FORTY SIX YEARS OF DEALING WITH MISCONCEPTIONS IN COMPOSITE AND ADHESIVE BONDING TECHNOLOGY FOR AIRCRAFT CONSTRUCTION AND REPAIR

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ABSTRACT

After over 46 years of working in composite and adhesive bonded repairs, Dr. Maxwell Davis has experience in almost all areas of the technology covering design, damage tolerance, application technology, training, quality management, materials, inspection, regulation and guidance. There are few stones that Max hasn't stubbed his toe on during this time. Along the way, Max has encountered many misconceptions about adhesive bonding technology and technology management.

In recent years Max was involved in an investigation of a helicopter crash and that led to the realisation that the level of understanding of adhesive bond failure forensics was exceptionally low, as demonstrated by crash investigation reports relating to the same helicopter type, where the conclusions drawn in relation to the integrity of structural bonds or the significance of bond defects may have been in error. Significantly, one outcome of this work has been the conclusion that current practices in damage tolerance analysis and Non-Destructive Testing for management of structural integrity of adhesive bonded joints may not prevent bond failures for certain joint designs.

Examples of deficient practices, poor misconceptions and down-right errors in adhesive bonding and repair technology will be outlined in this paper.

1. BACKGROUND

In 1972 Max Davis received a cadetship with the Australian Defence Department and undertook a final year project on adhesive bonded repairs for cracks in aircraft structure. This topic was the focus of the remainder of his career with over eighteen years with the Defence Science and Technology Organisation (DSTO) and nineteen years employed as a composite specialist by the Royal Australian Air Force (RAAF) until his "retirement" in 2007. He set up a small consultancy under the name of Adhesion Associates Pty. Ltd. and he remains the Director of that company. Whilst employed at Aeronautical Research Laboratories (part of DSTO) he was a member of the team that developed the use of bonded boron patches for repair of cracks in aircraft structure.

In 1989 Max was attached to the RAAF Amberley to supervise a major reinforcement of F-111 wing pivot fittings to address a fatigue cracking issue in the stiffener run-outs in the upper Wing Pivot Fitting (WPF) and in 1992 he was transferred to the RAAF as a resident composite specialist. One of his first activities with the RAAF was to undertake a review of the performance of bonded repairs being undertaken on F-111 and it was found that 40% of the adhesive bonded repair work being undertaken was to replace a previous repair that was no longer bonded. The RAAF was convinced to change the surface preparation from the chromic acid etch Pasajel 105 to the Australian developed grit blast and silane process used on the WPF repair. At the same time, the repair adhesive was changed from a 350F (180C) curing system to a 250F (120C) curing system for repairs where the lower glass transition temperature (T_g) could be tolerated. While a change of adhesive will not usually address disbonding issues, the change in adhesive colour did provide a visual indicator of when the repair was performed. At the same time, there was a significant improvement in the standard of training for the repair technicians. In the period between 1992 and 2007 only three cases of repair disbonding were reported, out of about 4500 repairs and in each case the quality management system that had been created identified that the failures were due to technician malfunction. In all cases where the correct procedures were implemented there were no reported bond failures. Hence, the repeat repair rate was reduced from 40% in 1992 to 0.06% over the period until 2007.

Some of the significant reasons for the improvement in repair performance were:

- The development of an engineering standard on composite and adhesive bonded repairs DEF (AUST) 9005 and two associated handbooks on repair design and repair processes.
- The creation of a number of training courses for engineers, technicians and quality managers.
- Implementation of validated surface preparation procedures.
- In-house development and introduction of a hot-bonding unit with considerable advantages over market available products.
- Establishment of quality management practices.

In the formulation of the adhesive bond technology management system many misconceptions were encountered that were entrenched in the pool of knowledge about adhesive bonding. These misconceptions drove a program to correctly manage adhesive bonded repair technology that will be discussed further.

2. BOND FAILURE MODES

One of the first misconceptions that persists even today is that when a bond fails it is because the adhesive selected was not adequate for the task. The frequent response to a bond failure is to change the adhesive type. Changing the adhesive type will only be effective if the failure has occurred in the bulk adhesive (see Figure 1). If the failure is occurring at the interface this is a direct result of deficiencies in the surface preparation process. The only result of changing the adhesive will be to change the colour of the disbond at the interface.

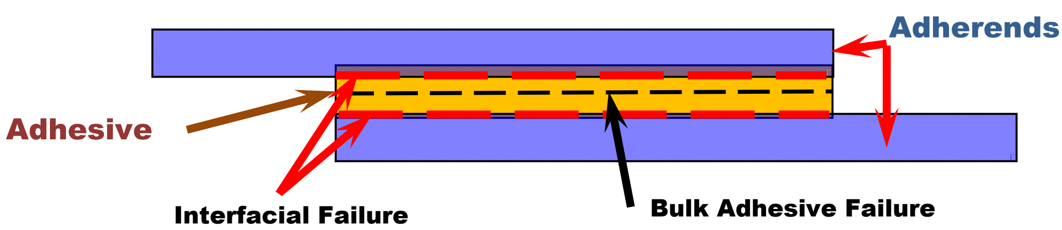

Figure 1: Failure methods for adhesive bonded joints.

The importance of failure modes in assessing failures in adhesive bonded structures has been known for some time [1]. In order to manage the structural integrity of adhesive bonded joints it is important to understand how specific bond failure modes may occur. Adhesive bonds may fail in four ways (see Figure 2):

- Cohesion[1] failure, where the adhesive is fractured by in-plane shear forces.
- Adhesion failure, where the adhesive separates from the adherend(s) at the interface.
- Mixed-mode failure where there is a variable combination of cohesion and adhesion failure.
- Peel failure, where tensile forces out of the bond plane result in a fracture of the adhesive.
- For fibre-composite adherends failure may also occur by ply separation within the laminate.

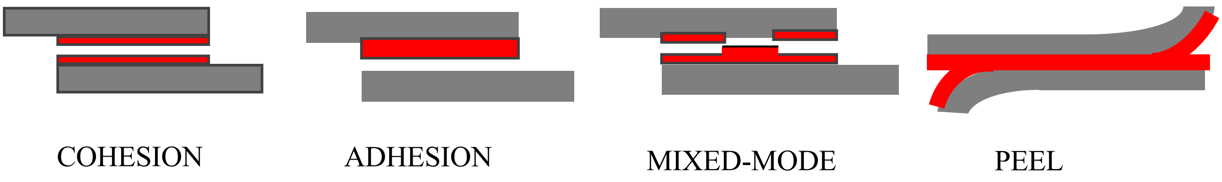

Figure 2. Adhesive bond failure modes.

Cohesion failure is characterised by the presence of residual adhesive over the entire surface of both adherends, and for film adhesives the failure typically propagates through the plane of the carrier cloth. **Adhesion** failures are characterised by the absence of adhesive on regions on one or both of the adherends, with the residual adhesive at a given location remaining on the other adherend (the adhesive may also separate totally from both adherends). Failure occurs at the interface, and there is a total absence of fracture through the adhesive material. **Mixed-mode** failure is characterised by a combination of cohesion and adhesion failures distributed over the bond. **Peel** failure is characterised by separation through the adhesive layer, but there may be an appearance that is similar to mixed-mode failure, and vision enhancement may be required to identify the presence of small "hackles" peeling up from the surface. Ply failure in bonded joints in **fibre composite** materials can occur in two forms; either the resin fractures (cohesion) due to excessive peel or inter-laminar shear or the fibre to resin interface fails (adhesion) and that may be caused by incompatibility between the resin and a size treatment applied to the fibres during manufacture of the fibres themselves.

2.1. THE EFFECT OF FAILURE MODE ON JOINT LOAD CAPABILITY

The failure mode also provides an indication of the overall bond load capability[2] with cohesion failure being the strongest and adhesion failure being the weakest (see Figure 3). The failure mode also provides some indication of the basic cause of the failure. Cohesion failure can indicate a design and certification deficiency, an incorrect selection of materials or a process deficiency that results in sufficient porosity or voids to reduce the bond load capacity or cohesion failure can indicate excessive service loads. Adhesion failure is a direct result of either contamination during the bonding process or degradation of the interface in service. Both causes are a direct result of surface preparation selection or implementation issues rather than

[1] **Terminology:** Note the terminology used. In the past the terms *Cohesive* and *Adhesive* were used to mean *Cohesion* and *Adhesion* failures, but that led to confusion between *Adhesive failure* (meaning Adhesion Failure), and *Adhesive Failure* which referred to a failure of the bulk adhesive material. Using the adverbial form *Adhesion* clearly delineates between the adjectival *Adhesive* and the noun *Adhesive*.

[2] **Terminology:** When bonds are tested the results are traditionally presented in terms of average shear stress at failure. As will be discussed in the section on Bonded Joint Design, average shear stress is a meaningless term and a poor measure of the strength of a joint. The true measure of the strength of a joint is the LOAD at failure, which I have termed the ***Load Capability***.

design. Mixed-mode failure occurs in bonded joints where the interface is in the process of degradation in service, and hence they are also an indication of surface preparation deficiencies. Mixed-mode failures are the result of an applied load exceeding the load capability of the bond at some time during the degradation process so load capability changes with time since manufacture. In early service life, degradation is mild so load capability is high, but as time progresses and degradation propagates, the load capability decreases.

