs are capable of maintaining strength at the highest service temperature.

Another inappropriate application of adhesive bonding technology is in the repair of adhesive bonds that have degraded in service. For many years aircraft SRMs have directed the use of injection repairs, where a liquid adhesive is injected into disbonds, ostensibly to re-bond the defect. As will be discussed later, adhesive bonding requires that the surfaces being bonded are clean and chemically active. The surfaces of disbonded adherends are not chemically active and some form of surface preparation must be undertaken to re-activate the surface so that the adhesive can form an effective chemical bond at the interface. Therefore, there is absolutely no possibility that an injection repair can restore *any* strength to a disbond [5]. All that is achieved by injection repairs is that the adhesive fills the air gap (without bonding to the adherends) such that the NDT inspection can not find the air gap. The only method for repair of disbonds is to remove the adherends, prepare the local area using effective surface preparation methods and then apply a patch to the region to restore strength. In cases where multiple repairs have been applied to any bonded component, there is a high probability that the entire bond is degraded and hence a more effective method for management of the structural integrity of the component would to completely rebuild the part [6].

4. PERCEPTIONS OF ADHESIVE BONDING

Structural adhesive bonding has been in common usage for construction and repair of aircraft sandwich structures for in excess of sixty years. During that period, adhesive bonding has had a chequered history, driven principally by a lack of understanding of the basic science behind the technology. The most frequent application of adhesive bonding has been in the fabrication of light, stiff sandwich structure for control surfaces and fuselage panels, typified by the method of construction of F-111. Such structures were susceptible to impact damage and disbonding, with repair being effected using adhesive bonding. The service history of such repairs was usually inadequate and often necessitated extensive re-work following water ingress through the defective repair, leading to further disbonding and corrosion. The paucity of repair technology was quantified [7] by a survey in 1992 that found that 42% of adhesive bonded repairs performed at the depot level facility at Amberley were associated with previous adhesive bonded repairs.

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[1] The Glass Transition Temperature is that temperature at which the adhesive changes from a relatively hard, glassy material to a rubbery, compliant material.

The poor history of these repairs has led to a mistrust of adhesive bonding in what one author terms "Grandma's Cup Syndrome": *I glued it and it didn't stick, so adhesive bonding is not to be trusted.* In practice, when correctly designed and (more importantly) properly implemented, adhesive bonded repairs do provide exceptional service performance. The evidence for this is that following the survey previously discussed, the processes[2] used for adhesive bonded repairs were improved, training was upgraded and the adhesive was (coincidentally) changed to a more modern system.

While the new generation adhesive may provide some level of improved performance, in reality the most significant change was the improved surface preparation processes. The different colour of the adhesive did however provide a method for assessing if repairs were undertaken before or after the change in processes was implemented. An extensive review of the service performance of 81 adhesive bonded repairs was undertaken in 2004 [8]. That review found that of 81 repairs assessed by non-destructive methods, three repairs exhibited symptoms of disbonding. Destructive assessment of these repairs showed that two cases were "false positives" in that the repairs were found to be serviceable. The only repair that had evidence of disbonding had been subjected to impact from adjacent wing structure. The report also stated that anecdotal evidence suggested that there was 'no evidence to indicate a general lack of strength or durability' of repairs installed over the previous ten years. This data demonstrates that where adhesive bonds are performed to appropriate standards, the repeat repair rate is effectively zero.

5. DESIGN METHODOLOGY

Common practice even in contemporary aircraft design [9] is to design an adhesive bond such that for a given design ultimate load the average shear stress is below some nominal "design allowable" stress. The allowable stress is usually determined from an exhaustive test program that generates a database of a sufficient statistical level of rigour to ensure that bond failure is improbable. This usually results in a design allowable stress that is substantially below the actual strength of the adhesive. *It is only the severe conservatism in this approach that prevents bond failures from occurring in service* [10].

