THE CONDITIONS WHERE NDI MAY NOT PREVENT FAILURE IN REAL BONDED STRUCTURES

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ABSTRACT: NDI of adhesive bonded structures on defence and commercial aircraft are underpinned by reliance on damage tolerance by testing and analysis of bonded joints to establish what are often inappropriately termed "tolerable defect sizes" such that the structure can sustain limit load with that size defect in place. Once analysis and testing have been used to validate a tolerable defect size, NDI methods are developed and NDI test standards are manufactured to enable detection of bond defects to determine the airworthiness of the component. The limitations of this approach for in-service adhesive bonds are not well understood and in some circumstances this approach can lead to a risk to flight safety of bonded structures, and the risk emanates from the interaction between short-term strength and long-term strength loss associates with interfacial degradation.

This paper will outline the relationship between failure modes for adhesive bonds and the load capability of that bond. It will explain the factors which influence the type of failure mode including bond design, materials selection, certification requirements, materials processing, materials handling and importantly the difference between the strength of the bulk adhesive and the strength of the interface, and how these relate to the overall joint load capability. The same discussion is valid for repair processes.

Despite the enormous commitment of resources and reliance on NDI for structural integrity to manage continuing airworthiness of bonded structures, in reality the role of NDI for in-service inspection is only of limited relevance to bond load capability, and under some circumstances can actually provide false confidence that the bond is sound. The gap between analysis and testing of pristine bonds with artificial defects of a known size, (and hence the requirements for NDI procedures and NDI test standard configurations) and what actually happens in real joints under service conditions can mean that under some circumstances failure of a bonded joint may actually occur before the real structure exhibits a defect of the designated tolerable defect size. While research is underway to address the detection of "weak bonds" these programs are not currently mature enough to provide a reliable measure of bond load capability. This paper will identify the conditions where NDI and damage tolerance may provide false confidence in structural integrity of bonded structures, and suggests that where these conditions occur, the only viable method for assurance of structural integrity may be to implement proof testing.

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A case study will be presented to demonstrate that a structure which had been inspected in accordance with the manufacturer's specification several times during the last 90 hours service actually failed, resulting in a fatal crash.

This paper will suggest that the means to control in-service bond failure is dependent on processes at the time of bonding, and if the correct approach to managing prevention of in-service bond failures is applied, the need for ongoing NDI of bonded structures can be dramatically reduced, resulting in a significant saving for aircraft maintenance costs and a significant improvement in flight safety. Adhesion Associates Pty. Ltd. has been working with US and European regulatory authorities to address the fundamental issues of this paper.

Keywords: Adhesive, Bond, Failure, Inspection, Damage Tolerance

1. INTRODUCTION:

For some considerable time, the structural integrity of adhesive bonded structures has been managed by use of NDI to inspect structures for defects equal to or greater than a tolerable defect size which is traditionally established by analysis and structural testing which demonstrates that a structure can sustain limit loads in the presence of such a defect. Typically Finite Element Analysis may represent the defect by disconnection of element nodes to represent the disbond. Testing usually involves the insertion of artificial defects to represent the defect and testing is undertaken to demonstrate that the structure can sustain the required load without failure. While that approach has served the aviation industry well for some time, there have still been examples of failures of bonded structures. In one case a bonded structure which had been inspected several times in accordance with the manufacturer's recommendations experienced in-flight failure resulting in a fatal crash soon after the structure had passed NDI inspection.

This paper will explain how stresses are distributed in adhesive bonds, how adhesive bonds function and importantly how and why adhesive bonds fail. The effects of different failure modes on bond load capability will be discussed leading to an explanation of the conditions where damage tolerance may not be appropriate for management of structural integrity of principal structural elements.

2. ADHESIVE BONDING AND DISBONDING MECHANISMS:

To understand the significance of deficiencies in the current approach to structural integrity management for adhesive bonded structures, it is necessary to understand the fundamental principles of how an adhesive bond functions, and also the mechanism of adhesive bond degradation. Structural adhesive bonds depend directly on chemical bonds formed at the interface between the adhesive and the adherend[1].These bonds are typically covalent, ionic or electro-static molecular bonds which are formed during the fabrication process at the same time as the chemical reactions produce the bulk adhesive material properties. So the load capability of the adhesive bond depends upon two distinct and separate aspects; the strength of the bulk adhesive and the strength of the interface.