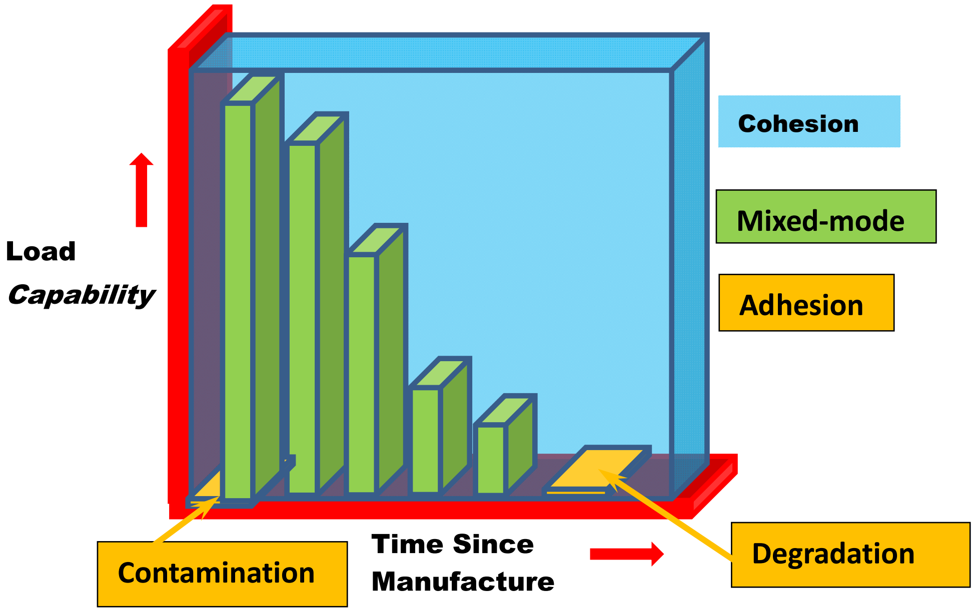

Figure 3. Variation of *Load Capability* against *Time Since Manufacture* for bonded joints exhibiting different failure modes.

3. BONDED JOINT DESIGN

One of the first misconceptions encountered relates to joint design. Traditionally, bonded joints have been designed on the basis of comparing the average shear stress at the design load against a "*Design Allowable*" shear stress which has been determined from extensive testing, together with considerable knock-down factors to negate the influence of many joint parameters. Essentially the design methodology relies on the adoption of a very low value of allowable shear stress such that failure does not occur in all combinations of design parameters and service environments. An extensive test program is required to demonstrate that failure is avoided for all joint configurations under all environmental conditions expected in service. This is the basis of the "building block" approach embedded in the FAA Advisory Circular AC 20-107B (EASA AMC 20-29) This approach was used by 78% of respondents to an FAA survey [2] in 2004.

The basic assumption in the average shear stress approach is that average shear stress is somehow related to bond strength, and if the calculated average shear stresses are excessive, then an increase in overlap length will result in a reduction of the shear stresses. This would be true if the bond was between inextensible adherends, but in real adherends, as load is introduced into one adherend through the bond, there is a variable strain developed in the adherends as load is transferred. Hence, the shear stresses peak at the ends and decays in the middle of the joint, as shown in Figure 4 for a joint between real adherends. Once a particular overlap length is achieved, the maximum shear stress does not change and any increase in the overlap length simply adds to the size of the zero shear stress region in the middle of the joint.

This deficiency in the average shear stress design method was shown by Volkersen in 1938 [3]. Hart-Smith

[4, 5] extended Volkersen's analysis to address plastic behaviour of the adhesive at the ends of the joint as the adhesive loads exceeded the elastic limit (see Figure 4). Testing using the thick adherend test ASTM D5656 shows that adhesives behave as elastic-elastoplastic materials (see Figure 5). Hart-Smith idealised that behaviour to elastic-perfectly plastic and provided that the area under the stress-strain curve is consistent, the strain energy to failure for the adhesive will be consistent between the model and the actual test curve.

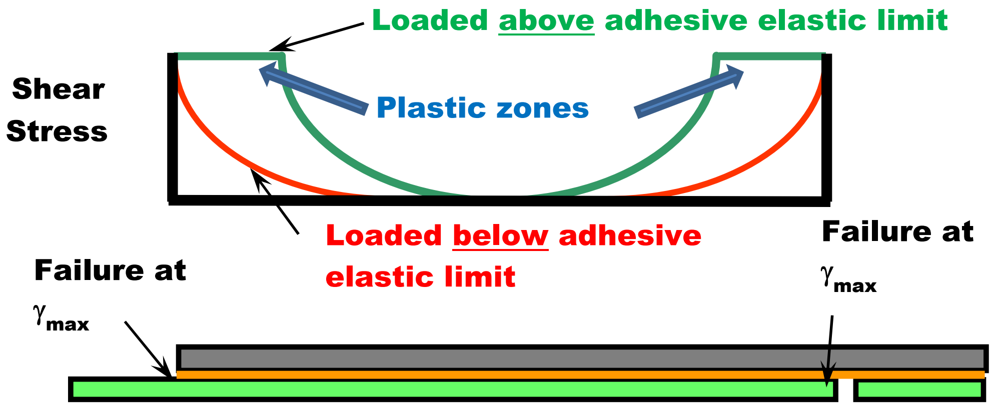

Figure 4. Schematic representation of the adhesive shear stress distribution for a bonded joint showing the formation of plastic zones at the ends of the joint.

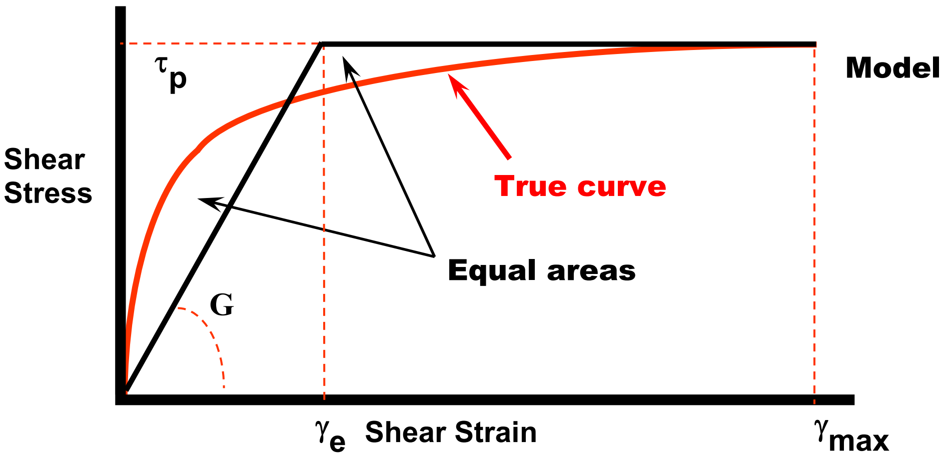

Figure 5. Schematic representation of how the shear-stress shear-strain curve derived for an adhesive using ASTM D5656 thick adherend test is modelled as ideally elastic-perfectly plastic.

Adhesive properties vary significantly with temperature (see Figure 6) with shear strength, failure shear strain, shear modulus and the proportions of elastic and plastic behaviour changing. Designs for bonded joints therefore should use the properties appropriate for the load conditions being analysed.

Hart-Smith's approach enabled the actual calculation of the potential load capacity of the adhesive in the absence of prior adherend failure. Importantly, the relationship between load capacity for the adhesive included all of the variables ignored by the average shear stress approach. Hence it is possible to calculate joint load capacity for changes in adherend elastic modulus, adherend thickness, adherend coefficient of thermal expansion, adhesive property variation with service temperature and residual stresses associated with cure temperature and operating temperature, so the use of knock-down factors is no longer necessary.

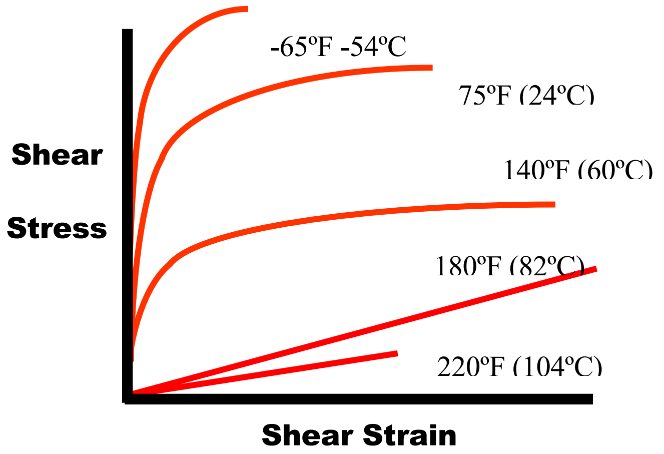

Figure 6. Schematic representation of variation of adhesive Shear-Stress vs Shear Strain for various test temperatures. Thick Adherend data ASTM D5656.