The average shear stress approach implies that if the overlap length of a bond is increased, either the shear stress is lower, or the joint can carry more load. The relationship between overlap and average shear stress is linear, with a doubling of overlap length resulting in half the shear stress for the same load. This can be easily demonstrated not to be true. The non-linear shear stress distribution in an adhesive bond has been known for many years since the early work by Volkersen [11] who showed that the adhesive shear stress peaks at the end of a joint and decays toward the centre of the joint. If the overlap length is sufficient, the shear stress decays to zero in the middle of the joint. Hence, any additional overlap length will simply add to the low-loaded area in the centre of the bond and will not alter the maximum shear stress in the bond which occurs at the ends of the joint. This analysis was later extended by Hart-Smith [12] to address elastic-plastic behaviour[3] that occurs as the maximum shear stress at the end of the joint exceeds the adhesive's elastic limit.

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[2] These procedures are now contained in AAP 7021.016-2.

[3] Hart-Smith's analysis of elastic-plastic behaviour is of importance since with modern adhesives, up to 80% of the bond strength derives from plastic behaviour.

Hart-Smith [12] advanced the concept for bonded joint design based on the load capacity[4] of the adhesive. The load capacity is determined (in the absence of thermal stresses) by the lesser value of:

$$P_1 = \sqrt{2\eta\tau_p\left(\frac{1}{2}\gamma_e + \gamma_p\right)E_i t_i\left(1+\frac{E_i t_i}{E_o t_o}\right)} \text{ and } P_2 = \sqrt{2\eta\tau_p\left(\frac{1}{2}\gamma_e + \gamma_p\right)E_o t_o\left(1+\frac{E_o t_o}{E_i t_i}\right)}$$

Where P is the load capacity, η is the adhesive thickness, τ_p is the adhesive shear stress at failure, γ_e is the shear strain at the elastic limit, γ_p is the plastic shear strain, *E* is the elastic modulus, *t* is the adherend thickness and the subscript i applies for the inner adherend and o for the outer adherend.

These terms describe the load that can be transmitted through each end of the joint. For adherends of different thickness or modulus, the shear strains at one end of the joint will become critical before the other end, and therefore the critical end will determine the load capacity of the bond.

This approach has been used in DEF AUST 9005 and AAP 7021.016-1 to establish a methodology for management of repair designs. Essentially, the objective is to ensure that more critical designs are managed by reference to an authority with competency in designing or testing to establish a higher level of design rigour. To achieve this, the repair is classified by comparing the adhesive load capacity against design loads. For example, where the adhesive load capacity is more than 20% greater than design ultimate load, the repair is classified as Condition 1. The requirements are detailed in Table 1. Clearly, as the joint Condition changes, the risk associated with the design also changes. Hence, the certification requirements increase as the risk of failure increases (see Table 2).

Design Condition	**Requirement**
1	**P ≥ 1.2DUL**
2	**1.2DUL ≥ P ≥ DUL**
3	**DUL ≥ P ≥ DLL**
4	**DUL ≥ P**

Table 1. Requirements for classification of adhesive bonded repairs.

[4] The load capacity refers to the strength that the adhesive could achieve *in the absence of failure of the adherend.* For cases where the adhesive is weaker than the adherends, this will be the bond strength. For cases where the adhesive is stronger than the adherends failure of the adherends will occur before failure of the adhesive. The load capacity of such joints is the (theoretical) strength that the adhesive could have achieved if the adherends were infinitely strong.

Condition	Outcome	Adhesive Certification	Notes:
Condition 1: Adhesive is stronger than 1.2 times design ultimate load.	Adhesive will not fail by shear for any load case.	By analysis and/or testing demonstrate that the load capacity is greater than 1.2 times design ultimate load.	Testing may be required.
Condition 2: Adhesive is stronger than that required to support DUL but less than Condition 1.	Adhesive should not fail by shear for any load case, but the adhesive will be the critical element in the repair.	By analysis and testing demonstrate that the load capacity is greater than DUL.	Testing or independent verification by a second analytical method may be required.
Condition 3: Adhesive is stronger than that required to support DLL but less than Condition 2.	Adhesive can not sustain DUL.	The structure shall be capable of supporting DUL in the absence of the repair.	Permissible as fatigue enhancement repairs only.
Condition 4: Adhesive can not support DLL.	The adhesive will be weaker than the structure.	The structure shall be operated under flight restrictions that ensure the structural loads do not exceed the load capacity of the adhesive.	These repairs are only permissible as one-time ferry flight repairs.

