CERTIFICATION OF ADHESIVE BONDS FOR CONSTRUCTION AND REPAIR

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ABSTRACT

Certification of adhesively bonded structures has traditionally been undertaken in a similar manner to that of conventionally fastened structures despite clear differences in design procedures and the strong dependence of adhesive bonds on rigorous process standards. A consequence of this reliance upon existing certification procedures is that the most significant type of in-service adhesive bond failure is due to interfacial degradation, a failure mode not examined by existing certification regulations. Examples of failures of structures certified under current procedures will be presented in this paper.

Because the residual strength of a degraded interface will eventually decay to zero, and because the degradation depends on time as well as environment, current certification requirements that concentrate only on demonstration of static strength and fatigue resistance will not guarantee continuing airworthiness for bonded structures. Even when accelerated testing methods such as elevated loading or temperature/moisture conditioning are used, these methods may not provide sufficient time for susceptible interfaces to exhibit their likely degradation characteristics.

A methodology is proposed whereby a combination of a series of design and testing requirements as the basis for certification of adhesive bonded structures. Additional considerations are addressed for certification of bonded repairs. The certification basis suggests that testing requirements may be reduced as confidence in the integrity of the design increases. A consequence is that for some configurations, failure of the bond is so improbable that the certification requirements are almost transparent to the presence of the bonded joint. For such structures, testing of the adhesive bond would constitute only a small proportion of the cost of certification of the surrounding structure.

Inclusion of bond processing aspects as part of the certification program for all types of joints is critical to the production of bonds that are resistant to in-service degradation. The objective is to prevent the occurrence of all interfacial failures, even where the joint can sustain the required ultimate loads during certification testing.

KEYWORDS: adhesive, bonding, certification, repair, bonded structures, aircraft

1. INTRODUCTION

The certification of conventional mechanically fastened aircraft structures has evolved to a stage where the traditional approaches based on demonstration of static strength and fatigue resistance can be relied on to reliably assure the airworthiness of an aircraft type. Similarly, certification methodologies for fibre reinforced polymeric composite structures

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have reached a level of maturity sufficient to provide acceptable service performances in combination with adequate levels of airworthiness. A significant contributor to the successfulness of these methodologies is that the principal causes of structural failures and/or inadequate durability have been identified and appropriate strategies developed to prevent their occurrence or to manage their existence in service.

Unfortunately, the same certification procedures, when applied to adhesive bonded structures, do not reliably produce structures with an adequate level of continuing airworthiness [1]. An example of where the use of a traditional certification approach failed to ensure the airworthiness of an adhesive bonded structure can be found by examining the Aloha Airlines flight 243 incident. Multi-Site Damage (MSD) in the fuselage lap splices led to separation of the entire aircraft upper fuselage whilst in flight. While the final failure was due to MSD, the cracking would most likely have never occurred if the adhesive bond in the lap splices at original manufacture had demonstrated adequate durability [2]. The aircraft manufacturer/designer must have demonstrated compliance to the relevant airworthiness regulations to receive type certification, but the testing and analysis required to meet certification was not sufficient to detect the loss in bond durability in extended service[3]. In this example, the selection of a room temperature curing film adhesive system contributed to moisture induced degradation of the adhesive bond and ultimately to the loss of the upper fuselage section. Although sufficient short-term static strength and fatigue endurance was demonstrated to meet the traditional certification requirements, the longer-term durability of the joint was compromised by the degraded interface formed during the cure of the adhesive.

By examination of the surfaces produced during bond failure, it is possible to distinguish between failures due to static overload and/or fatigue, and those caused by deficient processing at manufacture [3]. Interestingly, very few examples exist of adhesive bond overload or fatigue failures due to poor design, even though many structures have been analysed using methods which in some circumstances could be non-conservative [4]. The design methodology for certification proposed here would eliminate those instances of non-conservative analysis and through a new approach to certification offers a potential to reduce the cost of associated testing. However, the most fundamental change advocated in the overall methodology would be to include reliable validation of surface preparation in the certification requirements. This latter improvement to existing bonded structure certification is seen as having the greatest single benefit to the airworthiness of such structures.

2. DESIGN OF ADHESIVE BONDS

A major concern with adhesive bonded joints and repairs relates to what constitutes an acceptable repair design methodology. UK MoD airworthiness guidelines [5] suggests that

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[3] This example has been selected purely to demonstrate the ineffectiveness of current certification requirements. It is not intended to denigrate the manufacturer involved who, after all, did show compliance with the existing certification requirements. Examples from other manufacturers could also have been selected.

acceptable design practice may use allowable design values[4] derived from lap-shear tests such as ASTM D1002.Through implication this often leads designers into analysing joints by comparing the average shear stress with the lap-shear strength although the non-uniform shear stress distribution in adhesive bonds has been well understood since reported by Volkersen [6].