The load capacity P_{LC} is given by the ***lower*** value of the load transferred at each end of the joint (see Figure 7 for nomenclature):

$$P_1 + T_1 = \sqrt{2\eta\tau_p\left(\frac{1}{2}\gamma_e + \gamma_p\right)E_i t_i\left(1 + \frac{E_i t_i}{E_o t_o}\right)} + \frac{E_i t_i E_o t_o(\alpha_o - \alpha_i)\Delta T}{E_i t_i + E_o t_o}$$

$$P_2 + T_2 = \sqrt{2\eta\tau_p\left(\frac{1}{2}\gamma_e + \gamma_p\right)E_o t_o\left(1 + \frac{E_o t_o}{E_i t_i}\right)} + \frac{E_i t_i E_o t_o(\alpha_i - \alpha_o)\Delta T}{E_i t_i + E_o t_o}$$

$$P_{LC} = P_1 + T_1 \quad \text{or} \quad P_{LC} = P_2 + T_2 \quad \text{Whichever is lower.}$$

Hart-Smith [6] then proposed a novel design methodology for bonded joints. By assuming that all load at the design conditions is carried by the plastic zones only, an overlap allowance can be made to permit that condition to occur. Additional overlap is provided to ensure that the elastic trough is sufficient to provide creep and fatigue resistance (see Figure 8).

NOTE: Overlap length is highly dependent on temperature, with the largest overlap requirements occurring at higher temperatures. Hence overlap calculations should always be performed using the properties for the maximum service temperature.

Hart-Smith also showed that by comparing the adhesive bond load capacity to the design loads, up to a certain limit, it is always possible to design the joint in thinner materials such that the adhesive is always stronger in shear than the structural loads required by the design (see Figure 9). This is a very important observation, because if it can be shown that the bond can always be strong enough, then failure loads are limited by the structure itself, not the adhesive bond. *Bond failure through shear should never occur*, provided processing is adequate.

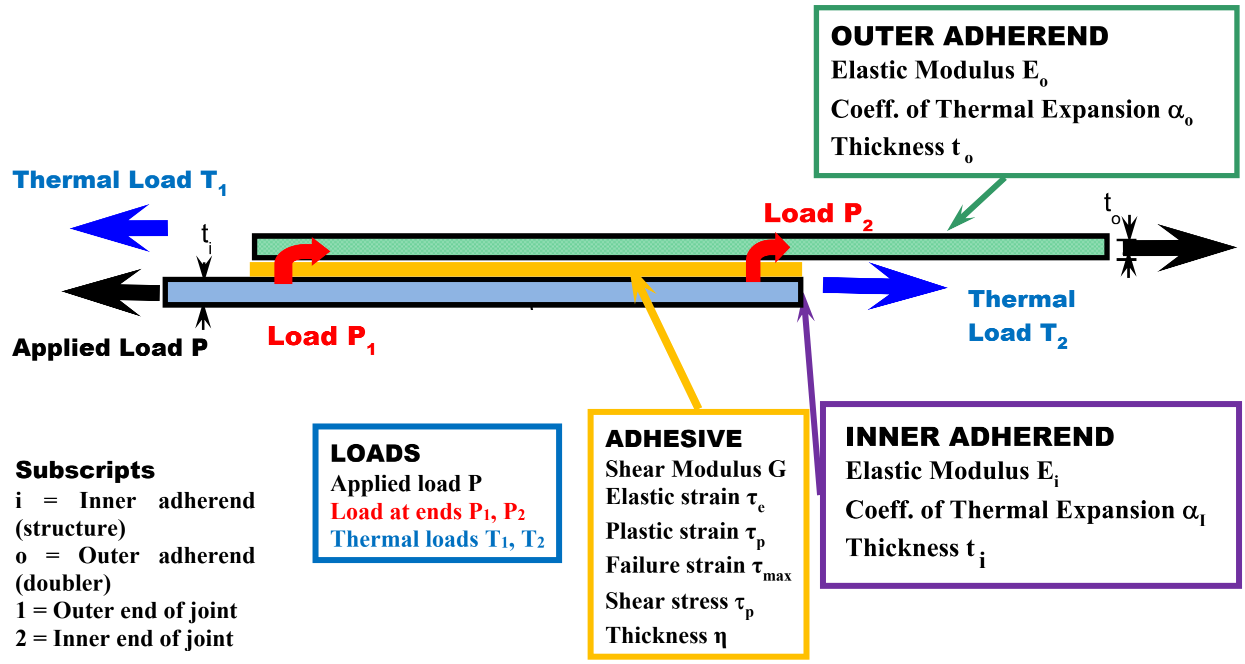

Figure 7. Nomenclature

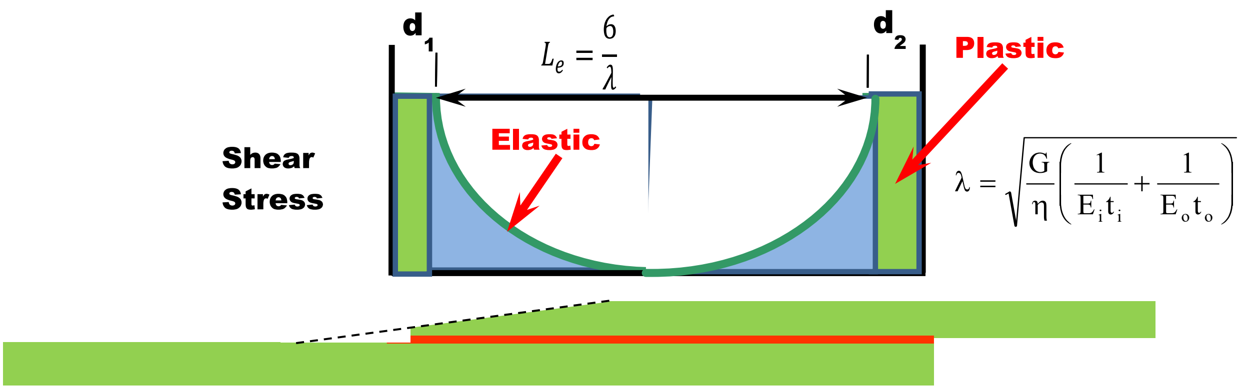

Figure 8. Schematic representation of the sizes of the plastic and elastic overlap allowance for the load capacity design method for adhesive joints. The total plastic zone allowed is $d_1 + d_2$ and the elastic trough size is L_e.

With regard to repair design, Hart-Smith's approach greatly simplifies analysis because if the adhesive is always stronger than the structure, then failure of the repair can only occur by propagation of the defect being repaired or by failure of the repair doubler and both of these failure modes can be managed by available structural analyses. There is no requirement for an exacting analysis of the adhesive bond in shear. Further, if the failure always occurs outside the joint, then the extensive test program required to certify joints designed using the average shear stress method may be significantly reduced. What is the sense of a large number of tests that only produce the strength of the adherends?

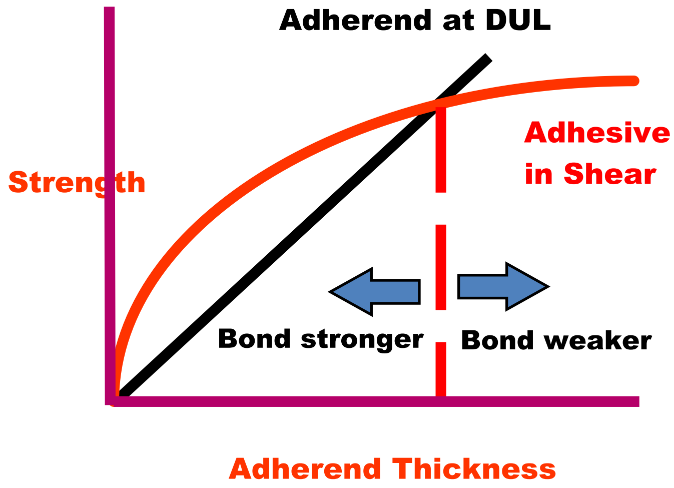

Figure 9. Schematic representation of the comparative strength of an adherend at Design Ultimate Load and the Load Capacity of an adhesive bond, showing that below a particular thickness, the adhesive bond may be stronger than the adherend.

3.1.1. Lessons Learned about Joint Design

The average shears stress design methodology is inappropriate for design of adhesive bonded joints and repairs. Correct application of the load capacity design methodology can lead to better, more reliable outcomes with fewer tests to certify structure.

4. DAMAGE TOLERANCE OF ADHESIVE BONDED JOINTS

It is well known that bond design alone is not sufficient to address cases where adhesive bonded joints experience defects that reduce bond strength. This led to the concept of damage tolerance where the design process provides sufficient reserve overlap to enable a defective joint to sustain the required design loads.

4.1. REGULATORY AND ADVISORY GUIDANCE

The structural integrity of adhesive bonds is managed as directed for civil aviation in FAA Regulation *14 CFR § 23.573(a)* supported by Advisory Circular AC 20-107B (EASA AMC 20-29):

> *14 CFR § 23.573(a) sets forth requirements for substantiating the primary composite airframe structures, including considerations for damage tolerance, fatigue, and bonded joints. Although this is a small airplane rule, the same performance standards are normally expected with transport and rotorcraft category aircraft (via special conditions and issue papers).*
>
> *(a) For any bonded joint, § 23.573(a)(5) states in part: "the failure of which would result in catastrophic loss of the airplane, 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."