Table 2 Certification requirements for possible Conditions for bonded repairs based on a comparison of bond load capacity with design load cases.

Condition 1 joints and repairs will have the capacity to sustain the design loads without failure, so the use of approximate analyses carries an acceptable level of risk. Condition 2 joints and repairs should also be capable of sustaining the design loads, but the reduced margin between DUL and the adhesive load capacity requires that additional design rigour is appropriate. Condition 3 joints would not normally be certifiable because failure of the bond could occur below DUL. However such repairs may be incorporated as fatigue enhancement repairs, provided that the original structure meets certification. Condition 4 repairs would only be appropriate for emergency repairs, provided that flight restrictions are applied to reduce the nominal “DUL” below the load capacity of the adhesive bond.

Further analysis of the adhesive bond in joints and repairs is required to ensure that cohesion failure is managed by appropriate design of the stresses in the adhesive bond, taking into consideration shear and peel stresses. For repairs, the shear strains at the edge of the patch and at the defect being repaired must be checked, while the critical peel stresses always occur at the edge of the patch. The design procedures contained in AAP 7021.016-1 detail analysis of shear and peel in a bonded repair.

5.1. Design data

The design data for the load capacity calculation is derived from the thick adherend test ASTM D3983. Note that only a limited number of manufacturers provide that data in their data sheets[5]. The thick adherend test is expensive and therefore the available data set for any adhesive is usually from a small number of specimens. The variability of adhesive properties is also more significant than for

[5] It must be recognised that adhesive manufacturer’s data sheets simply demonstrate classification of that adhesive against nominal values established by some reference standard such as MMM-132-A. Such standards stipulate criteria for classifying the adhesive and the test methods to be used. Typical tests are lap-shear ASTM D1002, T-Peel ASTM D1876 and climbing drum peel ASTM D1781. *The data generated by these tests is NOT design data that can be used for analysis of bonded joints and repairs*.

other structural materials. Therefore, to mitigate the risk associated with the accuracy of design data, DEF AUST 9005 requires the application of an *Adhesive Variation Factor* (AVF). The value selected for the AVF depends on the cure conditions used to generate the design data and the cure conditions for the repair. If the data set was generated using the same processes as would be used for the repair (e.g. vacuum bagging) then the AVF = 0.8. If however the adhesive data was generated using an autoclave cure and the repair is to be applied using vacuum bagging, then the AVF is reduced to 0.75 to allow for the increased variation in properties that result from the different processes.

6. PROCESSES

Adhesive bonding relies on chemical reactions that form molecular bonds (ionic, covalent, attractive and even metallic) at the interface between the adhesive and the substrate. The formation of these bonds provides one of the two essential elements for development of the strength of the adhesive bond. The other element is the strength of the adhesive itself. These elements drive the two available mechanisms for bond failure, with fracture of the adhesive (cohesion) limited by the adhesive strength and interfacial failure (adhesion) controlled by the resistance to degradation of the chemical bonds at the interface. Cohesion failure is addressed in the *Design Methodology* section of this paper. The most common cause of adhesion failure is hydration of oxides on the surface of the adherend and this is directly dependent on the surface preparation undertaken at the time the bond was formed.

Surface preparation is the most critical process in adhesive bonding. Contrary to common beliefs, it is not just *cleaning* of the surface. To enable the chemical reactions to occur at the interface between the adhesive and the adherends, the surface must not only be clean, it must also be chemically active. Chemical activity is promoted by either chemical methods such as etching, or by mechanical abrasion. Note that hand abrasion is considerably inferior to grit blast abrasion [13] and therefore the use of hand abrasion is not supported by DEF AUST 9005. Note also that chemical treatments that passivate the surface (such as the Alodine process) are not compatible with adhesive bonding.

