THE IMPORTANCE OF FAILURE MODE IDENTIFICATION IN ADHESIVE BONDED AIRCRAFT STRUCTURES AND REPAIRS

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ABSTRACT

The performance of adhesive bonded components and repairs in the aviation industry has varied significantly, resulting in a perception that adhesive bonding may not be reliable. The authors suggest that adhesive bond failures require closer scrutiny to accurately assess the causes of these failures as in recent history they have not received the same rigorous investigative scrutiny usually associated with fracture of metallic or mechanically fastened structures. Current poor understanding of adhesive bond failures in some areas of the industry has resulted in some defects being attributed to causes which, under closer investigation, are shown to be totally unrelated to the true cause of the failure.

The consequences of incorrect identification of the causes of adhesive bond failure include:

- Failure to correct defective bonding processes during manufacture.
- Use of inappropriate test methods for qualification of bonding processes.
- Continued use of inappropriate certification test methods for bonded structures.

This paper will present various failure mechanisms and their most probable causes together with case studies on how to identify the causes of bond failure from post-failure evidence. In most cases failures are directly related to processes used for initial production of the bond and are unrelated to the service loads. The authors recommend that adhesive bond failures be treated in the same rigorous manner as applied to metallic failures to ensure that the technology is applied correctly by the use of proper design, certification and production methodologies.

KEYWORDS: adhesive, adhesive bonding, defects, failure investigation, certification, aircraft

INTRODUCTION

Adhesive bonded aircraft structures and joints have demonstrated considerable variation in their reliability of service performance. The failure to recognise the cause of such bond failures has meant the continued use of deficient bonding processes both in manufacture of defective components and the use of poor repair technology [1, 2]. Further, the lack of knowledge of bond failure mechanisms has resulted in inappropriate test methods being used to assist selection of bonding materials and processes. This paper will address the essential elements of adhesive bonding technology and will present examples of bond failures which characterise the results of inappropriate bonding practices, based on extensive service experiences with bonded panels and repairs. The objective is to encourage better bonding practices by identification of the real causes of adhesive bond failure and to refute many fallacies frequently used to explain unexpected bond failures. Clear identification of the failure mode plays an important role in determining the cause of bond failure.

ADHESIVE BOND STRENGTH AND DURABILITY

There are four basic theories of adhesive bonding [3] which attribute adhesive bond strength to; surface roughness, diffusion of the adhesive into the bonding surface, weak molecular attraction, or a combination of weak molecular attraction and chemical bonds between the adhesive and the surface of the adherends. The latter theory listed is commonly known as the adsorption theory and is the most widely accepted. Adsorption theory can be used to provide a mechanistic explanation for short term (initial) bond strength, while the gradual degradation of the chemical bonds by hydration of the interface [4] (due to poorly prepared adherend surfaces) suggests why adhesive bonds may initially demonstrate high bond strength but have poor service durability.

A major contributing factor to poorly performing adhesive bonds is the failure of many production organisations and regulators to differentiate between bond strength and bond durability. Almost all bonding shops rely on strength tests (e.g. the lap-shear tests ASTM D1002) as a quality assurance test for bonding processes. Some researchers [5] have even used such tests for selection of appropriate surface preparation processes. Strength and fatigue tests may show that the bond strength is adequate and that the structure is sound and has sufficient fatigue resistance at the time of testing, but they do not verify that the component will be durable throughout its service life [6]. Bond durability is dependent on the resistance of the adhesive-to-adherend interface to attack by water. The resistance to hydration is established by the process used to prepare the surface of the adherends for bonding.

The diligence in which this process is performed and the adequacy of the process for the adherend/adhesive/environment combination influence the performance of the bond:

- A badly prepared or contaminated surface will not be chemically active and prepared to form the required chemical bonds with the adhesive. Such a surface will exhibit poor short term strength and exceptionally poor durability and can be identified by lap-shear tests performed as a quality control measure.
- An inadequately prepared surface may be chemically active and form a high number of chemical bonds to provide adequate short term strength however, if the surface is not resistant to hydration, the bond strength will gradually deteriorate. This is typical of an inappropriate process which is performed well and unfortunately, usually passes any short-term quality control tests.
- A well prepared surface will be chemically active, so that a high number of hydration resistant chemical bonds are formed with the adhesive. Such a bond will maintain a high strength for an extended period of service and will pass all quality control tests.

The difficulty encountered in quality acceptance of bonded structures is therefore the inability to differentiate between a surface which has been prepared well but using an inadequate process and a surface prepared by an appropriate method. To demonstrate, airworthiness regulators [6] typically rely on static strength and fatigue testing such that it is possible that bonded structures which meet current certification requirements may later fail in service due to degradation as a result of inadequate surface preparation processes used at manufacture. Because surface preparation is critical to the durability of an adhesive bond the authors contend that surface preparation must be considered as a critical element in any certification program for flight structures.

In contrast to occasional opinion, bond degradation is not significantly related to operational loading as demonstrated by bonded sandwich panel failures experienced by the Royal Australian Air Force (RAAF) when panels removed from storage failed prior to fitment on an aircraft. Similarly, the belief that structures which see only low loads do not need extensive surface preparation is also flawed. There are a substantial number of examples where such philosophies have led to the total failure of the bond. In Fig. 1, an adhesive filler had been added to a panel to dampen vibrations. Because the filler was not expected to carry loads, only a simple surface preparation process was used during manufacture. The subsequent disbond of the insert material led to water entrapment and severe corrosion of the underlying metal.

Figure 1. Corrosion damage resulting from moisture entrapment under a failed "non-load bearing" adhesive bond applied after minimal surface preparation.