A further problem exists in joint analyses where the adhesive is limited to elastic behaviour, ignoring the disproportionate contribution of adhesive plasticity to joint strength [7]. Hart-Smith [8] showed that for many modified epoxy adhesives, the contribution of plastic behaviour to load capacity can be such that plastic behaviour occurs at only 20% of the joint potential load capacity. Note that the issue of plastic deformation in adhesive bonds between adherends with a typical aircraft fuselage thickness does not carry the same connotations as plastic behaviour in metallic structure. Tests [9] have shown that repeated application of loads above the plastic limit for a joint does not lead to cumulative damage in the adhesive [10].

To undertake elastic-plastic joint designs, appropriate materials design data is essential. The only currently known tests that generate acceptable data are based on thick adherends such as ASTM 3983-93 or ASTM D5656-95. Note that the data for adhesives to display compliance to MMM 132 A is not suitable for joint design. MMM 132 A is a comparative standard and compliance simply indicates that the adhesive properties will be comparable to similar adhesives that have also been qualified. All of the tests specified by that standard are only valid for comparison of adhesives, and no tests required to generate elastic-plastic design data are specified by the standard.

A complicating issue is that there is no method of actually measuring the joint properties prior to installation because the material itself is formed while the bonding process is being undertaken. This means that as well as variability in material properties attributable to the adhesive manufacturer's process control, there will also be variability caused by process control during cure of the adhesive. Therefore, appropriate control of the adhesive cure parameters during bonding is essential.

3. PROPOSED DESIGN CERTIFICATION METHODOLOGY

3.1 Design For Shear Stresses

The approach in this paper is an extension of the design methodology first proposed by Hart-Smith [11] requiring bonded joint design to be based on the potential load capacity of the adhesive [5]. Hart-Smith showed that joints could be designed such that the adhesive would *never* fail. This of course assumes that the joint has been fabricated using processes that produce a durable bond, and that other failure modes are addressed separately. The

[4] DEF STAN 00 970 Chap. 402 para 6.3 actually states that use of lap-shear values is inappropriate, but Leaflet 402/3 para 4.1 states that lap-shear results may be used.

[5] The potential load capacity of an adhesive is the load that the joint could theoretically sustain in the absence of adherend failure. For joints where the adhesive is stronger than the adherend, the load capacity of the joint would normally be limited to the strength of the adherend.

certification methodology proposed here applies these principles to delineate between the various possible combinations of joint load capacity and structural design loads.

In the development of a certification program for bonded structures, due consideration must be given to the consequences of failure of the repair. Certification requirements for bonded joints in primary structure that are crucial to the integrity of the structure will naturally be more stringent than for other structure where failure does not compromise airworthiness. Bonded joints in primary structure will usually require validation of designs by a second, independent method or by structural testing.

The proposed certification methodology requires that the adhesive bond be certified separately from the surrounding structure. By separating the certification of the adhesive bond from certification of the associated structure, it is possible to delineate between joints where failure through the adhesive can never occur and cases where failure may occur through the adhesive. Clearly, if the adhesive bond can never fail under any load case, then the certification program must focus on certification of the structure and minimal effort is required to certify the bond. The bond is in effect transparent to the certification of the structure. However, in cases where the adhesive may be the locus of failure, extensive testing will always be required to assure structural integrity and durability. Thus, independent certification of the adhesive bond has the potential to minimise certification costs for bonded structures by reducing testing requirements.

Any certification methodology must identify all possible failure mechanisms. Bonded joints may effectively fail in one of four methods; by shear through the adhesive, by tensile peel of the adhesive, by failure at the interface between the adhesive and the adherend and failure of the structure. Interfacial failure is caused by ineffective surface preparation during manufacture of the bond, and thus is not a design consideration and as mentioned earlier an independent certification program should address failure of the surrounding structure [6]. The main failure mode to be addressed and certified through the design process is shear although joint. Adhesive peel stresses must also be managed through appropriate design (such as by tapering of the ends of the joint). The certification methodology proposed here also relies on the joint being designed with sufficient overlap to guarantee that the adhesive can achieve the required load capacity as calculated by Hart-Smith [7, 8].