While cleaning and chemically activating the surface enables the formation of chemical bonds at the interface, even this is not sufficient to ensure that the bond is durable. A surface that has been cleaned and chemically activated can produce bonds that have excellent short term bond strength. However, in many cases the strength of such bonds can degrade with time as the interfacial bonds hydrate. Therefore to produce a bond with acceptable durability, the chemical bonds formed at the time of bonding must also be resistant to hydration in service. For metals, some form of chemical treatment is essential. The most effective method uses phosphoric acid anodising, but test results and service experience show that surfaces treated using organo-functional coupling agents provide excellent bond durability. Such processes are the grit-blast and silane process in AAP 7021.016-2 and the sol-gel process developed by the Boeing Company.

The reason that many of the older adhesive bonded repairs failed is that they were applied using only a hand abrade and solvent degrease process only, or used the etchant Pasajel 105 or Pasajel 107 and those processes could not provide resistance to hydration.

7. CERTIFICATION

A further reason for the perception of deficient performance of adhesive bonded structures lies in the methods for structural certification [14]. All current certification bases require demonstration of static strength and fatigue resistance. This is usually undertaken on a "building block" approach (see [9] for example). Firstly, a large number of coupon specimens are tested to establish design allowables. This is followed by testing of a significant number of "element" specimens to encompass the various types and thicknesses of materials being joined and the overlap lengths. The next phase is to test a number of "detail" specimens that replicate specific parts of the structure that may have any unusual structural features. These tests are followed by sub-component tests where substantial parts of the component are replicated and finally a limited number of components are tested under design loads to certify the structure.

The problem is that interfacial degradation by hydration is time dependent. If a structure fabricated by adhesive bonding is tested before the interface has had time to hydrate, then the bond strength may not have degraded to a level where failure occurs. Similarly, if a bonded structure is subjected to accelerated fatigue testing, the outcome will depend upon the time since fabrication and the susceptibility of the interface to hydration. *Therefore there is a real probability that deficient bonded structures may pass all certification tests.* The consequence is that such certified structures may fail in service at loads well below DUL once the interface has hydrated.

Certification of adhesive bonded structures and repairs must give due cognisance to the risks to structural integrity that are unique to adhesive bonding. These risks include:

- The adhesive bond is the only fastener attaching the adherends. There is no redundancy.
- The material forming the structural joint is manufactured during the process, so there is no opportunity to verify the strength of the actual material before it is used. All companion coupon tests only verify strength by inference, not by an actual measure of the material in the joint.
- Available NDT methods do not provide assurance of bond integrity at the time of formation of the bond. NDT can detect bond defects such as voids and disbonds, both after production and in service, but can not provide assurance that the interface will continue to provide adequate durability.
- NDT can only indicate the presence of a defective bond *after* the bond has started to fail.

The current ADF approach to certification of bonded repairs embodied in DEF AUST 9005 is that no credit is given for bonded repairs to primary structure. In effect, this means that the structure must be capable of surviving DUL in the absence of the repair. The certification basis assumes that the bond *will* fail. DSTO and other organisations are currently collecting data on appropriately installed adhesive bonds to demonstrate that where bonds are performed using processes that comply with DEF AUST 9005 then such bonds demonstrate a substantial service life. The objective is to establish a set of certification requirements such that credit may be given for the contribution of the bond to structural integrity.

8. HOW TO ASSURE BOND INTEGRITY

Despite the risks to certification of bond integrity listed in the section on *Certification*, it is possible to establish a methodology whereby a sufficient level of confidence can be placed in bond integrity. The elements of such a methodology are:

- Demonstrate that the processes used in fabricating the bond provide an acceptable level of bond durability.
- Demonstrate that the design procedure ensures that the adhesive will never be the critical element in the structure or repair.
- Demonstrate that the procedures for handling, storage and use of critical materials eliminate risks associated with contamination of the products and/or bonding surfaces.
- Demonstrate that the processes are being performed in exact compliance with process specifications that replicate the processes that have been demonstrated to produce durable adhesive bonds.
- Demonstrate that the personnel performing the bonding processes have an adequate level of competency in performance of those processes.