DEMONSTRATION OF BOND DURABILITY

To assure on-going bond integrity, durability must be demonstrated prior to construction by a test which interrogates the resistance of the chemical bonds at the bond interface to hydration. This can not be achieved by either strength tests or fatigue tests even if specimens are moisture conditioned, as the test will only indicate the condition of the bond at a given time and not the potential for bond degradation during on-going exposure. An appropriate test is the wedge test (ASTM D3762), in which specimens are wedged apart in a hot, wet environment. The wedge cracks the adhesive leaving the chemical bonds in the joint just ahead of the crack under a very high tensile stress which exacerbates the effects of hydration. Any surface which is not resistant to hydration usually causes the joint to fail interfacially. By measurement of the rate of propagation of the crack over a reasonable period of time, a comparative measure of durability can be obtained. ASTM D3762 states that an acceptable bond will produce a crack growth of an average of 0.5 inches and a maximum of 0.75 inches in one hour exposure to 60°C and 95% RH. The RAAF and USAF believe that this value is unacceptably high [7, 8] and recommend that acceptable bonds must demonstrate no more than 0.2 inches growth in 24 hours and no more than 0.25 inches in 48 hours with less than 10% interfacial failure. The Australian Aeronautical and Maritime Research Laboratories (AMRL) have completed research that suggest that D3762 also requires guidance on the allowable size of the initial crack caused by the wedge [4].

The wedge test is a comparative test only and does not produce design data. However, experience has shown that it is the most discriminating test for bond durability, mainly because the bond is stressed to almost ultimate strength under tensile loading, a condition in which adhesives are known to be susceptible to accelerated degradation. Other durability tests such as ASTM D2919-84 do not subject the bond to anywhere near the same stress levels and the loading is predominantly shear at some fraction of limit load. The lower stress condition is not as effective in discriminating between surface preparation procedures.

In general, surface preparation which produces good bond durability involves three basic steps;

- Thoroughly degrease the surface.
- Remove the existing surface layer to produce a chemically active surface.
- Establish a stable, active surface which will form hydration resistant bonds with the adhesive or primer.

Each of the above steps is essential and must be performed in the above sequence if a durable bond is to be established. Many process specifications, reference books and repair manuals contain procedures which do not conform to the above sequence and consequently do not produce durable bonds [4, 9]. USAF Wright Laboratories [7] and the RAAF [8] only endorse two processes for field level bonded repairs; phosphoric acid anodising [10] and the use of a grit-blast and organofunctional epoxy-silane coupling agent [11, 12]. Surface preparation may be followed by application of a corrosion inhibiting primer, although the RAAF has not generally specified a primer with the grit-blast and silane method and has not experienced any corrosion under repairs in more than ten years service. Silane primers have been used elsewhere as a corrosion prevention treatment [13].

ADHESIVE BOND FAILURE MODES

There are three basic ways in which an adhesive bonded joint may fail:

- In one of the adherends outside the joint.
- By fracture of the adhesive layer (*cohesion*[1] *failure*).
- Interfacially between the adhesive and one of the adherends (*adhesion failure*).

Failure of the adherends outside the joint is achievable [14] for well designed and fabricated adhesive bonds in moderately thin adherend materials. This condition is highly desirable as it enables the full structural performance of the adherends to be utilised. Such joints may also facilitate certification processes [15] because if the adhesive has a load capacity which is higher than the strength of the surrounding structure, then only the surrounding structure may need to be tested to demonstrate structural integrity. Such bonds are also damage tolerant and can be designed using simple design procedures [8, 16]. Because the other forms of bond failure (cohesion and adhesion) are related to failures of the bond, the discussion will focus on those failure modes.

COHESION FAILURES

Cohesion bond failures result in fracture of the adhesive and are characterised by the clear presence of adhesive material on the matching faces of both adherends. Failure is usually by shear, but peel stresses or a combination of shear and peel may also cause a cohesion failure. This type of failure typically occurs in lap shear tests such as ASTM D1002 or peel tests such as ASTM D1781-76. In cohesion failures, the adhesive surface typically appears rough (see Fig. 2a) and may have a lighter colour than the bulk adhesive material. In film adhesive systems, failure usually occurs along the plane of the carrier cloth (a material added during the production of the adhesive roll to aid handling during use). Cohesion failures found in service are typically caused by poor joint design (insufficient overlap length or excessive peel stresses) although excessive porosity may also result in cohesion failure (see Fig. 2b). The high void content shown resulted from exposure of the pre-cured adhesive film to high humidity.

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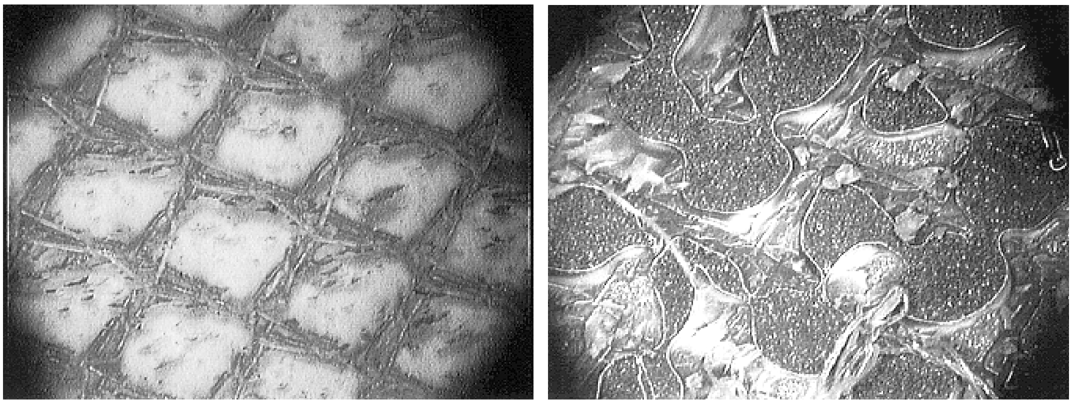
[1] Common practice is to use the adjectival form “adhesive” to describe interfacial failure. This risks confusion with failure of the adhesive material which is termed “cohesive” failure. In order to more clearly distinguish the forms of failure, the authors advocate the use of the words “adhesion” and “cohesion”.