The proposed certification methodology is based on comparing the load capacity of a joint in shear against the various design load cases. (The authors stress that the following certification methodology applies for the adhesive bond only.) Five possible conditions exist (see Figure 1).

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[6] This approach is valid for bonded metallic structures. However, for bonded fibre-composite structures failure through delamination of the laminate at or near the bond or interfacial failure of the resin-to-fibre bond are possible failure modes associated with the joint which must also be addressed.

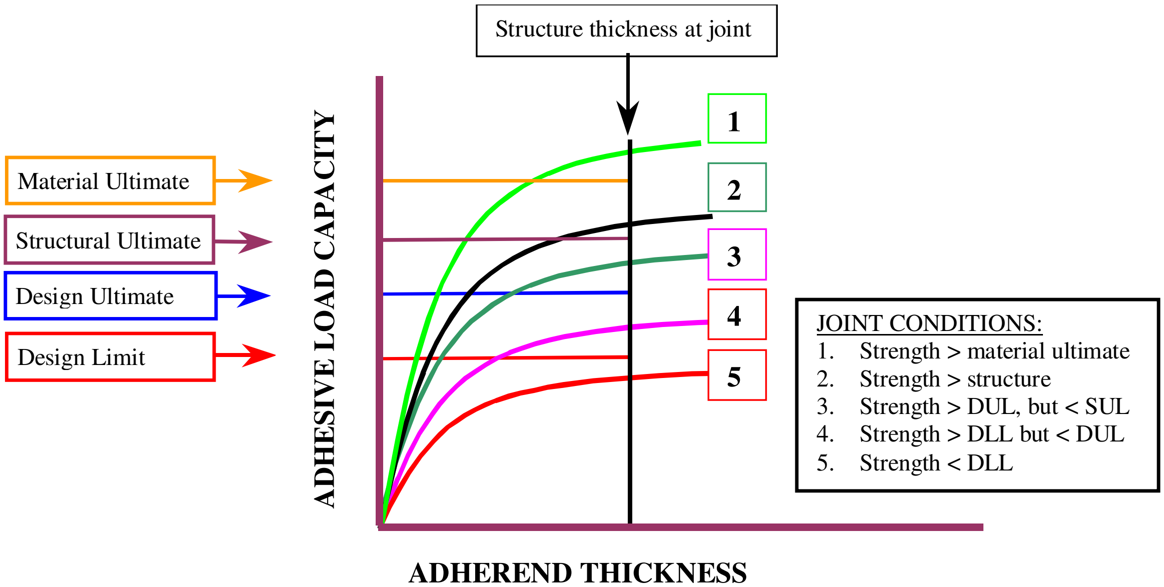

Figure 1: Possible static strength conditions for bonded joints and repairs when compared to structural design requirements

The failure conditions established by comparison of the potential joint load capacity and the structural load cases are:

a. **Condition 1:** Where the adhesive load capacity is greater than the unnotched ultimate strength of the material in the structure forming the joint. Failure by shear through the adhesive can never occur.

b. **Condition 2:** Where the adhesive load capacity is greater than a known Structural Ultimate Load (SUL) for the adjacent structure, but less than unnotched ultimate strength for the structural material forming the joint. Failure by shear through the adhesive should never occur because the structure will fail away from the joint.

c. **Condition 3:** Where the adhesive load capacity is greater than Design Ultimate Load (DUL) for the adjacent structure, but less than a known SUL for the adjacent structure. Failure by shear through the adhesive should not occur because the structural loads should never exceed DUL. However, the adhesive will be the weakest element in the joint and if the structure were tested to SUL, failure would occur through the adhesive.

d. **Condition 4:** Where the adhesive load capacity is greater than Design Limit Load (DLL) for the adjacent structure but less than DUL. Failure by shear through the adhesive should not occur in service, but the adhesive will not meet the original certification requirements for DUL. Such joints are only suitable for reinforcement repairs (eg. fatigue enhancement) where the original structure can sustain certification requirements in the absence of the repair.

e. **Condition 5:** Where the adhesive load capacity is less than Design Limit Load (DLL) for the adjacent structure. Such joints are only applicable for applications where the aircraft is operated under flight restrictions. Failure by shear through the adhesive is possible if operating loads were not restricted.

The certification methodology, and hence the level of testing to be performed for each joint condition, should vary with the dependence upon the bond to attain the design load condition. The more the joint is likely to fail through the bond, the higher the degree of assurance required to be demonstrated by testing.