4.2. THE DAMAGE TOLERANCE ANALYSIS MODEL

The Damage Tolerance requirement is traditionally met according to *14 CFR § 23.573(a)(5)* method (i) by simulation of a disbond by insertion of a non-adherent material (e.g. Teflon) into the joint during manufacture of a test article and then subjecting the joint to loads to demonstrate that the residual strength of the joint meets the design load requirements (see Figure 10). Fundamental to this model, the size of the defect determines the residual strength of the joint because the adhesive interface adjacent to the non-bonding insert is not degraded. This accurately represents the conditions that exist post-production where voids occur. However, the model should be compared against the model for interfacial degradation shown in the following Section.

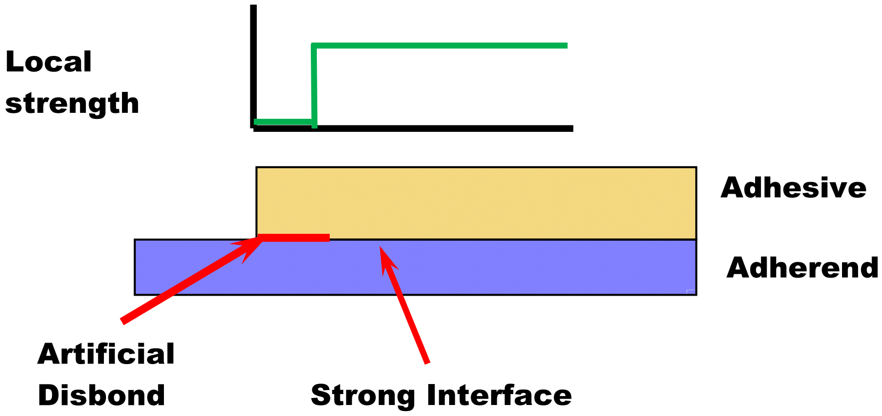

Figure 10. Schematic representation of Damage Tolerance Analysis by introduction of an artificial defect into a joint showing the effect of the artificial defect on local bond strength.

4.3. MECHANISM OF INTERFACIAL DEGRADATION (METALS)

Whilst the DTA model correctly represents the condition of the bond for production defects such as bondline voids, there have been deficiencies identified [7, 8, 9] in applying this model to represent the effects of in-service bond defects where the defect is caused by interfacial degradation.

To understand the mechanisms of interfacial degradation it is necessary to understand how adhesive bonds function. Adhesive bonding is a chemical process [10] that involves the formation of predominantly covalent bonds between the adherend and a bond primer (if used) or the adhesive itself if no primer is used. In metals, the bonds often occur with the oxides formed on the surface during the preparatory processing prior to bonding. In service many metals have an affinity over time to form hydrated oxides, (e.g. $Al_2O_3 \rightarrow Al_2O_3.2H_2O$). To form the hydrated oxide it is first necessary for the chemical bonds formed during the bonding process to dissociate and that leads to interfacial (*adhesion or mixed-mode*) failure [11, 12, 13]. This process is gradual and is driven by the level of moisture absorbed by the bulk adhesive during post-production environmental exposure.

As may be seen in Figure 11, the interfacial degradation is not uniform over the entire bond, but is localised to the end as moisture is absorbed in accordance with Fick's Law. Importantly, the weak interface extends beyond the size of the actual interfacial disbond. The *local* strength of the bond is zero at the disbond rising to full strength ahead of the degraded interface. The variable local strength is represented by Γ(x). Hence, because the reduced local strength of the interface extends beyond the size of the actual detectable defect, the use of a damage tolerance model based on artificial defects embedded in a pristine bond line clearly does not represent the true load capability of the bond and may be unconservative with a consequent risk to flight safety.

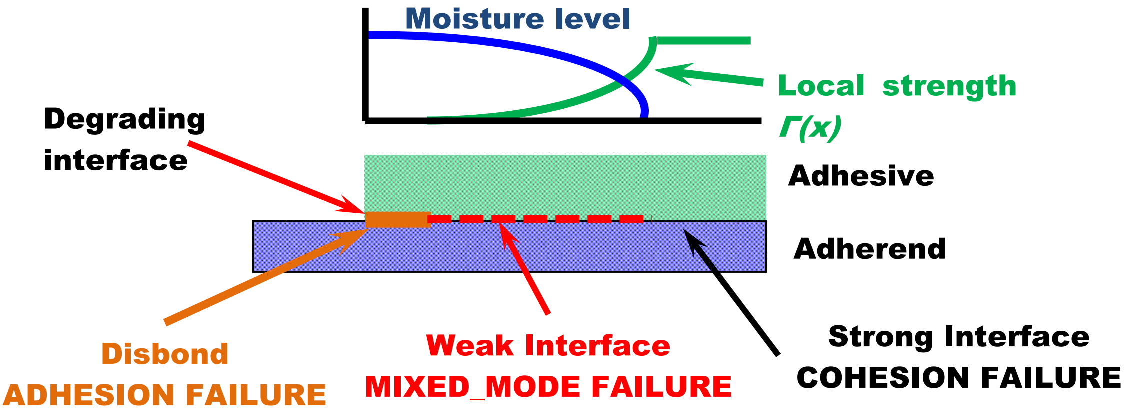

Figure 11. Schematic representation of the effect of moisture on the local strength of a bond interface as the surface oxides hydrate. Note also the changes in failure modes.

4.3.1. Case Study: Failed Adhesive Bond

The photograph in Figure 12 shows a skin-to-spar adhesive bond from a helicopter main rotor blade salvaged after the aircraft crashed. Extensive regions of adhesion failure can be observed, with the remaining regions exhibiting mixed-mode failure. There are no regions of cohesion failure. It may be concluded that this bond was extremely weak and bond failure may have contributed to the crash. The blade had passed tap-test inspection three times in 80 hours prior to the crash [8].

4.3.2. Lessons Learned about Damage Tolerance

It may be concluded that current Damage Tolerance Analysis methods are effective for production defects such as voids, but fail to adequately manage the structural integrity of degrading adhesively bonded joints. Current regulatory methods are therefore deficient and a reliable method is required to address this gap in aviation safety management.

5. NON-DESTRUCTIVE TESTING FOR ADHESIVE BONDS

Like many people, when I started out in adhesive bonding I had faith that if an adhesive bond passed NDT then the bond was capable of sustaining loads. In reality, NDT does NOT assure bond strength. The way most NDT (e.g. ultrasonics, tap testing) is currently applied it can only find air gaps that prevent a return signal. A lack of return signal indicates that there is a void that may interfere with the load capability of the joint. Damage tolerance then requires that the size of that void is less than the tolerable defect size for the part to be considered serviceable.

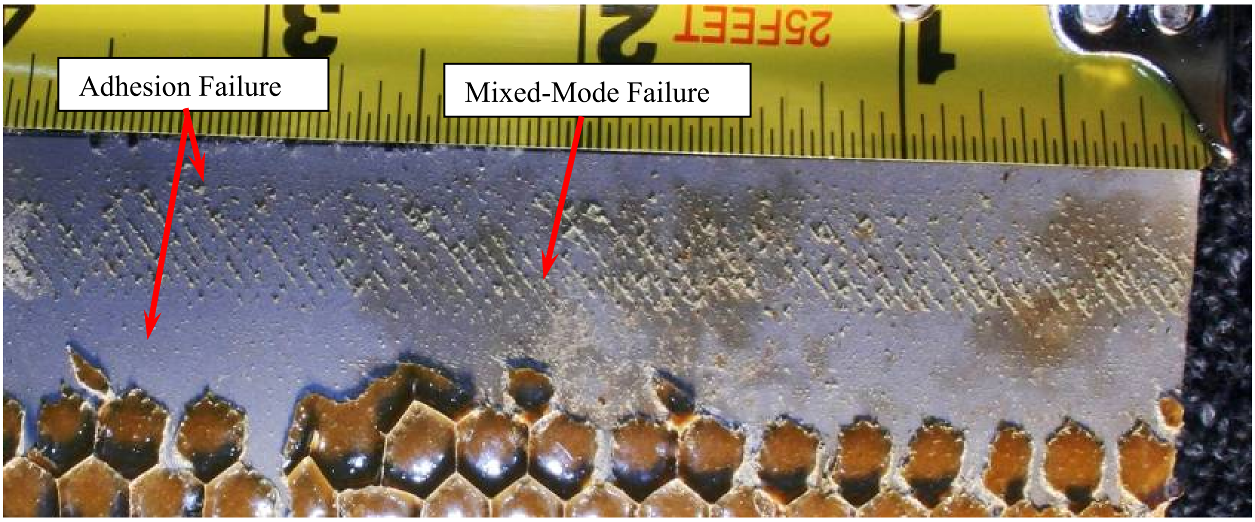

Figure 12. Photograph of a failed adhesive bond between the skin and main spar from a helicopter main rotor blade.

The problem with that approach to NDT is that it is possible for a bond with minimal strength due to a weak interface to pass NDT provided that there are no voids. This is commonly termed a "kissing" disbond. The author regularly demonstrates this by getting people to inspect a bonded sample by tap testing and almost everyone finds the large void in the sample and identifies the surrounding bond as a "good" bond. In fact the sample is bonded with common domestic double-sided adhesive tape, so none of the bond is a structural bond. Current NDT cannot interrogate the quality of either the adhesive or the interface. Of importance, the only feature in Figure 11 that current NDT can find is the actual disbond. In the weak interface region in Figure 11 there is sufficient contact such that a return signal can be achieved.