(a) (b)

Figure 2. Cohesion failure surfaces. The well formed bond (a) shows some light coloration while the highly voided bond (b) exhibits cohesion failure only in the regions where adhesive was present. The pattern is due to the carrier cloth which is approximately 0.5 mm pitch.

Adhesive bonds are very fatigue resistant [16] and only under certain circumstances will a cohesion failure be caused by fatigue. The PABST program [17] showed that provided the joint has sufficient overlap length and thin adherends (typical of aircraft skins), fatigue of the bond is unlikely to occur. The perception that adhesive bonds usually fail by fatigue has been perpetuated by historic FAA endorsed training publications [1] which are still being used as training reference material by some orgainsations [18]. Fatigue failures in adhesive bonds usually only occur where the structure being joined is quite thick and loads high. Fatigue failures always occur in the adhesive, not at the interface, and for film adhesives they usually propagate through the plane of the carrier cloth. Fatigue failures have occurred in adhesive layers which bond boron reinforcements to RAAF F-111 upper wing pivot fittings. Careful examination under a high power microscope can detect localised fatigue striations within the failure surface which are the evidence of fatigue failure (see Fig. 3).

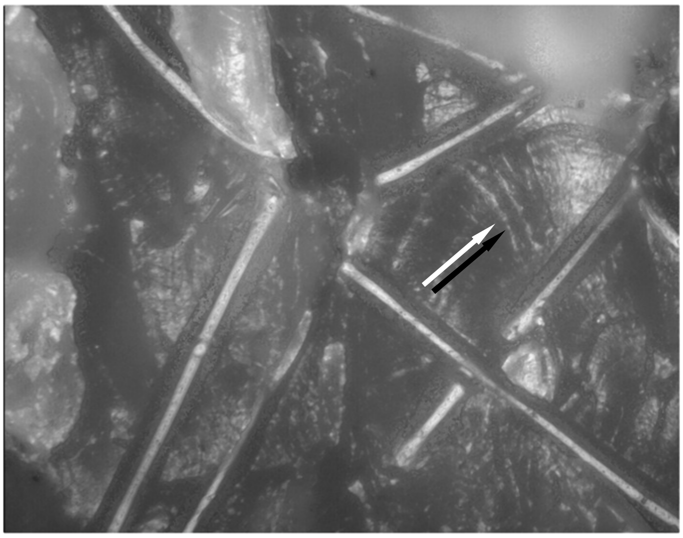


Figure 3. Fatigue striations occurring at the plane of the carrier cloth in adhesive FM73. (Reproduced by courtesy R.A. Pell, AMRL.) The pattern is due to the carrier cloth which is approx. 0.5 mm pitch.

ADHESION FAILURE

Adhesion failures are characterised by the absence of adhesive on one of the bonding surfaces. Failure occurs along the interface between the adhesive layer and the adherends and is due to hydration of the chemical bonds which form the link between the adhesive and the surface. Bonds between aluminium adherends usually fail because the metallic oxide naturally converts to the hydrated form which causes the original adherend/adhesive chemical bonds to dissociate leading to disbonding. Adhesive bonds which are formed on surfaces which are resistant to hydration will be durable.

There are three causes of adhesion failure;

- Failure to generate a chemically active surface due to ineffective performance or contamination of a surface preparation process during production,
- Use of an inappropriate surface preparation technique which is unable to produce a chemically active surface resistant to hydration, or
- The adhesive had cured before the bond was formed.

Any adhesion failure which occurs in service is a direct result of the manufacturing process. Other causes commonly advanced (peel stresses due to operating loads, fatigue, adhesive creep) may contribute to the final separation of two components which would have eventually failed by some other means, but they are not the cause of the premature failure if by adhesion.

In Fig. 4 an example of an adhesion failure on an elevator trim tab hinge attachment is shown. Despite the manufacturer's claims that the failure was due to peel stresses resulting from hinge actuating loads, the absence of significant fracture of the adhesive together with the clear replication of the hinge serial number confirms that this is an interfacial failure due to the surface preparation used during the original manufacturing process.

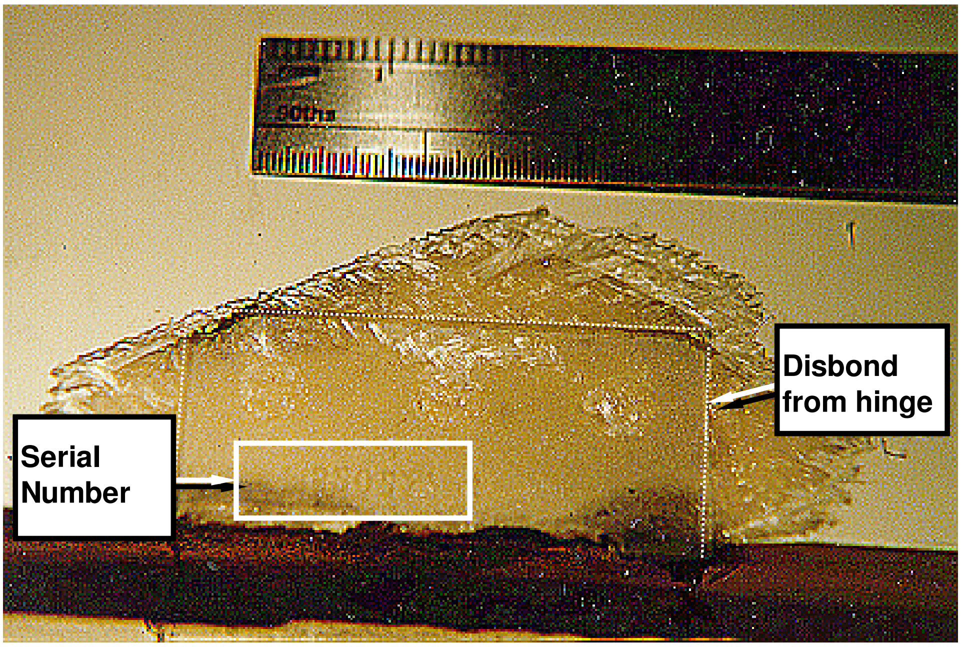


Figure 4. Adhesion failure surface. An elevator trim tab hinge attachment point shows the replicated serial number from the hinge surface cast into the adhesive. (Photograph courtesy Steve Emery, Civil Aviation Safety Authority, Canberra.)