Because adhesive properties are strongly dependent on temperature, assessment of adhesive load capacity is required at least in the following three conditions:

a. The maximum temperature expected in service.

b. The minimum temperature expected in service.

c. The temperature at which the critical load case occurs in service.

3.2 Certification Requirements for Condition 1 Adhesive Bonds

Certification of the static strength adhesive bonds that meet Condition 1 is relatively simple because the adhesive is stronger than the unnotched strength of parent material. Therefore no possible load condition will cause the adhesive to fail. Certification of the adhesive bond static strength for such joints or repairs may be based on analysis over the range of service temperatures with coupon tests to demonstrate that for the particular joint configuration, the load capacity of the adhesive exceeds material ultimate. Where previous data exists for tests using the same adhesive cured under the same conditions with the same adherend material, thickness and overlap length, then that data may be used. Structural or sub-component testing would be futile because failure will always occur in the structure, not the joint. The required certification testing for the rest of the structure should suffice to demonstrate structural integrity.

The bond overlap length must also be sufficient to provide a load capacity greater than the unnotched strength of the parent material in the structure.

3.3 Certification Requirements for Condition 2 Adhesive Bonds

In adhesive bonds that meet Condition 2, the adhesive is stronger than the structure and failure through the adhesive by shear should not occur. Certification of the adhesive bond static strength for such joints may be based on analysis to demonstrate that over the range of service temperatures, the adhesive load capacity is greater than the structural strength of the component. Representative joint tests will also be required to demonstrate that for the particular joint or repair configuration, the load capacity of the adhesive exceeds structural ultimate as determined by test or analysis. Where previous test data exists for tests using the same adhesive cured under the same conditions with the same adherend material, thickness and overlap length, then that data may be used. Structural or sub-component testing would be futile because failure will always occur in the structure, not the joint. The required certification testing for the rest of the structure should suffice to demonstrate structural integrity.

The bond overlap length must also be sufficient to provide a load capacity greater than the load at the static strength of the structure.

3.4 Certification Requirements for Condition 3 Adhesive Bonds

In adhesive bonds that meet Condition 3, the adhesive is weaker than the structure, but has sufficient load capacity to sustain DUL so that failure through the adhesive by shear should not occur. However, in any test of structural ultimate load, the failure would be through the adhesive bond. Certification of the adhesive bond static strength for such joints may be based on analysis together with testing of representative joint coupons to demonstrate that over the range of service temperatures the adhesive load capacity is greater than DUL for the component. For primary structure tests on sub-components and components should be mandatory to establish an acceptable level of confidence.

The bond overlap length must also be sufficient to provide a load capacity greater than DUL of the structure.

3.5 Certification for Condition 4 Adhesive Bonds

In bonded joints that meet Condition 4, the adhesive can not meet the requirements of DUL, but can meet DLL. Such joints would not achieve typical certification standards for aircraft structures, but may be acceptable for fatigue enhancement repairs where the existing structure is capable of sustaining an acceptable residual strength. Because the adhesive is the weakest part of the repair, a detailed structural analysis is required to demonstrate that the load capacity is greater than DLL of the component in the repair region so as to prevent the repair from failing in normal operations. Static strength testing should not be required for fatigue enhancement repairs because the capability of the original structure to sustain an acceptable load level in an additional requirement in this particular scenario.

The bond overlap length must also be sufficient to provide a load capacity greater than the DLL of the structure.

3.6 Certification for Condition 5 Adhesive Bonds

In bonded joints that meet Condition 5, the adhesive can not meet the requirements of DLL. Such joints would not achieve typical certification standards for aircraft structures. This condition is only acceptable for applications, where the aircraft is operating under flight restrictions.

3.7 Design for Peel Stresses

Peel stresses in a bonded joint or repair result from load path eccentricity in the region of the adhesive bond. Localised bending moments exist at the end of the joint or repair, resulting in through-thickness stresses in the adhesive. If these stresses exceed the peel strength of the adhesive, failure may occur. Tensile peel stresses must also be reacted out by the adherends, and if the joint involves composite materials, the peel stresses may exceed the inter-laminar tensile strength of the laminate and delamination may occur.

Because peel failures may occur at loads well below those that could cause shear failure, peel stresses must be addressed in joint and repair designs.

Analysis or testing using coupons that represent the joint geometry and materials may demonstrate peel strength. Where previous data exists for the same materials and geometric configuration, that data may be used.

