

Davis, M.J., Janardhana, M. and MacKenzie, A., *A Rigorous Approach to Certification of Adhesive Bonded Repairs*, FAA Workshop on Certification of Adhesive Bonded Structures and Repairs, Seattle, WA, 16-18 June 2004.

A RIGOROUS APPROACH TO CERTIFICATION OF ADHESIVE BONDED REPAIRS

By

Maxwell J. Davis¹, Madabhushi Janardhana² and Adrian MacKenzie²

Abstract:

The advantages of adhesive bonded repairs over conventional mechanically fastened repairs are well known, and this technology has provided very significant savings in repair costs for a number of military operators. While the ability to adequately design bonded repairs for aircraft structure has existed for some considerable time, a major limitation in the more widespread use of adhesive bonded repair technology especially for civilian aircraft has been the lack of a rigorous certification basis for adhesive bonded repairs. Several fundamental impediments exist that inhibit the development of a certification basis. A primary difficulty is that there is no NDT method that can provide assurance of bond integrity. All existing NDT methods only provide assurance of an absence of a defect, they do not foretell of the potential development of defects that may prior to the next inspection develop into critical defects in the bond. Another critical deficiency is that there is no current method for prediction of the life of an adhesive bond. The fact that the integrity of an adhesive bond is strongly dependent on processes simply adds to the difficulties in development of a valid certification basis for bonded repairs.

Existing approaches to certification of bonded repairs require that the damaged structure can sustain 1.2 times Limit Load *in the absence of the repair*. That approach is based on the premise that the adhesive bond *will* fail, and hence the structure must have sufficient residual strength to allow for such an eventuality. This paper will show that such an approach may in some cases result in unconservative designs that violate the certification basis of the original structure. Further, it will be demonstrated that the basic premise for this approach is an unwarranted impediment to repair certification.

The certification basis proposed here applies the approach developed in previous works in a manner that provides a conservative method for providing due credit for the repair, whilst also incorporating process validation as a certification item. This paper asserts that where processes have been effectively and correctly validated, and where an effective quality management structure is in place, then due allowance should be made for the contribution of the repair to structural integrity and reduction in crack growth rate. This assertion is backed by evidence from RAAF service experience where adhesive bond failures in repairs have been eliminated where the bonding was performed in compliance with validated processes. That achievement has not only provided RAAF with millions of dollars savings in maintenance costs, it has provided the platform for development of a rigorous certification basis for bonded repairs.

¹ Corresponding Author; Maxwell.Davis@defence.gov.au, ASI4D-DGTA, Bldg. 410 RAAF Amberley 4306 Australia.

² Directorate General Technical Airworthiness, Royal Australian Air Force

1 INTRODUCTION

Adhesive bonded repairs have been used to restore strength of aircraft structures for some considerable time. For honeycomb sandwich panel structure, adhesive bonding has been the primary method for repair. In the mid-1970's, the Royal Australian Air Force (RAAF) began use of adhesive bonded composite patches for repair of cracked metallic structure. That technology was based on research undertaken by the Defence Science and Technology Organisation. Repairs were implemented on a number of aircraft types including C-130, Mirage III-O, P3 Orion and F-111 [1, 2, 3]. There have since been numerous other applications of the repair method [4, 5, 6], [7]. These repairs demonstrated that the repair method was far superior to the conventional mechanically fastened repairs that were commonly used for repair of metallic structure. This specific repair technique enabled the RAAF to be the only operator of C-130E to attain life-of-type without changing the wing skins due to stress corrosion cracking, resulting in significant savings in maintenance costs.

The RAAF has advanced the repair method to the stage where repairs have been performed to cracked primary structure [8]. However, a major concern is that there is no clearly defined certification basis for the repair methodology. This paper proposes such a certification basis.