- Provide evidence that the adhesive has been exposed to the required cure conditions.
- Demonstrate by NDT that after manufacture the bond is free of significant defects.

These elements form the basis for the design, process validation, materials management, quality management and requalification of technicians contained in DEF AUST 9005.

8.1. Demonstration of Bond Durability

The first requirement for provision of assurance of bond integrity is to demonstrate that the processes used to fabricate the adhesive bond can produce an adequate level of bond durability. Any certification basis for bonded structures and repairs that does not address this requirement will be deficient.

As already stated, static strength and fatigue tests can not provide an adequate level of assurance of resistance to hydration. Therefore tests such as lap-shear ASTM D1002, T-Peel ASTM D1876 and climbing drum peel ASTM D1781 are of limited value in assessing bond durability. The most discriminating test for bond durability is the wedge test ASTM D3762 [15]. In this test, a standard wedge is driven into one end of a bonded strip, cracking the adhesive. The crack propagation is measured with time while the specimen is exposed to a hostile environment, usually 50-60°C and 95% RH. This test is particularly aggressive because the bond is placed in tension and is stressed to its ultimate strength at the crack tip. Hence, any deficiency in the interface will result in propagation of the crack. Further, if the interface is deficient, the failure will propagate along the interface in a manner that will be visible after the adherends are separated.

For the wedge test to be of use in validating the reliability of bonding processes there must be guidelines as to what constitutes an acceptable wedge test result. This requires some level of correlation between the wedge test performance and service history. The recommended acceptance criteria broadly follow the recommendations of TTCP Action Group 13 [15] and are stated in DEF AUST 9005 as:

- Initial crack lengths are to be measured one hour after insertion of the wedge while exposed in a laboratory environment. The crack length measured must not to exceed 1.2 times the crack length obtained from aluminium specimens prepared using the same adhesive to bond surfaces prepared using phosphoric acid anodising to BAC 5555. In all cases, the initial crack length must not exceed 50.8 mm (2 in.).
- The average crack growth rate must not exceed 5.08 mm (0.2 in.) in 24hrs exposure and also must not exceed 6.35 mm (0.25 in.) in 48 hrs exposure.
- The surface generated during exposure must not exhibit greater than 10% adhesion (interfacial) failure[6].

These criteria have been based on experience with bonded repairs within the USAF, RAF and RAAF. Anecdotal evidence from these organisations indicates that where these criteria have been met by particular bonding processes, then bonded repairs performed using those processes exhibit a very high level of bond durability. Data is currently being collected to quantify that evidence.

8.2. Adhesive Bond Design Procedures

The requirements for a successful design of an adhesive bond are that the adhesive has sufficient load capacity such that the adhesive can provide an adequate MOS above DUL. Next, sufficient bond overlap length must be provided to ensure that the adhesive can achieve that load capacity.

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[6] The USAF requirement is less than 5% interfacial failure. In fact, the US approach is slightly different. A specimen must meet the first two requirements initial crack length and crack growth rate) before it is assessed as an acceptable test. The specimen is then assessed against the third criterion, which is the sole criterion for acceptance.

Finally, an additional margin is added to the overlap length to provide resistance to creep under sustained load and/or high temperatures.

If these requirements are met, then the outcome is significant. Provided that the bond processing is adequate, then the adhesive bond should *never* fail. As a consequence, the strength of structures fabricated or repaired with such adhesive bonds is not dependent on the adhesive bond and the certification procedures applicable to conventionally fastened structures are applicable. If the adhesive can never fail, then the current practice of certification on a building block approach will be futile, because *every* specimen will fail outside the joint. The only variable measured by such tests will be the strength of the adherends. Hence, the design procedure whereby the joint is never the critical element in the joint or repair has the potential to eliminate a very substantial number of tests from certification programs.

The corollary is that if the adhesive *is* the critical element in the joint or repair, then the certification of such structures is only possible when the design is supported by extensive testing using the building block approach to certification.