Contamination, out-of-life adhesive and poor processing can usually be detected by low strength of companion coupon lap-shear tests produced during production and better manufacturers have quality systems in place to prevent such failures. Unfortunately, the same production quality systems will pass an inappropriate process provided it is performed well and these are the failures usually detected when in service. If more reliable validation tests (such as ASTM D3762) had been used in process selection, processes which produce inadequate long term durability would be eliminated. There is currently no NDI method to detect deficient bonds which will subsequently fail during service.

Care is required to correctly assess surfaces which show mixed adhesion and cohesion failure. Because interfacial degradation occurs over a period of time, if a partially degraded bond is subjected to a high load then the weakened interface may fail and overload the adhesive in the regions which have not fully degraded. This will give the appearance of a mixed mode failure (see Fig. 5). In joints utilising film adhesives, if the surface has evidence of both failure modes and in the cohesion failure regions adhesive has fractured close to the surface (not in the carrier cloth), then the failure is typically an adhesion failure which has occurred before the interface could fully degrade. True cohesion failures occurs in the plane of the adhesive carrier cloth.

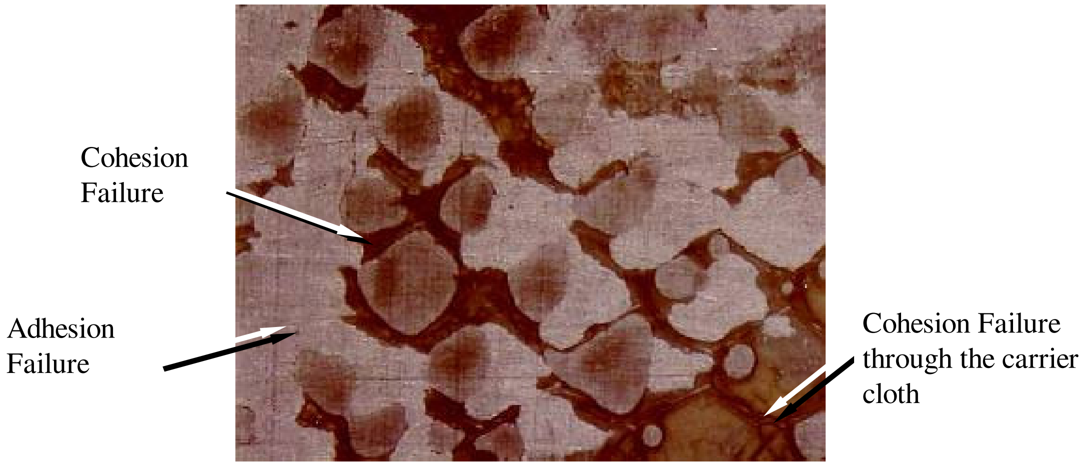


Figure 5. Mixed failure modes. The pattern is due to the carrier cloth which is approximately 0.5 mm pitch.

SANDWICH PANEL FAILURES

Many of the adhesive bond failures which occur in service occur in honeycomb sandwich panels. The honeycomb core is made from thin foils bonded together prior to expansion of the core to form the usual hexagonal cell structure which is then formed into a sandwich structure by adhesively bonding face sheets onto the ends of the core cells. Both adhesive bonds in a sandwich panel can fail. The cell node bonds where the cell walls were bonded together during manufacture of the core material may fail as can the fillet bonds where the adhesive used to bond the face sheets forms fillets onto the cell walls at the end of the core cells. Failures may also occur between the adhesive and the sandwich panel skin (see Fig. 6). These bonds may also experience adhesion or cohesion failure.

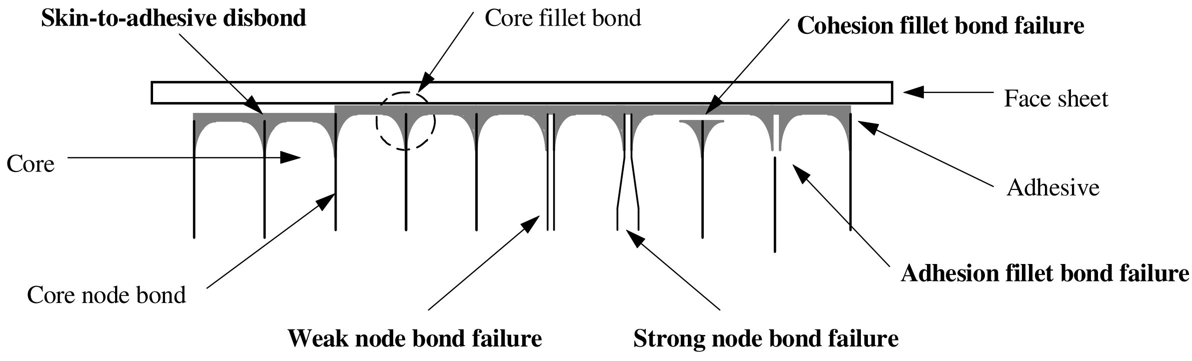


Figure 6. Adhesive bond failure modes for honeycomb sandwich panels.

Frequently, secondary damage such as corroded core will follow after disbonding in sandwich panels. Although corrosion is a common occurrence in service for bonded sandwich panels, repair methodology has usually concentrated on repair of the core rather than identification of the source of the corrosion which is usually moisture entry through a failed bond or through a poorly sealed fastener.