A critical deficiency in the way NDT is employed has been the almost total focus on finding bondline voids such that damage tolerance can be used to determine if the bond with a defect is safe to fly. As has been demonstrated in Figure 11, for bonds experiencing a degrading interface, damage tolerance may not provide assurance of flight safety. So is there a better way to assess bond integrity? The author suggests that the critical factor in assessing bond integrity is not the size of the disbond, and it also is not the size of the degraded zone in Figure 11, *IT IS THE SIZE OF THE ZONE THAT WOULD DEMONSTRATE COHESION FAILURE* because that zone would be expected to carry the remaining load. NDI should therefore not concentrate on finding weak bonds; it should concentrate on finding the extent of strong bonds. It is the ***Residual Effective Bond Overlap*** (REBO) that will determine the strength of the bond, irrespective of the presence of voids or interfacial degradation.

Recent studies [14] have shown that it is possible to use NDT to gain an indication of the ***local*** bond strength. Again in reference to Figure 11, it may be anticipated that the local strength of the bond at the disbond will be zero, and the local bond strength will increase towards the region where cohesion failure is anticipated. Roach showed that for samples with varying levels of interfacial contamination, there was a corresponding variation in the amplitude of the A scan signal (see Figure 13). It is suggested that a similar approach could be applied to bonded joints where the interface is degrading (see Figure 14).

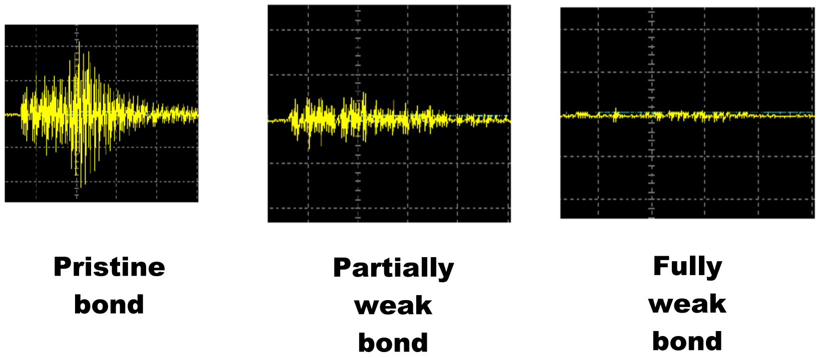

Figure 13. Through-transmission A scan results for variable levels of interfacial strength as a result of modified levels of interference with the formation of chemical bonds during cure. (*Courtesy D. Roach, Sandia National Labs.)*

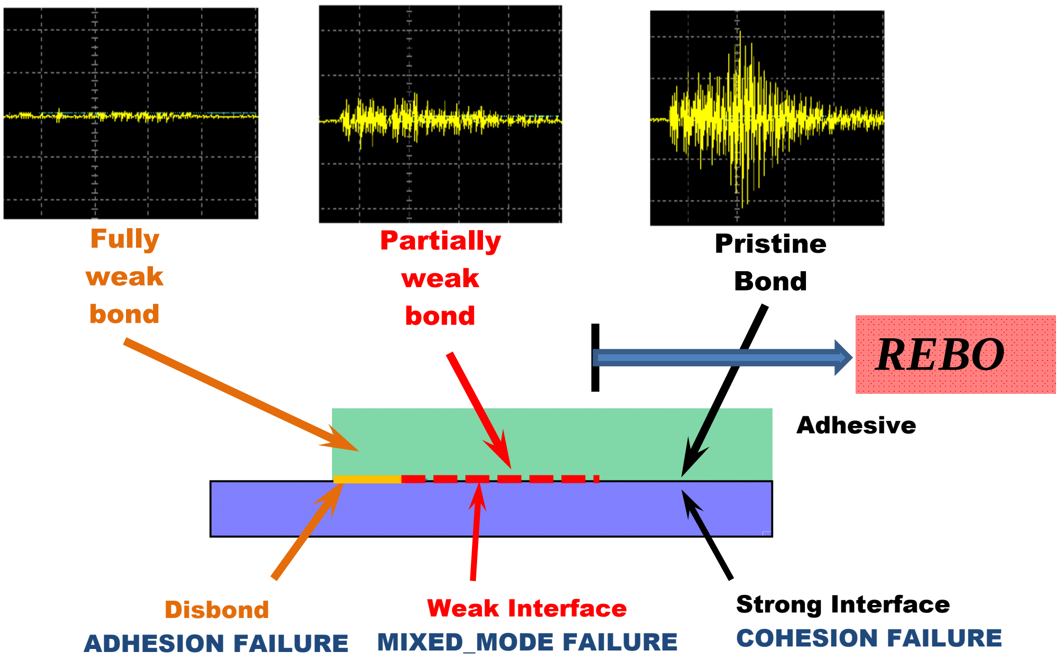

Figure 14. Application of Roach's results for bonds with variable strength to the variable local bond strength in a bonded joint experiencing interfacial degradation.

5.1.1. Lessons Learned about NDT

Current NDT approaches can only reliably find air gaps; they cannot interrogate the strength of the interface or bulk adhesive. The current concentration on detecting defects fails to realise that the strength of a bond depends on the Residual Effective Bond Overlap, not the size of the defect.

6. REPAIR PROCEDURES

Deficient repair practices mainly fall into four fields:

- Surface preparation, and
- Elevated temperature curing.
- Vacuum use during adhesive or resin cure.
- The use of ineffective repair concepts.

6.1. SURFACE PREPARATION

Inadequate surface preparation is the primary cause of repair failures and this largely stems from a lack of understanding of the mechanisms of adhesion and a subsequent failure to adequately validate long-term bond performance. There are essentially four theories of adhesion:

- Mechanical interlock, where the adhesive forms a mechanical bond due to surface roughness,
- Molecular diffusion, where the molecules of the adhesive diffuse through the molecules of the adherend,
- Electro-static attraction, where the polar nature of materials causes differences in electro-potential at each end of the molecule and the dissimilar charges are attracted to each other, and
- The adsorption theory, where there are true chemical bonds formed at the interface between the adherend and adhesive. These bonds are predominantly covalent but may also involve ionic and electrostatic bonds.

The inadequacy of mechanical interlock can be seen in Figure 15 which shows an aluminium surface that has been aggressively abraded prior to bonding. This bond was made in preparation of a training sample using the OEM approved surface preparation process at that time, so the bond had never seen any applied loads, yet the joint still disbonded.

The molecular diffusion model requires molecules to penetrate the molecular structure of the adherends, and that is not possible for metallic materials. Molecular diffusion can form bonds in examples such as joining certain plastics (Perspex™ for example) by application of a solvent to both surfaces which evaporates to leave a bond where molecules have diffused. Such a mechanism is not possible for metallic bonds.

Electro-static bonds exist and a classic example is domestic adhesive tape. However, the weak nature of electrostatic bonds cannot explain the high strength achieved by structural bonds.

Kinloch concludes that the adsorption theory is the only plausible explanation for the development of high bond strength. That theory also provides a plausible explanation for the failure of adhesive bonds in service due to interfacial degradation.

Once the chemical nature of adhesion is understood, then the fundamental requirements for surface preparation can be established. The surface must be clean and free of contaminants that would inhibit chemical reactions. This is well known but it must be understood that while a clean surface is a necessary condition for adhesion, it is not a sufficient condition. The surface must also be chemically active to enable reactions to occur, and this is the primary reason for abrading surfaces, not to roughen them. Chemical activity can also be produced by etching or other treatments such as plasma spraying.

Figure 15. A photograph of an aluminium surface that was prepared by the scuff-sand and solvent clean method.

So a clean, chemically active surface can produce sufficient conditions for adhesion to occur but together these conditions are not necessarily conducive to bond longevity. Many repair processes are validated by short term strength tests (such as the lap-shear test ASTM D1002). Provided testing is undertaken shortly after bonding, the results would suggest that the process is adequate for on-aircraft repair. Service experience with the scuff-sand and solvent clean process demonstrates that the process almost always results in disbonding.

Note that hydration of surfaces depends on time, service environment (temperature and humidity), moisture diffusion rates and susceptibility of surface oxides to the formation of hydrates. Service loads may play a minor role, but degradation can occur without the application of *any* loads. There have been cases reported where components experienced disbonding while in storage.

The conclusion from this discussion is that as well as having a clean, chemically active surface, there must also be an additional step that provides resistance to hydration of surface oxides to achieve bond longevity. Processes known to provide hydration resistance include phosphoric acid anodising and the use of silane coupling agents (the Australian grit blast and silane process or Boeing's sol-gel process). Processes known not to produce bond longevity include scuff-sand and solvent clean, corrosion passivation agents (e.g. Alodine), and acidic etchants (Pasajel 105 or 107, HF etch).