8.3. Design of Repairs

Repair design addresses the integrity of the three elements in a repair; the adhesive, the structure and the patch. As previously discussed, the adhesive integrity is managed by assurance that the adhesive is never the critical element in the repair, and provision of sufficient overlap length to enable achievement of the load capacity and resistance to creep. Analysis is also used to verify that the adhesive shear strains and peel stresses are acceptable. The patch design requires merely that the stress in the patch provides an adequate MOS over the strength of the patch material.

The approach to assessment of the structural integrity of the repaired structure depends upon the nature of the defect being repaired. For cracked structure, fracture mechanics is used to verify that the stress intensity has a sufficient MOS over the fracture toughness of the material in the structure. There are several analyses [16,17,18] available for estimation of the stress intensity for the crack under the repair. For primary structure, DEF AUST 9005 requires that cracks are removed as is common practice for conventional mechanically fastened repairs[7]. DEF AUST 9005 also requires a higher level of design rigour for primary structure.

For non-cracked structure, (holes, slots etc.) analysis is based on reduction of stresses that are caused by the local stress concentrations associated with the defect. The reduced stress is compared against the strength of the structural material to assure an adequate MOS. For undamaged structure, such as for a fatigue enhancement reinforcement, the design is based on comparison of the local stress under the reinforcement against the strength of the structural material to assure an adequate MOS.

This design methodology forms the basis for AAP 7021.016-1 and is also contained in the design software BR-S which will also soon be released by ASI-DGTA.

8.4. Quality Management

In the development of a quality product, there are essentially two approaches, Quality Assurance (QA) and Quality Management (QM). In the QA approach, samples cured at the same time as the product must meet a given level in acceptance tests based on a test regime established to demonstrate by inference that the coupons have equal or better properties to those that were demonstrated for the certified structure. These tests are usually coupled with post-production NDT.

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[7] There is evidence that removal of cracks actually produces a shorter fatigue life than if the crack is not re-worked. DEF AUST 9005 dictates that the crack must be removed because of the assumption that for primary structure there is no credit given for the repair, and hence the original certification basis for the structure would prevail and that would mandate that there are no cracks in the structure, so the crack must be removed.

In practice, it does not matter what processes were used, provided that the tests meet the required acceptance levels. One deficiency with this approach is that almost all tests relate to the strength of the bond at a given time shortly after fabrication, and hence these tests do not interrogate the bond durability. Better the test regimes contain wedge tests to provide a level of assurance of durability.

The fundamental problem with the QA approach is that quality is only inferred. The integrity of the bond itself is not measured because only the coupons are tested. The quality tests will never actually change the quality of the bond itself. Bad processes could under some circumstances produce a bond with sufficient short term strength to pass testing, but which will fail in later service. Hence, bond quality could degrade significantly due to poor processing and that would not necessarily be prevented if the acceptance criteria are inadequate or the tests are insensitive to the changes. A further limitation of the QA approach is that components and repairs can not be released for use until all tests have been completed and the results tabulated.

The authors contend that the measure of a successful bonded repair is not that it passes some test or batch of tests prior to release for service. *A successful repair is measured by the fact that it never requires to be repeated again in its remaining service life*. This can only be achieved by ensuring that the required processes are rigorously validated and then implemented in a manner that follows exactly the validated processes. This is the basis of Quality Management.

The QM approach is based on the premise that, if every step of the bonding process is performed to an acceptable standard, then such bonds will be of a high quality and will always pass any QA test regime. Firstly, the bond must be designed by competent engineers using validated design rules and reliable design data. The quality of performance of the bonding process requires certification of compliance with process specifications that have been validated by demonstration of bond durability. The process must be performed by competent technicians within a controlled environment to eliminate or minimise contamination. Materials must also be strictly managed using practices that assure that the quality of the materials used for bonding is maintained and contamination is excluded. The system also requires proof that adhesive cure temperatures and heat up rates have been achieved. Successful NDT is also required to ensure that defects within the bond are not structurally significant. Provided all of these requirements are met, then the bond will demonstrate a high level of integrity. The basic features of the quality management system for adhesive bonding are shown in Figure 1.