Reliable design data for peel strengths of adhesives is difficult to obtain. Typical peel tests such as climbing drum peel (ASTM D 1781-76) or T-peel (ASTM D 1876-72) do not provide acceptable design data because these standards also only provide comparative information, not design values. In the absence of reliable data, designs typically use a rule-of-thumb approach where peel stresses are kept below known acceptance limits for ductile and brittle adhesives [10].

Peel stresses may also be reduced by tapering the ends of joints or repair patches [10]. By thinning the adherend, the load path eccentricity is reduced. The more compliant end of the joint also reduces shear stresses. Standard practice is to taper the ends of all joints and repair patches even if the analysis indicates acceptable joint peel strength.

3.8 Design for Fatigue Durability

The resistance of adhesives to fatigue is well known [12]. The design method proposed here follows a safe-life approach. The authors propose, based on historical/empirical data and experience, that provided testing or analysis can show that the adhesive shear strain at Design Limit Load is below 80% of the elastic limit strain for brittle adhesives or 200% of the elastic limit strain limit for ductile adhesives, fatigue testing <u>of the adhesive bond</u> at coupon or sub-component level is not required [13] for bonded joints categorised as Conditions 1 and 2. Because the adhesive will be the locus of failure for bonded joints categorised as Conditions 3 and 4 analysis and/or testing may be required to demonstrate fatigue resistance. Condition 5 joints are intended only for short service lives and therefore fatigue testing should not be required.

4. CERTIFICATION OF BONDED REPAIRS

Adhesive bonded repairs are usually modelled as representative bonded joints [9, 14, 15]. Therefore, the certification of the adhesive in bonded repairs may be managed in the same manner as that for bonded joints in construction. The main difference lies in the methods for certification of the repaired structure. Baker [16] has provided a methodology whereby the zone around the defect is managed by damage tolerance and the outer region of the repair patch and surrounding structure is managed on a safe-life basis.

Current practice for bonded repairs is to require that the structure in the repair zone must be have an acceptable residual strength (typically 1.2 times DLL) *in the absence of the repair* i.e. the current approach treats repairs as Condition 4 joints only. The authors would advocate that a further requirement is necessary. *The repaired structure should be capable of sustaining DUL* i.e. the repair should be at minimum a Condition 3 joint. Such an approach not only provides a level of confidence in performance, but also will restore the complete certified capabilities of the structure.

While requiring structural integrity in the absence of the repair is appropriate for flight-critical components, such a limitation is extremely restrictive for other structure. The authors therefore advocate that certification of bonded repairs to non-flight critical components may be based solely on the requirement that the structure should be capable of sustaining DUL when the effectiveness of the repair is considered in the assessment.

A major concern with bonded repairs is that there is no method for assurance of bond integrity. Experience with repairs on a wide range of military systems has shown that, provided the bonding processes can meet the requirements for certification as detailed in Section 6, bonded repairs can be confidently expected to reliably exhibit long service lives without disbonding. However, the problem is that there is no inspection method that provides assurance that a bond is effective. All NDI procedures for inspection of adhesive bonds can only provide information on the absence of defects; none can provide assurance of bond integrity. Therefore continuing airworthiness must always be based on safety by inspection. For flight critical components, the risk of bond failure within an inspection interval, however slight, does inhibit more widespread usage of bonded repairs. The use of "smart patch" technology [16] may provide sufficient confidence in the ability to easily monitor bond performance on a regular basis that bonded repairs could be used with confidence.The "smart patch" may be able to monitor the load carried by the patch and use this in relation to the load carried by another portion of the structure to provide an indication of the effectiveness of the bond. As the bond degrades the repair will progressively take less load in relation to the surrounding structure and the reduction in this load ratio is a possible method of monitoring bond performance. This method does not provide *a priori* calculation of bond life and is really only an advanced safety-by-inspection method.

5. THE CAUSE OF MOST BOND FAILURES

Previous papers [1] explain that the main reason for the unreliability of certification procedures is that they do not adequately address the most common cause of in-service bond failure. Adhesive bonds rely heavily on chemical links [17] between the surface of the structure and the polymers that form the adhesive. Even with minimal preparation of the bonding surfaces it is possible to generate sufficient chemical bonds to provide adequate short-term bond strength. However, bonds formed on surfaces that are not acceptably prepared are susceptible to gradual degradation. This is particularly important with metallic substrates. The most common mechanism of this degradation is that moisture absorbed by the adhesive attacks the bond interface at the surface of the structure. With metallic adherends this is usually by formation of weak, hydrated oxides. The chemical links between the surface and the adhesive gradually become so weak that failure occurs *at the interface* at a service load within the normal flight envelope of the aircraft [3]. Such bond degradation guarantees that with time the bond would fail, even if the component were never to see excessive loading through use in service. There have been examples of failures in bonded structures occurring during fitment [18] never having been subjected to flight loading.