Over time in a service environment, both the bulk adhesive and the interface absorb from the atmosphere. The effect of the moisture on the bulk adhesive properties is to cause a slight reduction in the strength of the bulk adhesive which stabilises over time as the adhesive layer becomes saturated. This loss of strength is well understood and is usually accounted for during design and certification testing by establishing the strength of the bulk adhesive from moisture conditioned specimens.

It is the effect of moisture over time on the interface which is not well understood, and it is this mechanism which causes most bond failures which occur in service[2,3]. For adhesive bonds formed on metallic materials the chemical bonds formed at the time the adhesive is cured usually involve reactions with oxides on the surface of the metal. [4, 5] Many metals have an affinity for the formation of hydrated oxides, for example:

$$Al_2O_3 \rightarrow Al_2O_3.2H_2O$$

This hydration can occur at the interface of an adhesive bond while it is in service, with the water absorbed by the bulk adhesive reacting with the oxide layer. If this occurs, then the chemical bonds at the interface between the adhesive and the adherend dissociate to enable the hydration process to progress. This results in interfacial disbond between the adhesive and the adherend leading to a loss of bond strength and possible eventual failure of the joint.

3. BOND FAILURE MODES:

Physical examination of the failure surface can identify the type of failure, which provides a direct correlation with the load capability of the bond at the time of failure. Identification of the failure type also provides evidence on the probable conditions which eventually led to the bond failure. There are essentially three modes[6] in which an adhesive bond can fail (see Figure 1).

- **Cohesion failure**[3], which is a fracture of the bulk adhesive,
- **Adhesion failure** which is a failure of the interface, and
- **Mixed-mode failure** which is a mixture of cohesion and adhesion failure.

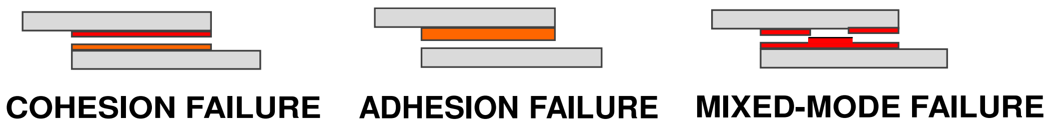


Figure 1: Failure modes which occur in adhesive bonds

Typically, cohesion failures exhibit a high load capability and adhesion failures exhibit a low load capability. In some cases adhesion disbonds have occurred in components without any load being applied[7]. Mixed-mode failures exhibit a reduced load capability which depends directly on the proportion of cohesion to adhesion failure; the more adhesion failure present, the weaker the bond is. It is important to understand that for metallic bonds (and possibly for bonds to composite materials) the driving mechanism is the degradation of interfacial strength driven by moisture. Because the rate of moisture uptake in a bond is dependent on time, it may be seen in Figure 2 that the load capability decays with time since manufacture.

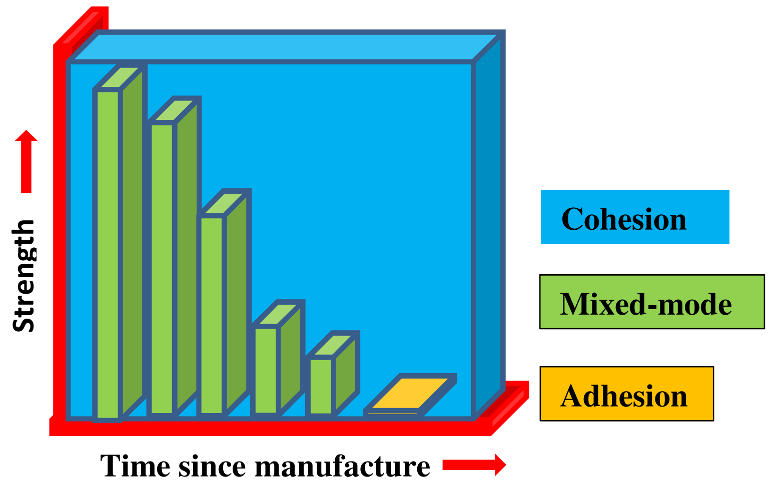


Figure 2: The relationship between load capability and failure modes for adhesive bonds.