COHESION FAILURES IN SANDWICH PANELS

Cohesion failures in sandwich panels may occur in the fillet bonds between the adhesive and the core or in the node bonds between the cell walls (they are uncommon in the skin-to-core adhesive as the fillet bonds tend to fail at lower loads). Most cohesion failures in sandwich panels are caused by internal pressure during heating cycles associated with bonded repairs. The pressure is caused by entrapped moisture vaporising as the component is heated. When the internal pressure exceeds the flatwise tensile strength of the fillet bond (where the adhesive has wet onto the core cell walls) failure occurs [19] (see Fig. 7). Cohesion failure of sandwich panels may occasionally be caused by impact damage, but only at energy levels sufficient to cause crushing of the core, and the failure occurs by fracture of the fillet bonds. Fatigue is not likely to cause cohesion failures in sandwich panels because the adhesive shear strength is substantially higher than the shear strength of core materials.

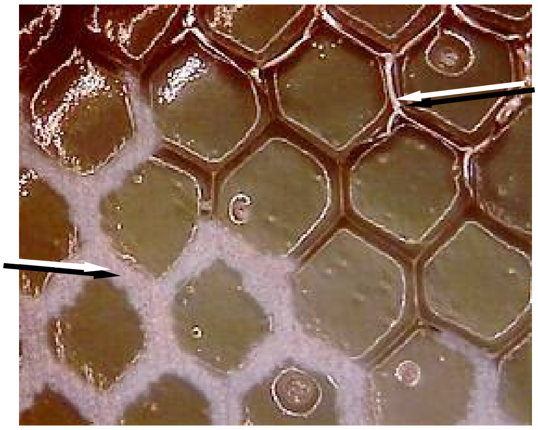


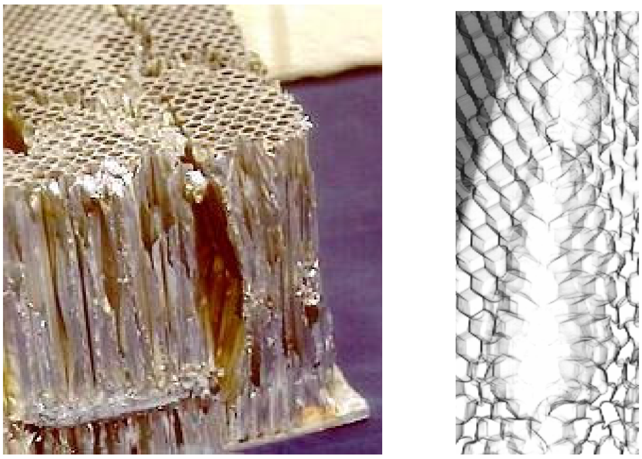
Figure 7. Flatwise tension failure of a sandwich panel. Internal pressure developed during a repair heating cycle causes cohesion failure of the fillet bonds and core cell wall fracture. The pattern is due to the core cells and each cell is approximately 3.2 mm wide.

Occasionally failure of the core node bonds may occur (see Fig. 8) in sandwich panels fabricated from lightweight core,. This is usually a result of internal pressures generated by heating panels which contain moisture. If the failure is a cohesion failure then the cell walls are usually significantly distorted (Fig. 8a). This form of failure (designated here as a “strong” node bond failure) is easily identified from X-ray inspections because of the clear image of the distorted cell walls (Fig 8b).

ADHESION FAILURES IN SANDWICH PANELS

Adhesion failures in sandwich panels may also occur in either the fillet bonds or the node bonds, but may also occur in the skin-to-adhesive interface (see Fig. 9). All skin-to-adhesive failures are invariably a result of adhesion failure, again caused by inadequate or ineffective surface preparation during fabrication. Impact or fatigue will only produce an interfacial skin-to-adhesive failure in a poorly bonded sandwich panel.

Core-to-adhesive adhesion failures are typified by the core cells pulling out of the adhesive fillets (see Figs. 9, 10 and 11). Adhesion fillet bond failure is of concern because the flatwise tensile strength of the core-to-adhesive bond may degrade by as much as 90% [20] in susceptible panels. Several in-flight failures of fixed panels and control surfaces caused by adhesion fillet bond failure have been reported [20]. Because the core appears to be in good condition (see Figs. 10a and 11a) technicians often attempt to rebond a repair to the existing core. However, unpublished results of tests [21] show that poor flatwise tensile strength results from bonds formed on core which has previously experienced adhesion fillet bond failure as a hydrated oxide layer already exists on the surface and it is very difficult to remove this layer or perform adequate surface protection prior to re-bonding. The only remedy is to replace the existing core.



(a) (b)

Figure 8. A "strong" node bond failure in a honeycomb sandwich panel. The high node bond strength results in crippling of the cell walls. The X-radiograph (b) shows the cell wall failures seen in plan view.