Surfaces susceptible to interfacial hydration (or any other mechanism that produces interfacial failure) will usually degrade to a minimal (possibly zero) strength given sufficient time. Reliance on NDI as specified in current regulations [1] is inappropriate because there is no NDI method that can determine the potential for bond degradation. Even methods which can detect weak adhesive bonds [19] are insufficient to distinguish between effective, durable bonds and those that display good short-term strength but degrade with time. NDI is still essential to detect significant bondline voids, but there is no method available capable of interrogating the hydration resistance of the interface.

There are a number of implications for certification of bonded structures from this failure model:

a. The demonstration of static strength of bonded structures is not sufficient to assure continuing airworthiness.

b. Because the mechanism of bond degradation is unrelated to loads, fatigue testing will not provide assurance of continuing airworthiness.

c. Any interfacial failure either in testing or in service is an indication that the bond strength is degrading.

d. Selection of processes must be based on a test method capable of distinguishing between processes on the basis of hydration resistance of the interface.

e. Any bonding process must use appropriate surface preparation to generate a hydration resistant interface, irrespective of the load to be carried by the bond. If not the joint will eventually fail[7].

Because certification procedures must address all known failure modes, validation of the bonding processes must be an essential element in any certification program.

6. <u>CERTIFICATION OF THE BONDING PROCESSES</u>

As already stated, the authors contend that the strong dependence of adhesive bonds on processes used for manufacture is so important that production processes (in particular surface preparation) must be included in any certification program. While FAR 25.603 calls for materials to meet industry specifications, there is no clear direction that processes themselves must meet some given level of performance. The implication is that certification and quality control testing will eliminate any deficient processes. This is not necessarily the case.

The real focus on adhesive bonding processes should be on eliminating processes that can regularly pass quality control and NDI, yet fail in service. Such failures are specifically related to the selection of inappropriate processing methods that do not produce an

[7] This requirement would disallow the common practice of injection “repairs”.

interface resistant to hydration. Because there is currently no method for detection of ineffective processes, selection must be based on a comparative test, using a baseline known from experience to produce durable bonds. Appropriate acceptance criteria should be set such that processes that produce poor bond durability are excluded *before they are used in production*.

Most processes with poor service durability have been selected by use of lap-shear tests such as ASTM D1002 (for example see [20]). Even if the test values meet nominal acceptance requirements, the test does not interrogate the resistance of the interface to hydration and therefore the test is not appropriate for evaluation of a surface preparation process. The same test is also used for quality control, where tests are performed on coupons cured at the same time as the bond to imply that bond quality exists if the test value exceeds acceptance criterion. In fact, lap-shear tests usually only fail if the processes are exceptionally bad. (The authors are aware of one case in the RAAF where the high humidity during bonding caused extreme micro voiding in the adhesive with a consequent reduction in lap-shear strength of test coupons. The results were so consistent that management reduced the acceptance value

Other manufacturers have relied on the strain endurance test to validate selected surface preparation processes. ASTM D 2919-84 uses lap-shear specimens that are loaded in shear to a set proportion of their lap-shear strength, while being exposed to a standard environment for a set period, usually 28 days. This test method is capable of excluding very bad bonding processes (such as the scuff-sand and solvent cleaning method) but has been known to provide false-positive results for processes that have a poor service performance. This test is favoured by some because the loading is by shear, which simulates the service loading conditions. However the intent of validation testing is not to simulate realistic loading; it is intended to clearly discriminate between good and bad processes.

Adhesive bonds are known to be highly susceptible to loading that places the bond under tension. Ideally, a test to certify a bonding process would place the bond under extremely high tensile loads. If an adhesive bond can demonstrate good performance under a high tension load, then it will always perform well under shear. In the wedge test (ASTM D3762) the adhesive is loaded in peel by a wedge driven into the bondline. Because this initially fractures the adhesive, the bond is placed under tension at or near ultimate. For this reason, the wedge test is far more discriminating that the strain endurance test ASTM D2919-84, where the adhesive is only loaded to a proportion of its shear strength.