2 CERTIFICATION OF STRUCTURES AND REPAIRS

Structures are certified by demonstration of compliance with some certification standard, such as DEF STAN 00 970, FARs, JARs or MIL HDBK 1530. While these standards regulate a vast array of issues that must be addressed, such as electrical bonding, flutter performance, aerodynamic response etc., the main certification issues addressed are static strength, damage tolerance and structural durability. All standards require that an aircraft can withstand Design Limit Load (DLL), the maximum load expected to be experienced by an aircraft once in its operational life, without permanent deformation of the structure. A further requirement is that the aircraft must be capable of sustaining Design Ultimate Load (DUL), which is DLL multiplied by a reserve factor usually 1.5, without catastrophic failure. Damage tolerance is demonstrated by showing that the structure with a known defect can sustain the required loads for a reasonable period without that defect growing to a critical size that would lead to loss of the aircraft. Durability is usually demonstrated by showing that the structure can sustain the expected variable service loads for a period that exceeds the expected service life of the aircraft.

The requirements for repairs are the same as for original construction. To achieve certification, any repair must restore the certification basis for the original structure. The repair must restore static strength to DUL, must not result in permanent deformation of the structure at DLL, must not degrade damage tolerance and must provide adequate durability.

2.1 Certification of Adhesive Bonds

Adhesive bonds must also demonstrate the same performance for certification as required for conventional mechanically fastened structures. Because of the process dependence of adhesive bonds certification is usually based on a multi-step approach using coupons, sub-structural elements and then full-scale tests to demonstrate compliance with the certification basis.

However, there are characteristics specific to adhesive bonds that differ from the requirements of conventional mechanically fastened structures:

- The material from which the structure is fabricated is actually formed as part of the production process and hence the design properties can not be measured prior to fabrication, as would be the case for more conventional construction materials and methods. Hence, the properties of the bond depend directly on processing variables.

- Unlike mechanically fastened jointing methods, adhesive bonds are a single fastener system, so there is no redundancy in the event of bond failure.
- There is no method either NDT or process quality control test based that can provide absolute assurance of bond integrity. Every existing test simply provides assurance of a *necessary* condition for bond integrity. No test or combination of tests interrogates a *sufficient* condition to provide absolute assurance of bond integrity.
- Adhesive bond failures can occur in the absence of structural loads by failure of the interface between the adhesive and the structure. Therefore successful strength and fatigue testing may not necessarily demonstrate bond durability because they do not interrogate the environmental resistance of the interface.
- There is no method available that enables prediction of the performance of the interface over time. Hence, there is no method for managing damage tolerance of adhesive bonds that is comparable to the application of fracture mechanics for metallic structures. Note that while many researchers have applied fracture mechanics to prediction of bond failure due to loads and fatigue, none of the available methods can predict degradation of the interface.
- There is no NDT method or combination of methods that can provide assurance of bond integrity because currently no method can interrogate the bond interface.
- NDT of adhesive bonds is only capable of detecting bond failure after the event. There is no method for detecting potential bond failure prior to its occurrence. While the early detection of disbonding may suggest that a damage tolerance approach could be possible, there is no method for predicting disbond growth rates for interfacial bond failures, and without that capability, a damage tolerance approach can not be validated.

From these points it may be concluded that current certification methodologies for conventional structures and repairs are inadequate for adhesive bonded structures and repairs, as may be easily demonstrated by reference to the number of adhesive bond failures that have been experienced in service [9, 10]. The most common form of bond degradation is that caused by hydration of the interface, which is directly controlled by the surface preparation methods used prior to formation of the adhesive bond [11]. This form of failure is time dependent, not load dependent. Unless certification methodologies address this issue, they will fail to address the most common cause of adhesive bond failures [12]. However, if the integrity of the interface can be assured, then existing regulations would be adequate for certification of the structure [13].

2.2 Current Certification Approach for Bonded Repairs

Because of the perceived unreliability of adhesive bonding as demonstrated by past service history of adhesive bonded repairs, current certification methods [13] are based on the assumption that the bond has failed, and that the structure must therefore be capable of safe flight without the repair. Current USAF procedures for certification of bonded repairs require that the structure must be able to sustain 1.2 DLL in the absence of the repair. In a similar manner, a damage tolerance assessment of a bonded repair to a metallic structure is based on determination of inspection intervals based on the assumption that the repair adhesive bond is ineffective.