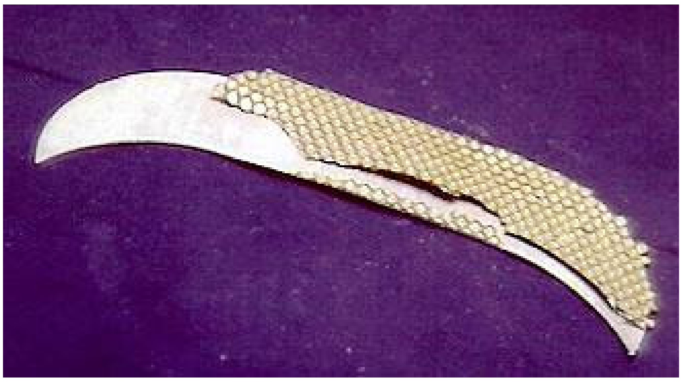
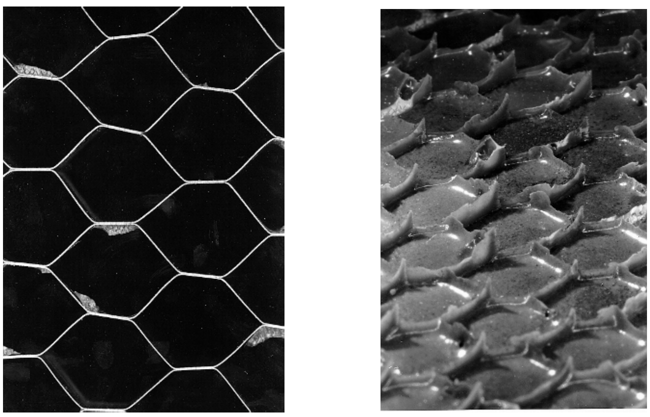
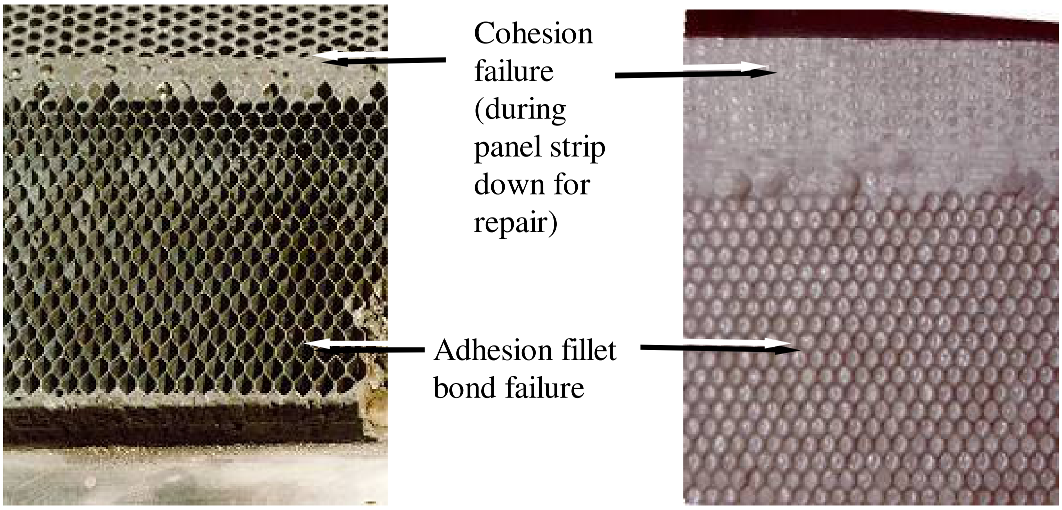


Figure 9. Skin-to-adhesive cohesion failure in a sandwich panel. Note that the component also presented a core-to-adhesive fillet bond failure.



(a) **(b)**

Figure 10. Core (a) and adhesive (b) surfaces after adhesion fillet bond failure. Note the minimal amount of cohesion fillet bond damage to the adhesive (b). (Photographs courtesy of R.A. Pell, AMRL Melbourne.)



(a) **(b)**

Figure 11. Disbonded sandwich panel: core (a) and skin (b). Note the different failure modes with adhesion failure of the fillet bonds leaving no trace of adhesive on the core cell walls.

If the cell node bonds are degraded then a "weak" node bond failure occurs (see Fig. 12). This is characterised by separation at the node bonds, but because these occur at lower internal pressures, the cell walls are barely distorted [20]. These failures may only be detected by careful examination of X-radiographs (see Fig 13).

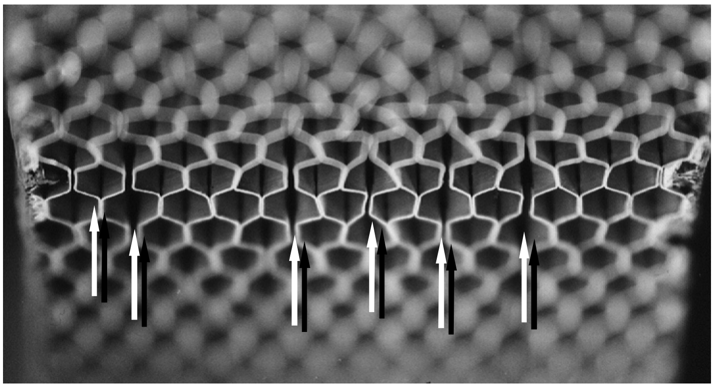


Figure 12. A "weak" node bond failure in a honeycomb sandwich panel. The comparatively lower pressure to fail the node bonds produces minimal cell wall distortion.

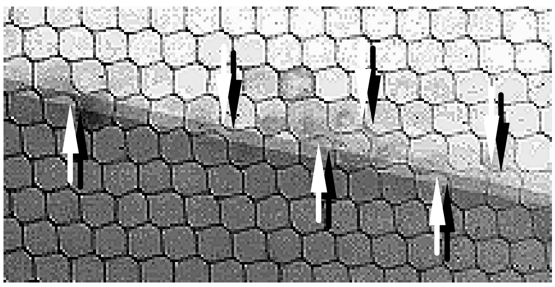


Figure 13. An X-radiograph showing weak node bond failures.

FAILURES IN BONDED REPAIRS

Failure modes for bonded repairs are the same as for bonded structure; either by cohesion or adhesion failure, with most failures occurring by adhesion failure due to the ineffectiveness of approved surface preparation procedures (see Fig. 14). A significant reason for the poor standing of adhesive bonding within some areas of the aerospace community has been the occasional exceptionally poor performance of adhesive bonded repairs, even when these repairs have been performed in accordance with aircraft structural repair manuals [9]. An example of this lack of confidence is the USAF mandate that all bonded repairs must be able to carry ultimate load *in the absence of the bonded repair* [7]. In contrast, the RAAF, using their own bonding procedures and extensive trade training, have used adhesive bonded repairs for cracked metallic aircraft structures since 1975, with great success and have achieved large savings in aircraft maintenance costs, even on cracks in primary structure [22]. Bonded repair failures are often discounted by manufacturers on the basis that the repair was installed incorrectly and this is an argument which is difficult for operators and repair stations to refute. However, RAAF experience suggests that the surface preparation processes recommended by some manufacturers are often inadequate for the repair requirements. This, when combined with the limited training of most technicians installing such repairs almost guarantees an unsuccessful bond. Consequently, there is a requirement for original equipment manufacturers to provide evidence that their approved repair methods are valid and provide a durable repair and an equal requirement for maintenance organisations to ensure that their staff are adequately trained in the installation of such repairs.