The wedge test has been in use for some considerable time, and it too has produced some false-positive results, principally because of the inadequate acceptance criteria stated in the ASTM standard. The stated values of a maximum of 0.75 inches and 0.5 inches average growth in *one* hour are considered to be grossly inadequate. (The authors are aware of two USAF Air Logistics Centres that deleted the requirement for the wedge test as a quality control measure because the tests never failed. Such a high success rate is not necessarily indicative of excellent process control as it may indicate poor acceptance criteria.)

As part of a collaborative program through The Technical Co-operation Program (TTCP) the authors have proposed that the following criteria be applied:

a. Tests are to be performed at 50°C, 95% humidity, non-condensing.

b. 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 specimens prepared using the same adhesive to bond surfaces prepared using phosphoric acid anodising to BAC 5555.

c. In all cases, the initial crack length must not exceed 50.8 mm (2 in.).

d. 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.

e. The surface generated during exposure must not exhibit greater than 10% adhesion (interfacial) failure.

These criteria have been selected on the basis of service experience with processes used for repairs that have provided effective service over extended periods. In effect, the criteria prevent the use of a process that exhibits interfacial failures[8]. For example, the grit-blast and coupling agent method [21, 22, 23] has been shown to meet these requirements. This process was adopted by the Royal Australian Air Force for use on F-111 aircraft in 1992. Since that time, only one small case [24] of interfacial failure (due to accidental misplacement of a release tape) has been detected in an organisation that undertakes 30 to 40 repairs per month.

Process specifications used for manufacture of adhesive bonded structures must follow the certified process exactly. Any change in process sequence or materials substitution is cause for re-certification of the entire process by wedge tests.

7. QUALITY MANAGEMENT

Even the very best adhesive bonded joint design methodology is useless unless competent technicians using validated processes have manufactured the joint from appropriate materials that have been stored and handled correctly and the bonding environment excludes all sources of contamination. Many of these issues can be controlled by implementation of quality management practices. Quality management requires strict compliance with validated processes to ensure that the bond is formed correctly. This approach will always produce reliable bonds. However many bonding shops will sacrifice quality provided that the quality control samples and NDI meet acceptance criteria.

Bond contamination may also cause interfacial failure, but the weakened bond should be easily found by quality assurance testing during manufacture. In service, localised contamination that occurred during manufacture (such as that caused by touching bonding

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[8] The authors recommend that regulators strongly resist proposals by some manufacturers of composite "kit" aircraft to accept interfacial failures in adhesive bonds, provided that the structure achieves DUL. ALL surfaces prepared using methods that produce interfacial failures will degrade with time until the strength of the bond falls below acceptable levels.

surfaces with bare hands) will cause a localised disbond. A generalised contamination (such as that caused by airborne contaminants) will reduce the number of chemical links and increase the chance of hydration of the remaining links. Again, witness coupons normally used for quality control should detect such contamination.

As has already been stated, lap-shear tests and NDI will not interrogate the hydration resistance of a bond. For production processes, wedge tests will give the most reliable assurance of bond quality. However, for repairs, the significant variations in bond line temperatures and pressures cause difficulty in correlation between witness specimens and bond quality. Also, very few aircraft structures have a large enough flat region adjacent to repairs where a wedge test panel could be cured. If test panels can be manufactured they are a valuable additional quality test but should not be used to replace a detailed quality management process. In practice, the most effective way to produce high quality bonds is through competent technicians complying with process specifications that have been correctly validated against reliable acceptance criteria. This approach relies on quality management, not quality control or assurance. Since 1992, the RAAF has not used companion coupons for repair applications, and in that time, only one interfacial failure has been detected. The omission of test coupons was only possible because of the application of quality management principles to the workplace.

8. CONCLUSIONS

The design certification procedure outlined here differentiates between joint designs where the adhesive is the probable failure locus, and those joints where the adhesive is stronger than the structure. Testing requirements for certification (undertaken on representative joints) may be reduced where the adhesive is not the failure locus, but additional requirements apply for joints in the load path in primary structure.

Any certification program must demonstrate the effectiveness of surface preparation methods for production of durable adhesive bonds. Methods that result in adhesion (interfacial) failures must not be used for construction or repair. The manufacture of such adhesive bonds using a validated process should maintain its quality through appropriate management rather than through control or acceptance testing.

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10. REFERENCES

1 Davis, M.J., *Deficiencies in Regulations for Certification and Continuing Airworthiness of Bonded Structure*, Int. Aerospace Congress, Sydney 25-28 Feb. 1997.

2 Macarthur Job, "*Aloha 243 - Are you Still Up*?", Air Disaster Vol 2, Aerospace Publications, Weston Creek, ACT Australia, 1996.