While this approach appears to provide a measure of safety for structures repaired with adhesive bonding, it in fact violates the certification basis for aircraft repairs, where if the structure is repaired, then static strength after repair should restore the capability to sustain DUL. Logically, if there is an inherent assumption that the repair will fail, then for the aircraft to be safely returned to service after repair the structure should be able to sustain DUL in the absence of the repair. That is the requirement for a repair so that it can return the aircraft to a state that complies with the original certification basis. There is an implication that if the repaired structure is only required to sustain

1.2 DLL without failure then the typical factor of safety of 1.5 is compromised. There may also be a possibility that while the structure may sustain 1.2 DLL, the reduction in structural integrity may lead to a situation where yielding may also occur at a lower load, and hence the structure may suffer permanent deformation at a load below DLL.

There are only two effective methods to maintain the certification basis of a structure if it is to be repaired using adhesive bonding; either the structure must sustain DUL in the absence of the repair, or the assessment of structural integrity must give credit for the repair. Given the low margins of safety on most aircraft structures at DUL, the requirement to meet DUL in the absence of the repair will preclude the use of that repair method for many cases where a bonded repair would otherwise be the most suitable alternative. Therefore, the methodology proposed here is based on developing guidelines such that credit may be given for the repair during assessment of the certification of the repaired structure.

3 THE PROPOSED RAAF REPAIR CERTIFICATION APPROACH

Any certification basis must identify all possible failure modes, and then require demonstration that those failure modes will not occur. For a bonded repair to a structure, design and management procedures are required to prevent the following possible failure modes:

- The adhesive bond may fail either by static overload, fatigue *or environmental degradation of the interface*.
- The repaired structure may fail either by static overload or by fatigue either at the end of the repair or at the repaired defect.
- The repair patch may fail either by static overload or by fatigue.

Strength and fatigue performance can be managed by adequate design rules such as those prescribed in the current FARs. However, resistance to environmental degradation is not a design factor because any bond with an interface that is susceptible to degradation will eventually have zero bond strength.

The proposed approach certification of adhesive bonded repairs firstly recognises that the processes used to perform an adhesive bond must be considered as part of the certification process. Thus, there is a requirement to demonstrate that the specific processes used to form the bond are capable of producing strong, *durable* bonds. Further, there must be a quality management system in place to ensure that those processes are implemented exactly in the manner that was used to initially demonstrate durability. The RAAF experience with adhesive bonded repairs demonstrates that where processes have been validated correctly, and where a quality management system is effective, then disbonding does not occur, and hence it is appropriate to allow credit for the repair in the assessment of structural integrity.

All other assessments of structural integrity of the patch and structure that are required by a current certification program are valid *only* when the adhesive bonding processes are correctly validated and implemented. Once the issue of bond durability has been addressed, design rules can be implemented to assure the integrity of the bond. The certification approach for the structure and patch broadly follow conventional certification methods for other structures.

4 RAAF EXPERIENCE WITH BONDED REPAIRS

In 1992 a survey was undertaken [14] of major adhesive bonded repairs performed at a major RAAF repair facility. Most repairs were bonds to metallic sandwich structure. That survey showed that 42% of all major adhesive bonded repairs were performed to address defects that resulted from failure of a previous bonded repair. At the time the survey was undertaken, the RAAF was in the process of making significant changes to repair procedures and materials. An improved surface preparation process was introduced after extensive testing to validate durability. The type of

structural film adhesive used for repair. Training content was also upgraded to provide a more acceptable level of competency, and quality management principles were implemented by provision of process specifications that had been rigorously validated. The improvement in performance of adhesive bonds made using the improved processes and materials could be monitored because of differences in color of the new and old adhesive systems.