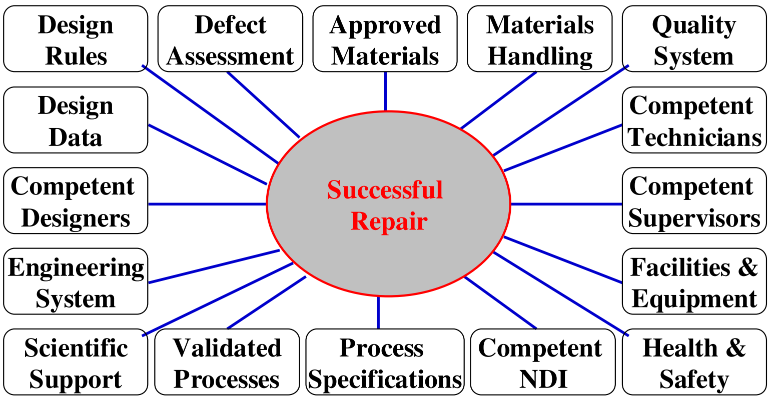

Figure 1. The elements required for quality management to enable production of successful bonded repairs.

In practice, the QM approach has the ability to manage quality into a bond such that the level of bond integrity is assured. It also has the capacity to maintain the high standards set provided that the approved specifications are followed exactly. Under these circumstances any QA tests would always be successful, so DEF AUST 9005 does not mandate QA testing where a rigorous QM system is in place. This not only saves the considerable costs associated with testing, it also makes the components available for immediate release once compliance with the approved specifications has been certified.

There are risks associated with use of QM for adhesive bonding. The entire system is reliant on the integrity of the people performing the tasks and their willingness to rigorously follow and document the approved procedures. The most significant risks arise from personnel who deviate from the approved processes or who use unapproved alternative materials and equipment. Such deviations are more probable where contractors have in the past worked under a QA system where deviations that did not impact on short term test results were considered acceptable. To mitigate the risk of such deviations, DEF AUST 9005 requires annual requalification of technicians and auditing of process performance, equipment and facilities.

9. DIFFERENCES BETWEEN DEF AUST 9005 AND RAAF STD ENG C5033

DEF AUST 9005 provides a framework for the establishment of a system for design and implementation of reliable, effective adhesive bonded repairs. It introduces a higher level of rigour into the design process than that which existed under the older RAAF STD ENG C5033, but at the same time reduces the high level of conservatism that was inherent in RAAF STD ENG C5033.

The more significant reductions in conservatism result in much smaller overlap length requirements. RAAF STD ENG C5033 required that there was sufficient overlap length to carry the unnotched material ultimate strength of the parent structure, whereas the current requirements are that the overlap length can sustain the loads prescribed for the joint Condition.

The previous concept of the Rapid Repairability Criterion[8] has been replaced by a structured approach to classification of the bond on the basis of comparison of the load capacity against the design loads, as discussed in *Repair Design*. The methodology for calculation of the tolerable defect size has also been amended to provide an increased level of creep resistance for adhesive bonds that contain bondline defects such as voids.

10. HOW TO INCREASE USAGE OF BONDED REPAIR TECHNOLOGY.

Although RAAF STD ENG C5033 has been released for almost ten years, apart from repairs to sandwich structure, the usage of adhesive bonded repair technology continues to be limited to a few applications, usually where conventionally fastened repairs are intractable. Many reasons have been advanced for the lack of use of the technology, and these mainly arise from the reluctance of designers and technicians to step outside the comfort zone afforded by existing repair technology.

A significant factor that inhibits more widespread use of bonded repairs is the requirement for engineering disposition for every repair. Such dispositions usually take an inordinate amount of time and hence the requirement to keep the aircraft in service dictates that only rapid approval procedures can be employed. Hence, the usual approach is to use existing mechanically fastened repairs in preference to bonded repairs. That decision in itself also reduces the level of competency for the repair designers because of the infrequent use of the design procedures.