6.1.1. Validating Surface Preparation Processes

As already stated, part of the reason that inadequate surface preparation processes have become standard practice is the failure to differentiate between short term strength and long term bond longevity. Hence strength and fatigue tests have traditionally dominated validation programs for bonded structures and repairs. The results of such tests may vary significantly depending on the time between bond formation and testing. As part of the RAAF training for adhesive bonding technicians, lap-shear specimens are prepared with various surface preparation processes. Half of the specimens are tested the next day and the remaining half are exposed in the open environment until they are tested by the following course several months later. The results are always consistent, with only a small variation between a poorly prepared specimen and a well prepared specimen if tested soon after bonding. Yet the same specimen types show a significant variation in strength for the specimens tested after a period of exposure.

In testing adhesive bonds, the civilian regulations require that environmental effects on adhesive bonds are taken into consideration. (Part 14 FAR 2x.603). Traditionally, this requirement is addressed by testing “moisture conditioned” specimens, where the specimens are exposed to a controlled humid environment for 30 days. It must be realised that moisture conditioned specimens will only provide an indication of the effect of absorbed moisture on the properties of the bulk adhesive. These tests will NOT interrogate the hydration resistance of the interface because the time required for hydration may be longer than 30 days.

An international body of Defence science organisations (The Technical Co-operation Program (TTCP)) established a sub-committee (Action Group 13) to examine certification of adhesive bonded repairs. AG13 recommended the adoption of the wedge test ASTM D3762 (see Figure 16) for comparative assessment of the influence of surface preparation processes on the longevity of adhesive bonds. [15].

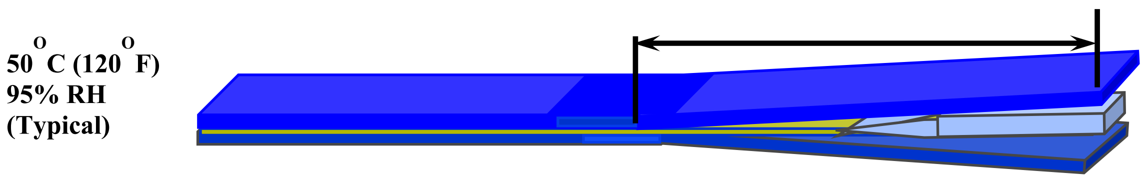

Figure 16. Schematic representation of the wedge test.

In the wedge tests, two 150 x 150 mm (6in) plates of the candidate adherend material are prepared using the candidate processes then bonded together using the proposed adhesive. The cured sample is cut into 25mm (1 in.) strips and a standard wedge is inserted at the end. The specimens are exposed to a set environment (typically 50ºC (122º F) and 95% RH) and the length of the crack in the adhesive is monitored. It was noted that the acceptance criteria stated in the ASTM standard were considered inadequate for assurance of long-term bond performance and the TTCP recommended the use of:

- Crack growth shall not exceed 5 mm (0.2 in.) after 24 hrs exposure.
- Crack growth shall not exceed 6.35 mm (0.25 in.) after 48 hrs exposure.
- On completion of the test, the adherends are separated and the extent of interfacial (adhesion) failure shall not exceed 10% of the surface exposed during the test.

RAAF and USAF experience with processes that achieved these requirements [16, 17] showed an almost total absence of bond failures in over 15 years of repair service. The FAA has a program with the University of Utah to recommend amendments to ASTM D3762.

Note that the wedge test is a comparative test that enables elimination of deficient surface preparation processes. Hence, the use of standard environmental exposure conditions is appropriate. Once a candidate surface preparation process has been identified according to the development of resistance to hydration, then consideration could be given to tests undertaken in the specific environmental conditions experienced in service.

6.1.2. Lessons Learned About Surface Preparation

Strength and fatigue testing, even for moisture conditioned specimens, is not sufficient validation for demonstration of bond longevity for materials susceptible to interfacial hydration at the interface. The wedge tests ASTM D3762 with modified acceptance criteria as recommended by TTCP AG13 is the best accelerated test method for evaluation of bond longevity.

6.2. ELEVATED TEMPERATURE CURING PROCEDURES

Many bonded on-aircraft repairs require the use of elevated temperature curing systems to achieve an acceptable glass transition temperature (T_g). As a general rule, the higher the maximum service temperature, the higher the required T_g and since T_g is loosely related to cure temperature, for even moderate service temperatures there may be a requirement for elevated temperature cure of adhesive systems. Further, if a bonded composite doubler is used, the cure conditions for the resin system must also be considered.

6.2.1. Heater configuration

Reference to almost any aircraft SRM will show procedures based on a single heater blanket with a standard configuration of thermocouples (e.g. 3 at 120º apart or 4 at 90 º apart around the repair). For structures with even a minor variation in sub-structural heat sinks such configurations of heater and thermocouples will not provide an adequate temperature distribution and the operator will be unaware of the deficiency because the thermocouples may not be located where critical thermal conditions exist.

Consider the repair shown in Figure 17 where damage has occurred in thin skin adjacent to the intersection between a heavy frame and a longeron. If a single heater blanket is utilised to heat the region, the outcome will depend on the location of the controlling thermocouple. If the controlling thermocouple is located over the frame or longeron, the temperature indicated will be low because of the thermal mass in the structure. As a consequence, the thin skin away from the thick structure may overheat. If the controlling thermocouple is located over the thin skin to prevent overheat, then there may not be sufficient heat supplied to enable the skin over the thicker structures to achieve the required temperature.

To achieve an adequate temperature regime in a repair zone it is essential to assess the presence of heat sinks within the repair zone and then to install separately controlled heat sources for each heat sink [18] (see Figure 18). Using this approach, each heat source will supply the correct amount of heat to enable each zone to achieve the required temperature without risking overheating the structure.

6.2.2. Thermocouple Placement

Thermocouples are used for repair heating for two purposes:

- To avoid overheat damage to the structure and repair, and
- To provide assurance that the adhesive and/or resin system has achieved the required temperature for cure.

Both of these requirements must be addressed separately. It is extremely improbable that placement of thermocouples in a set standard arrangement (e.g. 3 at 120º apart) will ever provide sufficient information to meet both purposes. Further, if the standard arrangement is configured with a different starting point, then a completely different temperature profile may be achieved, depending on if the new positions are located over thick structure.

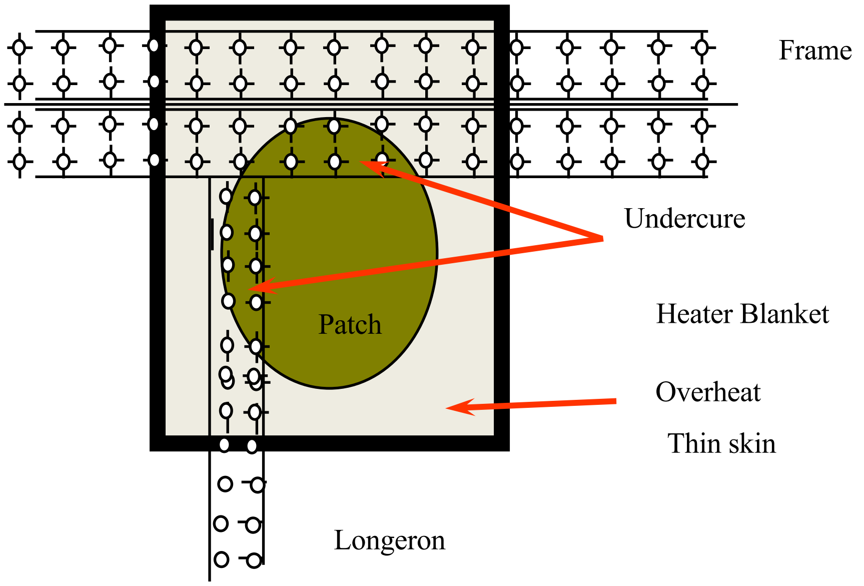

Figure 17. Risks associated with heating complex structure with one heat source.

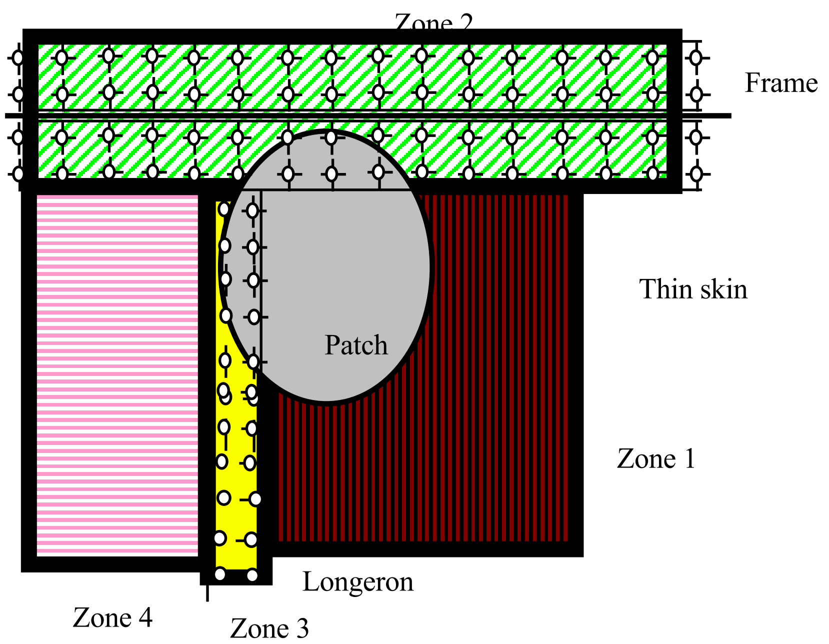

Figure 18. A suggested heat source configuration for complex structure.