As a consequence of those changes, not one single repair has disbanded where the repair has been applied in strict accordance with the written procedures. (There were two cases, one major and one minor where repairs exhibited disbonding, but in both cases there was clear evidence that appropriate procedures had not been followed.) At an approximate repair rate of thirty repairs per month, this represents a database of over three thousand repairs where the evidence shows that, provided correct procedures were followed, disbonding did not occur.

To establish a more rigorous database on service performance of adhesive bonded repairs, data has been collected from repairs undertaken over the period 1997-1999 to determine which repairs were performed using validated processes. A physical examination of those specific repairs was undertaken to evaluate the service performance of those repairs. Xxxx repairs were inspected for evidence of disbonding. XXXXXXXXXXXXXXXXXXXX *Insert actual results of data survey.*

Hence, there is substantial *evidence* to suggest that where processes have been demonstrated to produce durable bonds and where there is a quality management system in place to provide assurance of compliance with validated processes, then it should be possible to give credit for the repair in the certification of bonded repairs.

5 SUGGESTED AMENDMENTS TO THE FARs

If as demonstrated durable adhesive bonds can be achieved under repair conditions, then durability should easily be achievable under production environments, and there are many examples of durable structures in service. However, there are also numerous examples of bonded structures that exhibit deficient service performance [9] (see Figure 1). Because these structures were all certified against some standard, then the fact that some structures are deficient while others are adequate suggests that the current regulatory framework does not prevent inadvertent certification of deficient structures.

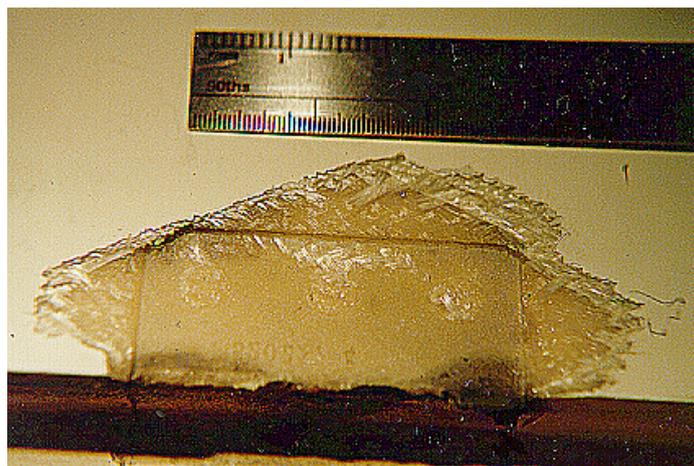


Figure 1. Disbonded elevator trim tab hinge from a commuter aircraft exhibiting interfacial failure. Note the part serial number cast into the adhesive.

The current Federal Aviation Regulations (FARs) do not adequately address adhesive bonded structures [12] because they principally require demonstration of static strength, fatigue resistance and damage tolerance. None of these requirements will prevent the gradual, time-dependent loss of strength of an adhesive bond that is formed on surfaces that are not resistant to hydration. Given that many adhesive bond failures in service are interfacial [9, 15], the current regulations do not

prevent the most common form of loss of structural integrity of bonded structures. In fact it is relatively easy to produce a bond that can demonstrate adequate bond strength and fatigue resistance if tested soon after fabrication using very basic cleaning processes. However, if that bond were tested after sufficient time to allow the interface to hydrate, then the joint would fail at a much lower load, and possibly fail without any load being applied. Hence, strength, damage tolerance and fatigue resistance alone or conjointly will not provide sufficient evidence of bond durability. The implementation of measures to ensure bond durability requires only minor amendments to the existing FARs by requiring the demonstration of bond durability as well as static strength and fatigue endurance. Some examples of possible amendments follow:

Sec. 25.605

Fabrication methods.