The design processes for adhesive bonded repairs contained in AAP 7021.016-1 are comparatively cumbersome. This complexity is necessary to ensure that all possible failure modes are assessed to provide an effective design. However, the length of time involved in undertaking the design is a significant factor that adds to the resistance to use bonded repair technology. ASI-DGTA has addressed this by the development of a repair design tool BR-S that undertakes the design

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[8] RAAF STD ENG C5033 required that designs must demonstrate that the load capacity of the adhesive was greater than the unnotched strength of the parent material. This was known as the Rapid Repairability Criterion because it eliminated the requirement for complex design of the adhesive bond because there was absolute assurance that the bond would never fail. While the current DEF AUST 9005 approach for Condition 1 adhesive bonds also provides assurance that the bond will never fail, the current approach accepts a lower margin between the load capacity of the bond and the structural loads.

calculations, using stored data for adhesives, composites and metallic materials. This software will significantly reduce the time required to develop an approved bonded repair.

Another factor that inhibits use of bonded repair technology is the level of confidence and competency exhibited by the technicians. Because bonded repairs are not being performed on a regular basis on weapon systems that do not have sandwich structure, the technicians can not maintain an adequate level of competency in the hand skills necessary for the processes. The low rate of incorporation of bonded repairs further erodes their ability to maintain the necessary competencies.

A further issue that results in a low usage of adhesive bonded repairs is the broadly held perception that bonded repairs are only suited to repair of complex problems in primary structure. This has resulted from a number of high profile repairs such as the F-111 wing pivot fitting reinforcement and the repair of fatigue cracks on Mirage and F-111 wing skins. The application of these repairs to primary structure dictated that very high level designs were supported by extensive validation testing. This led to the perception that all bonded repairs require such a significant level of input that the costs of such programs could only be justified for critical repairs. In reality, the method is far easier to apply to simple repairs to less critical structure because of the reduced certification requirements for such structure. Application of the design tool BR-S to such repairs enables bonded repairs to be designed and certified in timeframes that are competitive with times required for mechanically fastened repairs.

Any proposal to increase the usage of bonded repairs must address the design approval delay, the number of repairs being designed and the lack of currency for the technicians. These requirements could be addressed by a program to introduce pre-approved typical designs in the aircraft SRMs for typical repairs. In effect, where a mechanically fastened repair exists in the SRM, there should be a pre-approved alternative repair inserted as a pink page supplement. The availability of the design tool BR-S will greatly facilitate that process. This approach would increase the usage of the design procedures and eliminate the approval delays while addressing the frequency of repair implementation by enabling the technician to make the decision on which repair method to use.

A further measure that would increase the usage of bonded repairs would be to give credit for bonded repairs on primary structure. DSTO is currently tasked to develop the justification for allowing credit for the repair on the basis of service performance of adhesive bonds.

11. CONCLUSIONS

Successful application of adhesive bonding for construction and repair requires design procedures such that the strength of the adhesive bond is never the limiting factor in joint strength, together with stringent implementation of processes that have been rigorously validated against specific acceptance criteria using the wedge test ASTM D3762. Tests must demonstrate that processes produce a clean, chemically active surface that is capable of resisting hydration in later service. Quality of the adhesive bond must be managed throughout the production process to ensure the integrity of the bond. The QM approach requires evidence that processes have been performed using materials of an assured acceptable quality and that processes have been performed in strict accordance with validated process specifications by technicians who have been regularly assessed as competent. Equipment and facilities must also be assessed to assure that they meet minimum requirements. The ADF has achieved all of these requirements with the impending release of DEF AUST 9005, AAP 7021.016-1 and the existing document AAP 7021.016-2, together with the impending release of the design software BR-S.

There are no technical reasons that inhibit the use of adhesive bonded repairs at least for non-significant repairs. The lack of use of the technology is strongly influenced by the length of time to approve bonded repairs and this may be overcome by proactive incorporation of pre-approved generic repair designs in aircraft SRMs. Organisations where adhesive bonding is currently rarely performed usually exhibit low levels of competency, and hence a lack of confidence in their ability to perform adhesive bonded repairs. This could be addressed by the increased frequency of repairs that would result from the inclusion of pre-approved generic repairs within existing SRMs.

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