3 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.

4 Hart-Smith, L.J., *The Bonded Lap-Shear Coupon – Useful for Quality Assurance but Dangerously Misleading for Design Data*, 38th Int. SAMPE Symp. and Exhib., Anaheim, May 10-13 1993.

5 DEFSTAN 00-970

6 Volkersen, O., *Die Nietkraftverteilung in zungbeanspruchten mit Konstanten Laschenquerschnitten,* Luftfahrtforschung 15, 4-47 1938.

7 Hart-Smith, L.J., *Adhesive Bonded Single Lap Joints*, NASA CR 112236, January 1973.

8 Hart-Smith, L.J., *The Design and Analysis of Adhesive Bonded Joints,* Air5 Force Conference on Fibrous Composites in Flight Vehicle Design, Dayton OH, Sep 26-28 1972.

9 Baker, A.A., *Crack Patching: Experimental Studies, Practical Applications*, Bonded Repair of Aircraft Structures, (A.A. Baker, R. Jones, (editors)), Martinus Nijhoff, 1988.

10 Davis, M.J., *How Relevant are Load Rate Effects to Realistic Bonded Joints?* The International Conference on Composite Materials - 11, Gold Coast, July 14-18, 1997.

11 Hart-Smith, L.J., *Design and Analysis of Adhesive Bonded Joints*, USAF Conf. On Fibrous Composites in Flight Vehicle Design, Dayton OH, Sep 26-28, 1972.

12 Hart-Smith, L.J., *An Engineer's Viewpoint on Design and Analysis of Aircraft structural Joints*, Mc Donnell Douglas Paper MDC 91K 0067, also published in Proc. Inst'n. Mech. Engrs., Part G, Journal of Aerospace Engineering, Vol. 209, 1995, pp 226-238.

13 RAAF Engineering Standard C5033, Logistics Systems Agency, Royal Australian Air Force, 04 Sep. 1995.

14 Rose, L.R.F., "Crack Reinforcement by Distributed Springs", J. Mech. Phys. Solids, V35, pp 383-405, 1987.

15 Hart-Smith, L.J., *On the Relative Effectiveness of Bonded Composite and Riveted Patches over Cracks in Metallic Structures,* The 1999 USAF Aircraft Structural Integrity Program Conference, San Antonio TX, 30 November – 2 December 1999.

16 Baker, A.A., *Issues in the Certification of Bonded Composite Patch Repairs for Cracked Metallic Aircraft Structures*, The Symposium of the International Committee on Aircraft Fatigue ICAF 99, Seattle WA July 10-15 1999.

17 Kinloch, A.J., *Adhesion and Adhesives*, p 78, Chapman and Hall, 1987.

18 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.

19 Heslehurst, R.B, Baird, J.P., Williamson, H.M., and Clark, R.K, *Can Aging Adhesively Bonded Joints Be Found?* Proc. 41st Int. SAMPE Symp. and Exhib., pp 925-935, Anaheim, Mar. 1996.

20 Bonk, R.B., Osterndorf, J.F., Ambrosio, A.M., Pettenger, B.L. and Froelich, K.A., *Evaluation of Adhesives for Adhering Carbon/Epoxy Composites to Various Metallic Substrates,* Proc. 41st Int. SAMPE Symp. and Exhib., pp 1472-1485, Anaheim, Mar 24-28 1996.

21 Arnott, D.R., Wilson, A.R, Rider, A.N., Olsson-Jacques, C.L., Lambrianidis, L.T., Pearce, P.J., Davis, M.J., and Swan, G., *Research Underpinning the Adherend Surface Preparation Aspects of the RAAF Engineering Standard C5033*, Int. Aerospace Congress, Sydney 25-28 Feb. 1997.

22 Kuhbander, R.J., and Mazza, J.J, *Understanding the Australian Silane Surface Treatment,* 38th Int. Symp. and Exhib., SAMPE, Anaheim, 1993.

23 Poole, P., Stone, M.H., Sutton, G.R., and Wilson, R.N., *Effect of Adhesive Bonding Variables on the Performance of Bonded CFRP Patch Repairs of Metallic Structure,* The Repair of Aircraft Structures Involving Composite Materials, AGARD CP402, 9.1-9.21, 1986.

24 Davis, M.J, and Bond, D.A, *Principles and Practices of Adhesive Bonded Structural Joints and Repairs,* Int. J. Adhesion and Adhesives, 19 (1999) 91-105.