*[(a)] The methods of fabrication used must produce a consistently sound **and durable** structure. If a fabrication process (such as gluing, spot welding, or heat treating) requires close control to reach this objective, the process must be performed under an approved process specification **that has been demonstrated to produce a structure that is strong and durable.***

*[(b) Each new aircraft fabrication method must be substantiated by a test program **that demonstrates that the process used is capable of producing a structure that is strong and durable.**]*

Sec. 23.573 (25.573 is reserved)

(5) For any bonded joint, the failure of which would result in catastrophic loss of the airplane, **the processes for fabrication must comply with Sect. 23.605 and** the limit load capacity must be substantiated by one of the following methods

- (i) The maximum disbonds of each bonded joint consistent with the capability to withstand the loads in paragraph (a)(3) of this section must be determined by analysis, tests, or both. Disbonds of each bonded joint greater than this must be prevented by design features; or
- (ii) Proof testing must be conducted on each production article that will apply the critical limit design load to each critical bonded joint; or
- (iii) Repeatable and reliable non-destructive inspection techniques must be established that ensure the strength of each joint.

Other matching FARs would also require amendment. These relatively minor amendments to the FARs have the potential to eliminate inadequate bonding processes that are in current use, such as the process used to bond the aileron trim tab for a commuter aircraft shown in Figure 1.

6 A RECOMMENDED METHOD FOR DEMONSTRATING DURABILITY

One key aspect of the proposed approach is that the durability of the bonding process must be demonstrated prior to fabrication of the structure. This must be undertaken prior to any other certification testing of the structure. However, the method for demonstrating bond durability must be sufficiently rigorous to ensure that only reliable processes will achieve certification.

The most significant threat to bond durability is time-dependent hydration of the bond interface, so any test program must rigorously interrogate that threat. Strength tests such as ASTM D1002 are inappropriate for validation of resistance to hydration because these will only provide evidence of strength at the time of testing. Another commonly used test to demonstrate durability is the load endurance test, ASTM D 2919. In these tests, a lap-shear specimen prepared in accordance with ASTM D1002 is subjected to monotonic tensile loading at about 50% of the bond strength. Shear and peel stresses are generated in the bond. The test is conducted in a hot-wet environment with success gauged by the fact that the bond does not fail within a predetermined exposure period, usually twenty eight days. While load endurance tests are capable of eliminating processes known

to produce bonds with unacceptable levels of durability, these tests are not sufficiently discriminating to avoid acceptance of processes that have provided only mediocre durability in service.

By far the most reliable accelerated test that has shown a sufficient level of discrimination is the wedge test ASTM D3762 [13]. In the wedge test, specimens are forced apart under high peel stresses generated by the insertion of a standard size wedge into one end of the specimen. The specimens are tested under exposure conditions to high temperatures and humidity, and the rate of crack growth in the specimen is measured over a period of time. At the completion of the test, the specimen is broken apart so that the failure surface can be examined to determine the locus of failure during the exposure period.

However, experience has shown that the measure of success must be significantly more stringent than that stated in the ASTM standard for the wedge test. The Royal Australian Air Force requirements [16] state that an acceptable wedge test results requires:

- (i) A minimum of twenty specimens (four bonded panel pairs) is required to validate a surface preparation process. (Requalification of technicians may be based on five specimens (one bonded panel pair).
- (ii) Tests are to be performed at 50°C, 95% humidity, non-condensing.
- (iii) 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 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.). (For requalification of technicians, tests are based on adhesive FM 300. The maximum initial crack length is 45 mm (1.75 in.).)
- (iv) 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.
- (v) The surface generated during exposure must not exhibit greater than 10% adhesion (interfacial) failure.

The RAAF service experience reported above demonstrates that processes validated using the wedge test and the stated acceptance criteria exhibit excellent bond durability.

The USAF interprets the test in a different manner. Their acceptance criterion is that if the test falls within the above parameters (except (v)), then for a process to be considered capable of producing a durable bond then there must be no more than 5% adhesion failure within the test area.

The most significant criticism of the use of the wedge test is that it does not experience representative service loading. In reality the test interrogates the interface, not the adhesive and so the type of loading is of no consequence. Adhesives are known to be highly susceptible to peel stresses and in the wedge test the peel stresses exceed the peel strength until the crack in the adhesive arrests. The wedge test is therefore applying a stress that far exceeds any stress expected in normal service. Hence, if the interface can withstand such a high stress level with the worst type of loading known, then it should by inference withstand any other loading condition up to the strength of the adhesive (which can be measured by other tests) that could possibly be imposed by any other load related to testing or service.