4. IDENTIFICATION OF BOND FAILURES:

4.1 Cohesion failures

Cohesion failures are characterised by having residual adhesive on both surfaces as a result of fracture of the bulk adhesive material. Cohesion failures indicate that the overlap length available to carry the loads was inadequate, and there are two causes for such failures; poor design and process induced voiding. For cohesion failures which occur in the absence of voids or porosity, the adhesive fractures because the design was inadequate, caused by inadequate overlap length, poor selection of a weak adhesive or inadequate management of thermal stresses. Cohesion failures in service are caused by overload and therefore are directly related to design or operational issues. In all cases, cohesion disbonds are usually highly energetic and

[3] Note the terminology used here refers to "cohesion" and "adhesion" failures in lieu of the common terminology "cohesive" and "adhesive". The old terminology often led to confusion between "adhesive" failure (interfacial disbonding) and "adhesive failure" meaning failure of the bulk adhesive material. A recent meeting of the FAA Bonded Structures Working Group in Salt Lake City UT 16-18 July 2014 resolved to adopt the above terminology.

invariably result in total separation of the joint. In such cases for film adhesives, failure will occur through the plane of the carrier cloth[6] (see Figure 3).

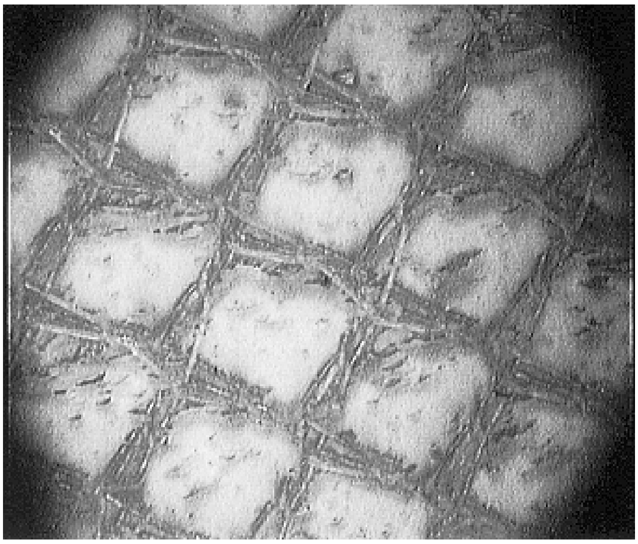


Figure 3. Cohesion failure of an adhesive bond showing that the failure progresses through the plane of the carrier cloth.

4.1.1 Voiding in adhesive bonds:

Processing deficiencies may result in bondline voids which reduces the overlap length, or a defective design process may result in an inadequate overlap length to carry the required loads. The voids may be macro-voids caused by large gaps in the bondline, or micro-voids (porosity) see Figure **4**.