Figure 14. An adhesively bonded patch which has suffered adhesion failure in service.

Repair manual procedures often rely on fasteners as well as adhesive bonds to attach a repair. Such a practice is futile because while the bond is effective, the adhesive carries almost all of the structural loads and when the adhesive disbonds, the fasteners act as stress concentrations which may lead to fatigue cracking which may propagate outside the repair zone [16]. In sandwich panel repairs, fasteners provide a moisture entry path into the core, leading to corrosion (see Fig. 15) and an increased chance of bond degradation. Ironically, repairs to this type of structure have typically concentrated on repairing the corrosion rather than identifying the real cause of the defect which was the inadequate bond design/manufacture which necessitated the fasteners.

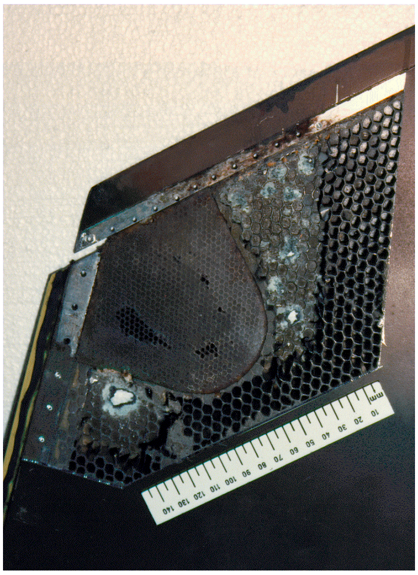


Figure 15. Corrosion damage in a sandwich panel caused by moisture entry through the fasteners.

Injection "repairs" of adhesive bonds are common practice throughout the aircraft industry and appears in almost all structural repair manuals. These repairs attempt to rebond failed adhesive bonds by drilling small holes through to the bondline into which is injected new adhesive. The authors suggest that it is impossible to re-develop a durable bond in a disbonded region that has suffered an adhesion failure as the surface is chemically inactive and requires extensive surface preparation. All that is achieved by this practice is that the defect is filled with ineffective adhesive to the extent that the void can no longer be detected by NDI. There may be some benefit to this process for a region which has suffered a cohesion failure although this necessitates being able to determine the failure mode. The ineffectiveness of injection repairs to adhesion failures may be seen in Fig. 16 where a replicate of the failed bonding surface has been formed in the injected adhesive by later adhesion failure between the old adhesive and the injected material.

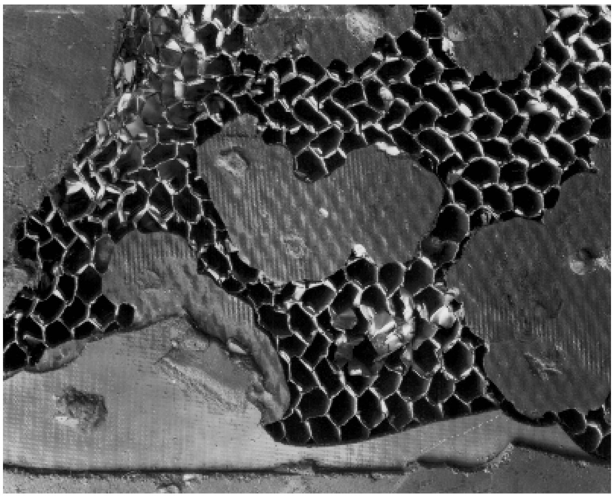


Figure 16. A failed injection repair showing the replicated impression of the surface which had disbonded prior to the injection repair.

Service exposure of panels repaired by injection frequently results in moisture entry through the injection holes and the initiation of corrosion damage (see Fig. 17). Repair of secondary damage due to past injection repairs constitutes a major proportion of the bonding workload in support of RAAF F-111 aircraft and as a consequence a proposal to prohibit injection repairs is being considered.

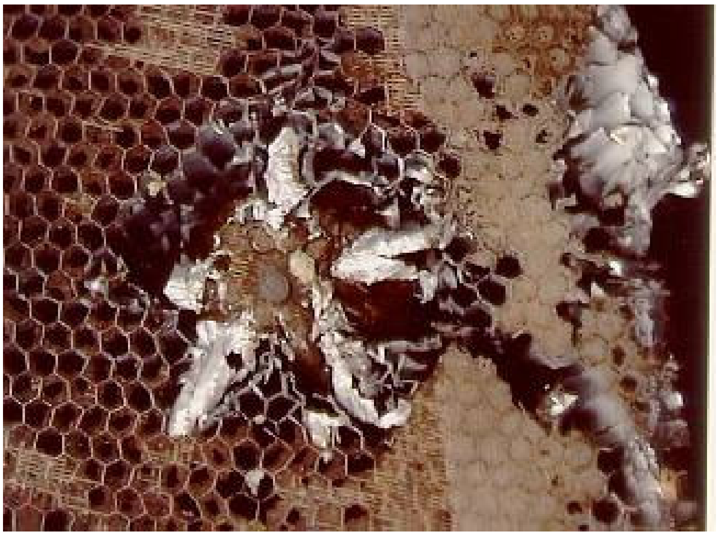


Figure 17. Corrosion damage due to a previous injection repair in a honeycomb sandwich panel.