A further consideration is that there is no direct correlation between wedge test results and the service life of an adhesive bond. To address this situation, the RAAF is undertaking a risk and reliability assessment for the bonding process and that will be reported elsewhere.

7 DESIGN OF BONDED JOINTS

A common approach to bonded joint design is to establish by a coupon level test program a “design allowable shear stress” and then to design the joint on the basis that the average shear stress is below that design allowable. The design is then validated by sub-element and full scale tests. Unfortunately, the use of average shear stresses for design can be unconservative, unless the test program used the specific material thicknesses and overlap lengths proposed for the actual structure.

Hart-Smith [17] provided a methodology to estimate the potential load capacity of an adhesive bond based on an elastic-plastic model of adhesive behaviour using design data derived from a thick adherend test ASTM 3983. That approach provides an estimate of the load that the adhesive bond could sustain in the absence of failure of the adherends. For adherends that have the same thermal expansion coefficient, the load capacity for a single overlap joint is given by the lower value of:

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

If the load capacity of the bond is greater than the strength of the adherends, then failure of the adhesive in shear will never occur. Hence it is possible to design an adhesive bond that is always stronger than the structure, provided the structure is not excessively thick. If the load capacity of the joint is less than the strength of the adherends, then the result of the calculation will give the strength of the joint. Hart-Smith also provided [18] a methodology to determine an overlap length such that the load capacity of the adhesive was assured. Because of the significant variation in adhesive performance with service temperature, the assessment of load capacity must be undertaken at the maximum and minimum temperatures experienced by the structure.

As an example of how the average shear stress approach can be unconservative, consider a bonded joint using FM300 adhesive to join 0.5 inch thick 7075-T6 adherends. The joint is required to transfer 12,000 lb/in. The room temperature lap-shear strength given by the adhesive manufacturer as 5415 psi. After an extensive test program including lap-shear tests at a range of temperatures and in a range of environments, load endurance tests and fatigue tests using lap-shear specimens, materials engineers typically specify a design allowable well below the lap-shear strength. For the sake of the example, assume the allowable shear stress is 2000 psi. To carry 12,000 lb/in requires an overlap length of 6 inches. Using Hart-Smith’s equations and appropriate thick adherend data from FM300 adhesive, the potential load capacity is actually 10,348 lb/in so the joint would not achieve the design load irrespective of the overlap length provided. Hence, the use of a design allowable even where it is well below the lap-shear strength may be unconservative.

8 THE RAAF DESIGN METHODOLOGY

Firstly, the RAAF methodology assumes that only properly validated processes are used, so adhesion failure of the interface will not occur. The RAAF design methodology [16, 19] for bonded repairs is based on the Hart-Smith approach, using a comparison of the load capacity of the adhesive against the design loads to determine the degree of rigour required to verify the design of the bond and the level of validation testing required. As a second step, a calculation is made of the overlap length required to provide the capability to support the design loads. There are four joint Conditions as shown in Table 1. As the risk of failure increases, the level of rigour and testing increases to mitigate the additional risk. This approach is used in conjunction with an assessment of the significance for the repair based upon the likelihood and consequences of failure to determine the level of rigour required for the design, as well as the level of design substantiation required.

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.	The factor of 0.2 is applied to account for reduced levels of confidence in the design data 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 <u>absence</u> 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 1 Certification requirements for possible Conditions for bonded repairs based on a comparison of bond load capacity with design load cases.

Condition 1 bonds would be required if the repair was considered significant, but Condition 2 bonds may be used if there is sufficient substantiation to justify the lower margins of safety. Condition 3 repairs are only suited for fatigue enhancement repairs, where the existing structure can be certified in the absence of the repair. Condition 4 repairs are only suited to ferry flight repairs where flight restrictions are applied to ensure that the flight loads do not exceed the adhesive load capacity.