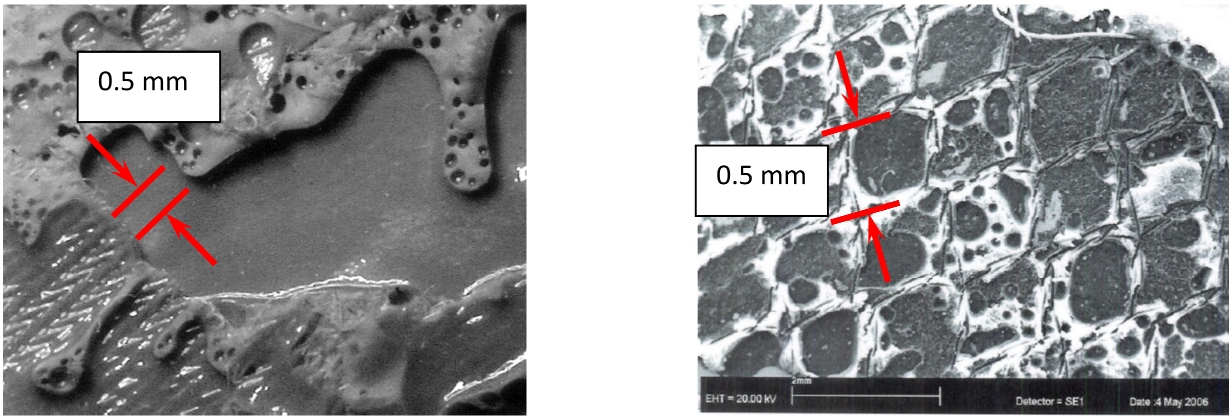


Figure 4: Voids which may reduce overlap length causing cohesion failure. Macro-voids (left) and micro-voids or porosity (right).

The causes of voids are directly associated with production deficiencies. Adhesives exposed to humid environments prior to cure will absorb moisture from the atmosphere and that moisture boils off as the adhesive is heated, leading to the formation of small voids (porosity) or if the amount of water is excessive, macro-voids may form. Macro-voids may also occur due to poor fit-up or poor pressure application. With regard to NDI the detection of macro-voids is exactly what NDI is intended to find and the effects are reasonably well managed by damage tolerance analysis and testing.

The presence of detectable macro-voids in an adhesive bond is therefore one of the conditions in which flight safety IS adequately managed by NDI and damage tolerance.

In contrast, porosity is a lot more difficult to detect and almost impossible to correlate with damage tolerance studies. Testing has shown that significant strength loss[8]] can result from porosity with 53% loss of T-peel strength (ASTM 1876) and 28%

loss of honeycomb peel strength (ASTM D1781). Apart from the difficulty of correlating the overall loss of bond overlap length with the number and sizes of the small voids, another problem with damage tolerance analysis for porosity is that the strength of the adjacent adhesive is assumed to be pristine, when the reference test data clearly shows that the load capability of a porous bond is significantly compromised.

The presence of porosity throughout an adhesive bond is therefore one of the conditions in which flight safety IS NOT adequately managed by NDI and damage tolerance.

4.1.2. Fatigue in adhesive bonds:

It is possible to encounter cohesion disbonding due to fatigue, although this condition is exceptionally rare and will not occur in well-designed bonded joints. Tests[9] show that repeated applications of <u>moderate</u> loads to bonded joints may initially result in some residual offset when unloaded, but this effect may diminish with repeated moderate loads and should not result in fatigue of the bond (see Figure 5) because the damage is not cumulative.