DISCUSSION

The data presented shows that adhesive bonds fail by either cohesion or adhesion failure. Cohesion failures are characterised by the presence of adhesive on both surfaces, the causes of which are summarised in Table 1 along with the related design issues which should be considered by certification requirements for bonded joints.

Inadequate overlap length	Poor design
Peel stresses	Poor design or service incidents
Fatigue	Poor design (attempting to bond adherends which are too stiff) (Rare in well designed joints.)
Excessive void content	Moisture contamination or poor pressurisation during production
Impact	Service incidents
Skin-to-adhesive failure in sandwich panels	Internal pressure exceeds flatwise tensile strength

Table 1. Causes of cohesion failures.

Adhesion failures are characterised by the absence of adhesive on one of the adherend surfaces and a replication of the surface from which the bond has separated on the other. Adhesion failures occur because of poorly prepared bonding surfaces, selection of a surface preparation process which is incapable of producing a durable bond, or due to use of adhesive which has cured before the bond was formed. These are manufacturing issues, not related to service incidents. If operators recognise the distinct features of adhesion failures and are aware that they can only be caused by production deficiencies, market forces would encourage manufacturers to select only reliably validated processes with stringently enforced quality management systems to guarantee bond integrity. Unlike issues which cause cohesion failures, adhesion failures are not eliminated by existing certification test requirements. Inclusion of surface preparation validation as a certification requirement is currently being advocated [6, 23, 15].

CONCLUSIONS

Adhesive bond failures should be treated in the same rigorous investigative manner as is applied to metallic failures. By identifying the type of failure from the surface characteristics, the true cause of the failure can be identified and corrective action implemented. The consequences of such action will be that proper design, certification and production methodologies will be adopted to ensure that the true structural capabilities and low maintenance costs, which are possible when the technology is applied correctly, are fully attained.

REFERENCES

1. *Airframe and Power Plant Mechanics, Airframe Section* EA-AC65-15A, FAA.
2. Hart-Smith, L.J., *On the Futility of Performing Local Repairs to Adhesively Bonded Metallic Structures Failing Globally from Environmental Attack,* McDonnell Douglas Paper MDC 94K0100, presented to 16th European SAMPE Conference, Salzburg 30 May-01 Jun 95.
3. Kinloch, A.J., *Adhesion and Adhesives*, p 78, Chapman and Hall, 1987.
4. 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.
5. 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.
6. Davis, M.J., *Deficiencies in Regulations for Certification and Continuing Airworthiness of Bonded Structure*, Int. Aerospace Congress, Sydney 25-28 Feb. 1997.
7. Mazza, J.J. private discussion. Data will be published in 1999 in Handbooks being developed under Wright Laboratories' *Composite Repair of Metallic Structure* program.
8. RAAF Engineering Standard C5033, Logistics Systems Agency, Royal Australian Air Force, Sep. 1995.
9. Davis, M.J., *A Call for Minimum Standards in Design and Application Technology for Bonded Structural Repairs,* Proc. Symp. on Composite Repair of Aircraft Structures, pp4-1, 4-15, Vancouver, Aug. 1995.
10. Askins, B., *Surface Preparation Using the Phosphoric Acid Containment System (PACS),* Proc. 3rd. Int. Wkshp. on Composite Repair of Metallic Aircraft Structures, Ottawa, Sep 14-15, 1993.
11. Arnott, D.R., Rider, A.N., Olsson Jacques, C.L., Lambrianidis, L.T., Willson, A.R., Pearce, P.J., Chester, R.J., Baker, A.A., Morris, C.E.M., Davis, M.J., and Swan, G., *Bond Durability Performance - The Australian Silane Surface Treatment,* 21st Congress of ICAS, Melbourne, 13-18 Sep 98.
12. Kuhbander, R.J., and Mazza, J.J, *Understanding the Australian Silane Surface Treatment,* 38th Int. Symp. and Exhib., SAMPE, Anaheim, 1993.
13. Matienzo, L.J., Shaffer, D.K., Moshier, W.C., Davis, G.D., *Environmental and Adhesive Durability of Aluminum Polymer Systems Protected with Organic Corrosion Inhibitors*, J Mat Sci, v21, n 5, May 86 pp 1601-1608.
14. Hart-Smith, L.J., "Effects of Flaws and Porosity on Strength of Adhesive-Bonded Joints", Douglas Aircraft Company Report MDC J4699, November 1981.
15. Davis, M.J. and Bond, D.A., *Towards an Airworthiness Standard for Adhesive Bonded Structures and Repairs*, ICAF 99, Seattle, July 1999.
16. 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.
17. Thrall, E.W., Jr, *Bonded Joints and Preparation for Bonding*, Proc. AGARD-NATO Lecture Series No. 102, pp. 5-1,-5-89, dated 1979.
18. Australian National Aerospace Trade Curriculum, Volume 2: Structures Maintenance, National Aeroskills Project, October 1994.

19. Perl, D. R., *Evaluation of Damage to F/A-18 Advanced Composite Honeycomb Sandwich Parts Caused by Elevated Temperature Cure Cycles*, 39th Int. SAMPE Symp. and Exhibition, April 1994
20. Davis, M.J., Chester, R.J., Perl, D.R., Pomerleau, E., Vallerand, M., *Honeycomb Bond and Core Durability Issues; Experiences within CREDP Nations*, The Aging Aircraft Conference, Williamsberg, VA, 30 Aug.-02 Sep1998.
21. Arnott, D.R. unpublished data reported at the 14th International Meeting of the Composite Repair Engineering Development Program, San Diego, Nov. 1998.
22. Davis, M.J., Kearns, K.J., and Wilkin, M.O., *Bonded Repair to Cracking in Primary Structure: A Case Study*, PICAST2-AAC6 International Aerospace Congress, Melbourne 20-23 March 1995.
23. Kerr, A., *Certification of Bonded Repairs*, The Aging Aircraft Conference, Williamsberg, VA, 30 Aug.-02 Sep1998.