For design of bonded structures, Condition 2 should be the minimum requirement, with Condition 1 being preferred due to the reduced level of rigour required. The other bond conditions would be inappropriate for construction.

9 DESIGN DATA

To use the Hart-Smith approach to bonded joint design requires shear stress-shear strain data for elastic plastic behaviour of the adhesive. This can not be accurately determined from thin adherend tests such as the lap-shear test ASTM D1002 because of the contribution to displacements provided by the adherends themselves. The adhesive shear properties can only be derived from tests where the adherends produce minimal strains, in other words the adherends must be thick. One such test is the thick adherend test ASTM D 3983 in which the shear strains are measured using devices such as the Kreiger extensometer.

Unfortunately, the available data from thick adherend tests is limited and is drawn from a small database, so the design data would not meet the usual level of certainty that would apply to B-basis data for metallic materials. To mitigate the risk associated with data inaccuracies, an Adhesive Variation Factor (AVF) of 0.80 is applied to the calculated load capacity of the adhesive for assessment of the bond Condition.

$$P' = P \times AVF$$

The properties of an adhesive also vary with the method of pressurisation used, with vacuum bagging producing lower properties than autoclave processing. For vacuum bag applications where the only design data available refers to autoclave processing, then the AVF is taken as 0.75.

This level of conservatism could be reduced by the establishment of a higher level of confidence in material properties that could be achieved by pooling of design data to provide an adequate statistical basis for the data. Perhaps MIL HDBK 17 could provide a repository for such a database.

10 REDUCING TESTING REQUIREMENTS FOR BONDED STRUCTURES

One significant factor that impacts on the use of adhesive bonding for design of aircraft structure is the significant number of tests currently required to demonstrate compliance with the certification basis. Specimens are required for establishment of design allowables, then specimens are used for coupon, sub-component and component testing. This “building block” approach is considered necessary to establish the performance of the bond under simulated service conditions and to allow for differences between test items and the actual bonded joints.

Using the above approach, Condition 1 joints should successfully pass all testing because of the 1.2 safety factor required for the adhesive load capacity and the allowance for the AVF. Because of the uncertainty involved, testing would still be usually required to validate the design.

However there is an adhesive bond design methodology that is a special case for Condition 1 joints, and such designs can significantly reduce requirements for testing. Hart-Smith showed that where the potential load capacity of an adhesive bond exceeds the unnotched strength of the parent material and the overlap length is sufficient to ensure achievement of that load capacity, bond failure will always occur outside the joint. This is because the strength of the bond is greater than the adherends. Under such circumstances, coupon, sub-element and component tests will never cause failure of the bond because tests will always fail outside the joint. All that an extensive test program will provide is a database on the strength of the parent material. The case can be made that if a small number of tests at coupon level demonstrate that the bond is stronger than the parent material, then a large test program would always produce failure away from the adhesive bond. Such a program would be futile, and therefore the size of the test program could be reduced substantially once it has been demonstrated that the adhesive load capacity is greater than the adherends.

11 CONCLUSIONS

The most significant factor in the certification of adhesive bonded structures and repairs is the requirement to assure that the bonding processes produce chemical bonds that are resistant to environmental degradation. The method for preparation of the bonding surfaces determines the durability of the adhesive bond. Therefore the method for preparation of the bonding surfaces must form part of the certification basis for the structure.

A methodology is presented here whereby the degree of rigour required for design and certification is determined from a comparison of the load capacity of the adhesive bond with the load requirements for the design. For significant structure, a higher level of rigour is required. However, for less significant bonds a simple methodology has been presented which would enable a significant reduction in the test matrix normally required for validation of the design of bonded structures and repairs.

ACKNOWLEDGEMENTS

The authors wish to acknowledge WGCdr Greg Young, SQNLDR David Zemel and the staff of Platform Systems Laboratories for their guidance in the development of this approach to adhesive bond certification.