Another misconception that had to be addressed was the use of thermocouples located within the heater blanket. Just because the heater source reaches a set temperature is no guarantee that the structure being heated achieves the same temperature. (It is easy to demonstrate the deficiency in this approach by simply placing the system off the aircraft and turn it on. Eventually the system will achieve the required temperature. But what is the temperature of the structure being repaired? There is no information on structural temperatures provided by that system.) To provide information on the temperature of the structure, it is essential that thermocouples are located actually on the structure being heated, not in the blanket and not on a caul plate over the repair.

Once the heat sources are selected, the next issue is to decide on locations for **control** thermocouples. There should be sufficient thermocouples placed at locations where the highest temperature is anticipated to occur within each heated zone. Control by the hottest of these points will ensure that the structure is not overheated. Multiple thermocouples may be installed to ensure the **hottest** point under each heat source is located. Some SRMs recommend control by the coldest point near a repair, but such a practice can lead to overheat damage to the structure. Next, thermocouples are installed as close as practical to the bond line to provide assurance that the adhesive or resin has achieved an acceptable cure cycle. For this purpose it is essential to find the location where the **coldest** point occurs near the repair. That point will determine if the adhesive has been adequately cured. Thermocouple configurations are shown in Figure 19.

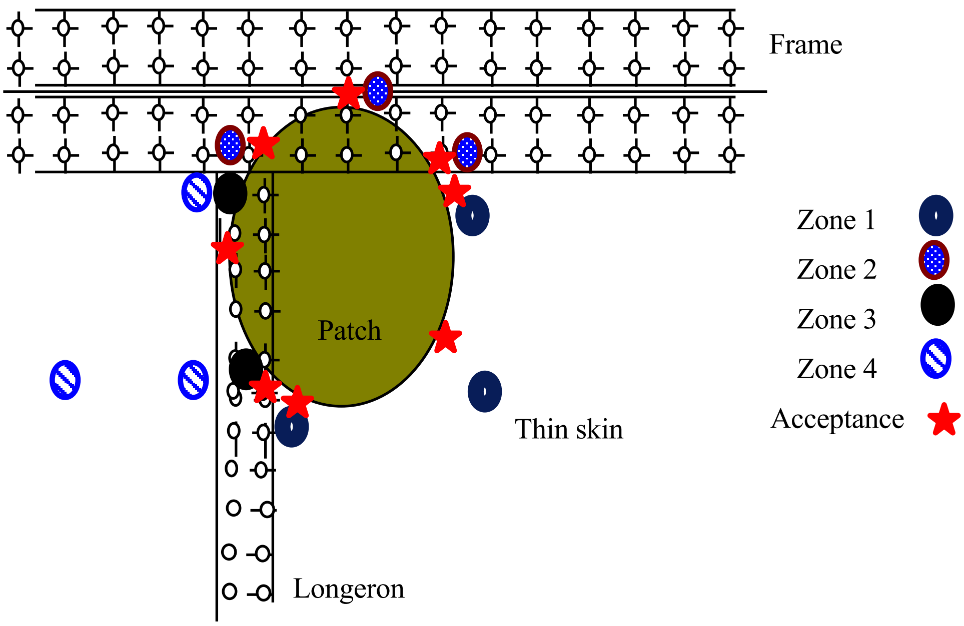

Figure 19. A suggested configuration for thermocouples for control and acceptance of adequate cure.

6.2.1. Off-Optimum cure of adhesives

One issue that often complicates repairs for complex structure is the insistence of many SRMs on curing the adhesive at a set cure temperature. In reality most adhesive systems have a relatively wide cure envelope, where lower temperature cure is possible provided that the cure cycle time is extended. Figure 20 shows a typical cure cycle envelope [22, 23]. To apply this approach to a repair, the temperature at the coldest acceptance point is used to determine the duration of the cure cycle.

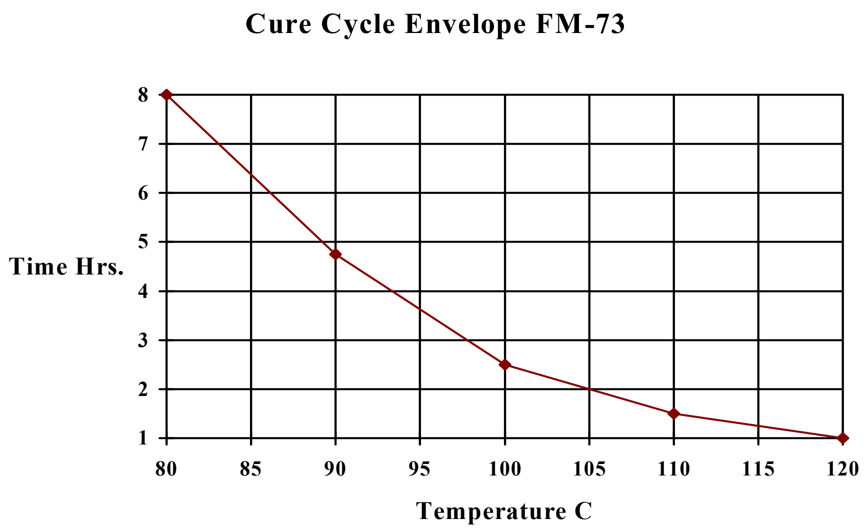

Figure20. A typical cure cycle envelope where the cycle duration may be extended to ensure full cure of the adhesive.

6.2.2. Case Study: Single Heater Blanket Repair

Figure 21 shows the bonding surface of a doubler that had been installed on complex structure by the use of a single heater blanket. The doubler spanned a thick frame. (*In fact this is the structure used in the previous Figures in relation to heating methods.*) Note that over the thin skin, the adhesive has fractured by cohesion failure which indicates that this region was properly cured. However, the entire bond over the frame area exhibits a mixture of adhesion and mixed-mode failure because the adhesive in this region was never fully cured. The repair failed soon after returning to service.

While initial investigation pointed to the adhesion failure and it was suggested that the surface preparation was deficient, a check of the cure cycle records soon showed that the technician had selected locations for the thermocouples that provided the answers he wanted and ignored the thermocouples that were giving the information he needed.

6.2.1. Lessons Learned from Heating Methods

Single heat sources and set thermocouple placement patterns will rarely provide a reliable cure cycle for bonded repairs. Control must be based on the hottest point in each heated zone for the heater in that zone. Acceptance or modification of the cure cycle duration must be based on the coldest point around the repair. Thermocouples must be located on the structure being heated. Management of low temperatures can be undertaken by extending the cure cycle duration.

6.3. POROSITY DURING ADHESIVE OR RESIN CURE.

Many SRMs direct the application of maximum vacuum for on-aircraft cure of adhesives or resins, principally because it is assumed that vacuum will draw out trapped air and volatiles being liberated during the heating process. In fact, application of full vacuum leads to the development of significant levels of porosity [19]. For adhesives that contain a carrier cloth, the adhesive will flow and the adherends will press down until the carrier cloth is compressed and consolidation ceases to occur. If there are any remaining volatiles that are liberated after consolidation ceases they will remain trapped and will not escape to vacuum. Worse yet, low pressure causes the volatiles to expand and it is the adhesive that is expelled from the bondline.

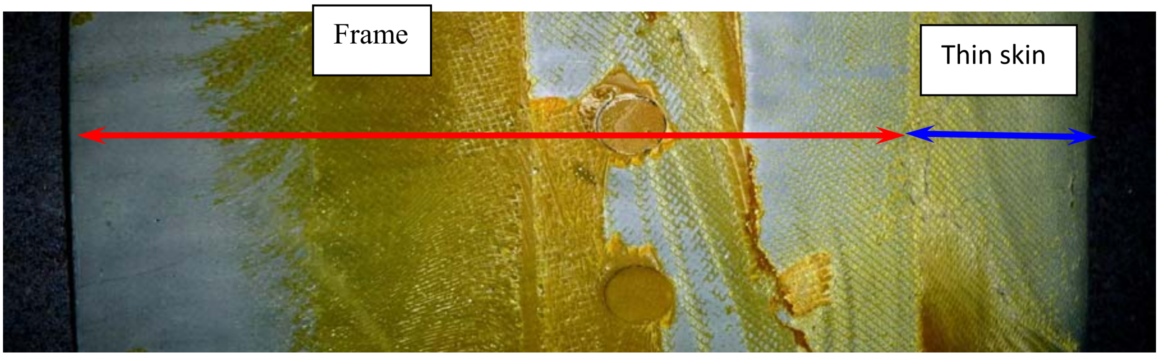

Figure 21. A failed bonded repair caused by the use of a single heater blanket and incorrect positioning of thermocouples.

To manage porosity for on-aircraft repairs, the RAAF approach adopted was to apply high vacuum at the start of the cure cycle and maintain that level until the adhesive flow temperature was achieved. The vacuum level was then reduced to -35 kPa (~10.0 in Hg). That cycle enabled any trapped air to be expelled and then caused any remaining trapped volatiles to significantly reduce in size as the pressure increased.