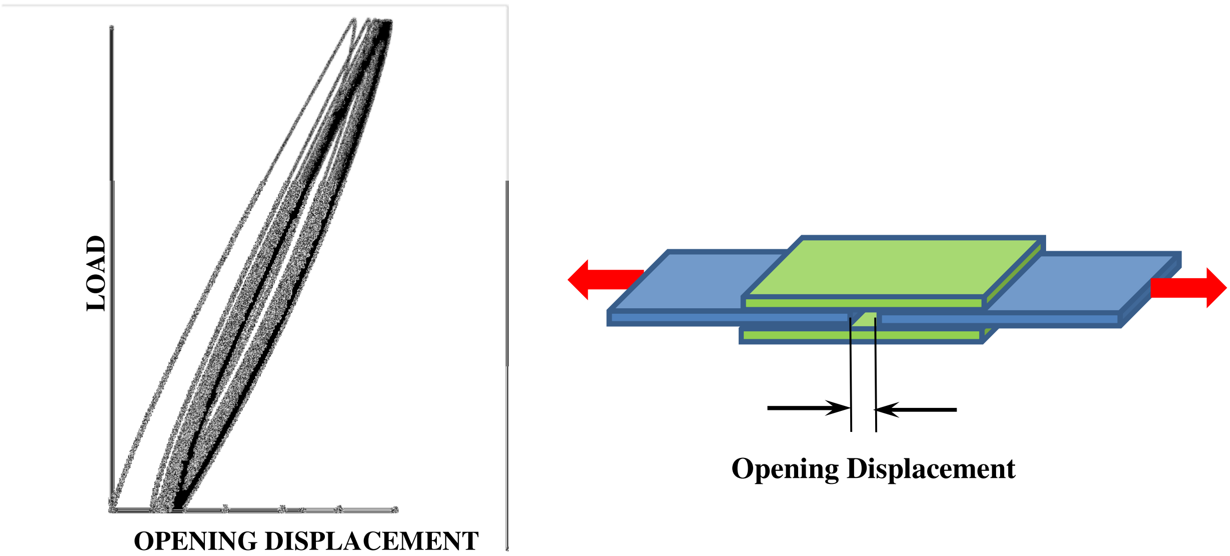


Figure 5: The effect of repeated loads on the opening displacement of a double overlap bonded joint.
Note the offset at zero load after the first cycle, and that the amount of offset reduces with repeated loads.

If failure does occur, fatigue striations are usually evident on the failure surface (see Figure 6). Fatigue may also occur in bonds containing macro-voids or porosity. Fatigue of an adhesive bond in the absence of voids usually only occurs for short-overlap joints or in highly loaded joints between stiff or thick adherends due to poor design practices. Because of the thickness of the adherends and the common complexity of highly loaded structures, most NDI methods such as ultrasonics or tap-hammer inspections tend to be unreliable.

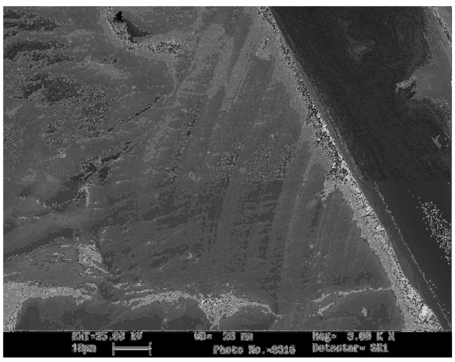


Figure 6. Fatigue striations in an adhesive bond. (Photo courtesy Patrick Conor DTA-NZ.)

4.2 Adhesion failures

Adhesion failures are characterised by total separation of the adhesive from the adherend at the interface (see Figure 7). Adhesion failures are also characterised by an absence of fracture of the bulk adhesive with the failure occurring at the interface(s) between the adhesive and the adherends.

4.2.1. Adhesion failures caused by production issues:

Adhesion failures may also result from production issues. Contamination at the time of production will result in failure to form the chemical bonds at the interface resulting in adhesion failure. In the case of contamination caused disbonds, the defect usually becomes evident in the early service life of the component, once flight loads separate the faces of the "kissing disbond". Similar disbonds can also occur from inadequate cure of the adhesive during the cure cycle but these should be excluded by quality assurance during manufacture.