-
- 1 Baker, A.A., *Crack Patching: Experimental Studies, Practical Applications*, Bonded Repair of Aircraft Structures, (A.A. Baker, R. Jones, (editors)), Martinus Nijhoff, 1988.
 - 2 Baker, A.A., *Certification of Bonded Composite Patch Repairs For Cracked Metallic Primary Aircraft Structures*, Proceedings of the 20th Symposium of the International Committee on Aeronautical Fatigue (ICAF), Seattle, USA, July 1999.
 - 3 Baker, A.A., *Bonded Composite Repair of Metallic Aircraft Components - Overview of Australian Activities*, AGARD SMP Meeting on Composite Repair of Military Aircraft structures, Seville, 3-5 Oct. 94.
 - 4 Fredell, R., and Guyt, C., *Repair of C-5 Fuselage Cracking with Bonded Glare Patches*, Proc. 41st Int. SAMPE Symp. and Exhib., Anaheim, Mar 1996.
 - 5 Elliott, W. R., Lincoln, J. W., and Register, D. C. *Assessment and Terminating Action for Widespread Fatigue Damage in C-141 Wing Fuel Transfer Holes*, Proceedings of the 18th Symposium of the International Committee on Aeronautical Fatigue (ICAF), Melbourne, Australia, 1995.
 - 6 Schweinberg, W. H., Jansen, R., and Fiebig, J., *Advanced Composite Repairs of the C-141 Wing Structure*, Proceedings of the Composite Repair of Aircraft Structures Symposium, Vancouver, Canada, August 1995.
 - 7 Mazza, J. J., Forte, M. S., and Cramer, B. D., *F-16 Fuel Vent Hole Bonded Repair Update*, Proceedings of the Air Force 4th Aging Aircraft Conference, United States Air Force Academy, Colorado, July 1996.
 - 8 Baker, A.A. Chester, R.J., Davis, M.J., Retchford, J.A., and Roberts, J.D., *The Development of a Boron/Epoxy Doubler System for the F-111 Wing Pivot Fitting - Materials Engineering Aspects*, Int. Conf. on Aircraft Damage Assessment and Repair, Melbourne, Aug. 1991.
 - 9 Davis, M.J., *A Call for Minimum Standards in Design and Application Technology for Bonded Structural Repairs*, Proc. Symp. on Composite Repair of Aircraft Structures, pp4-1, 4-15, Vancouver, Aug. 1995.
 - 10 Davis, M.J. and Bond, D.A., *The Importance of Failure Mode Identification in Adhesive Bonded Aircraft Structures and Repairs*, The International Conference on Composite Materials – 12, Paris, 05-09 July 1999.
 - 11 Comyn, J., *Adhesion Science*, Royal Society of Chemistry, Cambridge, 1997
 - 12 Davis, M.J., *Deficiencies in Regulations for Certification and Continuing Airworthiness of Bonded Structure*, Int. Aerospace Congress, Sydney 25-28 Feb. 1997.
 - 13 *Certification of Adhesive Bonded Structures*, Final Report of The Technical Cooperation Program (TTCP) Action Group 13, February 2001.
 - 14 Davis, M.J. *The Role of Materials and Processes in Defective Bonded Structural Repairs* Proc. 41st Int. SAMPE Symp. and Exhib., pp 936-950, Anaheim, Mar. 1996.
 - 15 Hart-Smith, L.J., DAVIS, M.J., *An Object Lesson in False Economies - The Consequences of NOT Updating Repair Procedures for Older Adhesively Bonded Panels*, 41st. Int SAMPE Symp. and Exhib., Anaheim, 25-28 Mar 1996.
 - 16 RAAF publication DEF AUST 9005 *Composite and Adhesive Bonded Repairs*.
 - 17 Hart-Smith, L.J., "Adhesive Bonded Single Lap Joints", NASA CR 112236, January 1973.
 - 18 Hart-Smith, L.J., *The Design of Repairable Advanced Composite Structures*, Douglas Paper 7550, presented to SAE Aerospace Tech. Conf. Long Beach CA., 14-17 Oct. 1985.