Excessive porosity in an adhesive bond can lead to significant losses in peel strength. In the reference paper it was reported that a sample of FM300 adhesive exposed to 30°C and 70% RH for 4 hrs resulted in a 53% loss of T-peel strength (ASTM 1876) and a 28% loss of honeycomb peel strength (ASTM D1781). Anecdotal evidence also suggests similar degradation in shear strength.

The solution to porosity is to address the causes of the release of volatiles and then to instigate procedures to minimise the level of porosity during the cure cycle [20]. Porosity is largely caused by the absorption of atmospheric moisture when the adhesive or resin is exposed prior to cure. All epoxy materials absorb moisture and that moisture is liberated as steam during the cure cycle. The moisture content can be controlled by minimising exposure of the uncured material to humid environments during transport, storage and in-process handling. Ensure that packaging is totally impervious to moisture and is not damaged.

The working environment where adhesive or resins are exposed also has a significant effect on porosity. Unfortunately, the guidance provided within the civil aviation regulatory framework is confused. FAA Advisory Circular AC 20-107B (EASA AMC 20-29) para 6 states:

> *The environment and cleanliness of facilities used for bonding processes are controlled to a level validated by qualification and proof of structure testing.*

This guidance is often interpreted that if the proof of structure test samples pass testing and were prepared in a low standard environment (for example an open hangar) then production can be undertaken in a similar facility irrespective of variations in humidity and temperature. However, FAA Advisory Circular AC 21-26 para 8 requires humidity be controlled to:

- Below 46% at 75°F, (23 ° C)

- Below 63% at 65°F, (18 °C)

The author strongly advocates the adherence to AC 21-26 and recommends that the regulators address this discrepancy in guidance.

6.3.1. Case study 1: Porosity

In one example witnessed by the author, at one bonding facility every sample tested failed to achieve the minimum strength required for an ASTM D1002 lap-shear test used for quality assurance. The solution adopted was to lower the acceptance value! On examination of the facility, it was found that the adhesive was stored in rolls in a freezer room with absolutely no protection against moisture. The piece of adhesive required was cut from the roll and placed on a bench to thaw prior to use. Staff were directed to store the adhesive in sealed plastic bags. It was found that the lap-shear values were still low and further investigations revealed that the bags had been sealed using adhesive tape, which easily peeled once it was frozen. The bags were heat sealed from that point onwards.

Next, it was found that materials were being accepted where there had been tearing in the plastic bagging at receipt from the supplier. The supplier stated that they were “only small tears” and were not significant. Materials were returned to the supplier with a comment that, like a contagious illnesses, it is not the extent of exposure that matters, it is the fact that exposure had occurred at all that was important.

Eventually a procedure was established whereby supplies were only accepted in good order and then the rolls were broken down in a controlled environment into useable pieces which were individually stored in heat sealed metallised plastic bags which were heat sealed.

6.3.2. Case study 2: Porosity

In 2007, the author participated in a helicopter crash investigation where it was suspected that the blade had disbonded in flight. As part of that investigation, a sample of a blade from a different crash that occurred due to an operational issue not related to blade failure was examined. It was noted that there was extensive porosity in the bond (see Figure 22). When the manufacture’s attention was drawn to the porosity and it was suggested that there was a need for humidity control in his facility, the response was that they are located in a desert environment so there was no requirement for humidity control. At the author’s insistence production and meteorology records were examined and showed in fact it had rained on the day that this blade was manufactured. That facility now operates with humidity control.

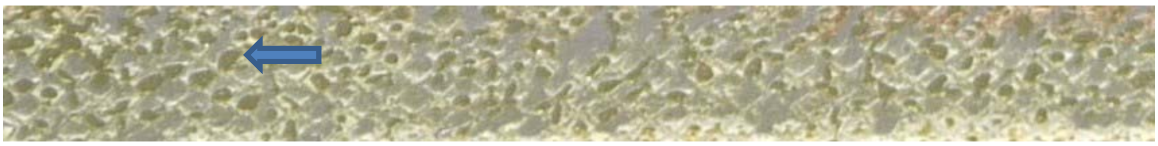

Figure 22. Photograph of a helicopter adhesive bonded joint. Porosity appears as the darker spots throughout the adhesive such as the one indicated by the arrow.

7. THE USE OF INEFFECTIVE REPAIR CONCEPTS.

During the survey of repeat bonded repairs referred to in Section 1, it was noted that many of the defective repairs being replaced were old injection repairs which were performed to attempt to bond together disbonds found by NDT. Several holes were drilled to provide access to the disbond and fresh paste adhesive was injected into the cavity. This repair method is used to correct production voids as well as repairing disbonds that occur in service. For production defects, the surface of the cured adhesive is fully reacted during the cure cycle so it is not chemically active hence one of the fundamental requirements for adhesion is not achieved. For service defects, in almost all cases the disbond is due to interfacial degradation and since the surface is fully hydrated the requirements for chemical activity necessary for adhesion cannot be met.

Injection repairs only achieve two things:

1. They fill the air gap so that NDT can no longer find the defect.

2. The technician gets a warm fuzzy feeling that he has repaired the defect.

Structurally, the bond strength remains unchanged, but the added holes provide a path for moisture to enter the component causing corrosion and further interfacial degradation.

7.1.1. Case study: Production Injection Repair

Figure 23 shows a large injection repair performed during a re-build of an aircraft rudder to correct a very large void between the core and the rudder mast structure. The pale yellow material is the original adhesive. The insert photographs show mating surfaces of the original adhesive and the darker injected paste adhesive. Note that the failures are totally by adhesion failure, indicating that the injected adhesive failed to react with the original adhesive. This defect was never re-bonded.

Figure 23. An injection repair to an aircraft rudder that failed in flight.

This core-to-mast bond transfers shear loads out of the rudder body into the mast. The effect of the disbond was to cause all of the shear loads to be transferred by the metallic skin of the rudder rather than the bond. A consequence of this load redistribution was the development of fatigue cracking in the skin and during a high load manoeuvre the rudder failed from that fatigue crack.

7.1.2. Lessons Learned about Injection Repairs

Because the surfaces of voids and disbonds are not chemically active, injection repairs cannot restore bond strength. The same conclusion is true for injection repairs for voids in laminated structure.

7.2. OEM REPAIR PROCEDURES

Despite the pre-eminent authority vested in aircraft SRMs and OEM engineering dispositions, the number and frequency of basic errors in repair application technology in authoritative procedures is of concern. So let us examine the proposition of the OEM holding an unquestionable status in repair technology. The OEM undoubtedly has sufficient data on loads, materials, flight profiles etc. as well as all of the data generated during the certification program, production and assembly. So surely, they have the ability to design and specify bonded structural repairs? Just because a manufacturer can design, and certify a structure and develop methods for manufacturing the item, does it really mean that they have the ability to develop bonded repairs for that structure both for SRM repairs and also for cases subjected to engineering disposition?

The author suggests that is not always the case, especially where the production processes cannot be replicated under field conditions. Almost all composite and bonded structure produced by OEMs for aircraft use tank-immersion processes for metallic surface preparation and autoclave curing for composites and adhesives. *These procedures are almost universally physically not possible for most bonded on-aircraft repairs.* Therefore it may be implied that the OEM’s experience and expertise in repair application technology under field conditions is considerably less than that applied for original design certification, manufacture and assembly.

Examples of poor processes can be found in SRMs for a recent helicopter acquisition[3] for the Australian Defence Orgaisation. Elevated temperature curing bonded repairs to laminated composite structures are applied using procedures that specify the use of a single heater blanket irrespective of the complexity of the structure. Worse yet, only ONE thermocouple is used, so there is a total absence of information on hot and cold points. There is no instruction to dry the laminate before heat is applied. In this example, there is a severe risk of deficient repairs or delamination development in the existing structure. Yet these are OEM approved procedures.

7.2.1. Lessons Learned about OEM Repair Procedures

OEM repair application methods must be carefully scrutinised rather than being given carte blanch acceptance. The author suggests that there is a glaring need for a basic standard or advisory circular that defines the minimum standards expected from repair methods.

8. EPILOGUE

Despite the significant outcomes in repair performance, the RAAF decided in 2015 to downgrade the engineering standard DEF (AUST) 9005 and scrap the two handbooks that supported that document. The stated objective was to align RAAF practices with civil industry. Whilst that decision may seem appropriate, one outcome has been to reinstate the pre-eminence of the OEM processes in SRMs. Injection repairs are now permitted and training staff are compelled to teach processes that were not permitted under the engineering standard such as scuff-sand and solvent cleaning for repair surface preparation.

9. CONCLUSIONS

Given the number of deficiencies identified in this paper in relation to on-aircraft adhesive bonded repairs, the author suggests that there is a need for the regulators to provide better guidance on minimum standards for repair processes [20]. Such guidance should include:

[3] No reference is provided for the particular helicopter repair manual referred to in this section to protect the manufacturer’s reputation. More information can be supplied by the author on a need to know basis.

- A requirement that surface preparation procedures must not only achieve the required strength but also must produce equivalent or better bond longevity than the manufacturing processes.
- Materials handling must prevent contamination, especially from atmospheric humidity.
- Repair heating methods must take due consideration of the presence of heat sinks within the repair region, and measures must be taken to prevent overheat damage to the structure whist at the same time assuring that the repair achieves an adequate cure cycle.

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