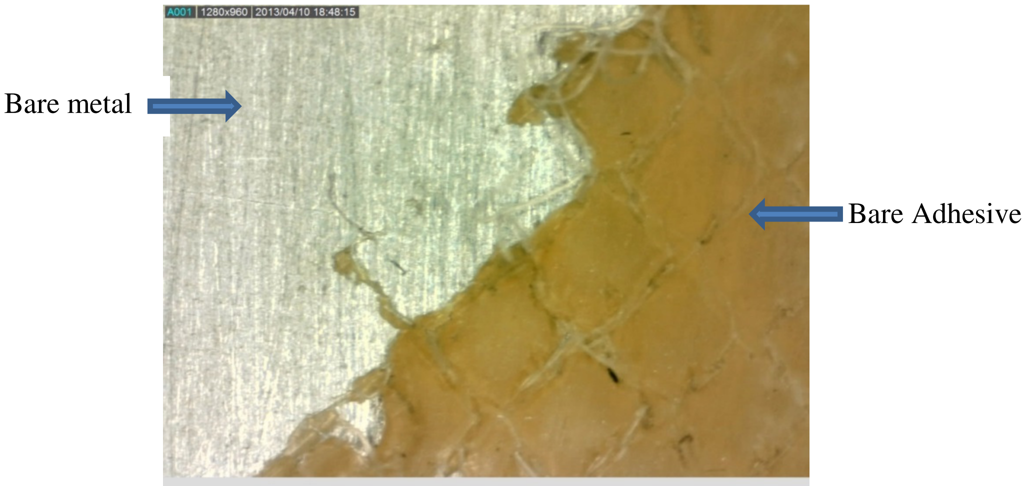


Figure 7: Adhesion failure showing separation of the adhesive from the adherend at the interface. Note the absence of fracture of the adhesive layer and the lack of exposure of the carrier cloth.

The extent of loss of load capability will vary depending on the extent of contamination and the size of the defect. Localised contamination such as from a finger-print which is smaller than the tolerable defect size may have no significant effect on load capability, whereas gross contamination may lead to excessive load capability loss. Unfortunately most current NDI methods cannot easily distinguish between localised disbonds and the initial phases of disbonding caused by gross contamination. Such cases should be managed by repeated inspection of the part at short inspection intervals until arrest of the defect can be confirmed. Any progression of defect growth should be grounds for withdrawal of the part from service, *even if the defect is smaller than the tolerable defect size,* because the limit of the contamination is unknown and the bond adjacent to the defect will not exhibit the strength of a pristine bond.

4.2.2. Adhesion failures detected in service:

In contrast, adhesion disbonds found in later service are almost certainly due to interfacial degradation such as results from hydration of metallic surfaces. Adhesion failures are **NOT** related to fatigue, because fatigue of adhesive bonds due to load should manifest itself as failure through the plane of the carrier cloth in film adhesives, and will only propagate along the interface in bonded joints which already exhibit load capability loss due to interfacial degradation.

In cases where adhesion failure occurs in service, the defect usually initiates at the edges of joints which are exposed to the environment or in sandwich panels where moisture is trapped. As already stated, adhesion failures occur at low loads and in extreme cases total bond failure can occur in the absence of any loads. *These are weak bonds.*

Because current NDI methods can only find adhesion failure related disbonds once there is an air gap, and by that time the interface adjacent to the disbond has already degraded, NDI and Damage Tolerance is of limited value for assurance of the capability of the structure to sustain limit load.

4.3 Mixed-mode failures

Mixed-mode failures (see **Figure 8**) are in reality a direct result of the initiation and progression of interfacial failure such as that caused by hydration on metallic adherends. As the interface degrades the proportion of adhesion failure will increase and the load capability will decrease until eventually some service load exceeds the load capability of the joint and failure occurs. If the degradation is advanced, then failure may occur at a relatively low load. At the extreme case where degradation is complete, the failure is fully adhesion and the load capability of the bond is zero.

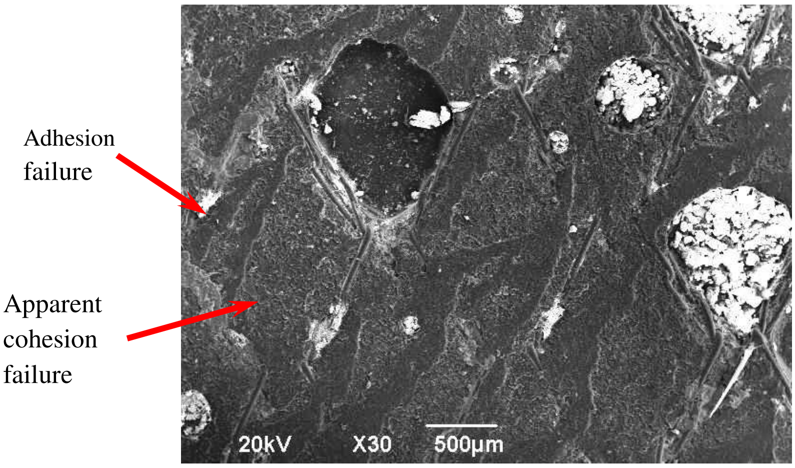


Figure 8: Mixed mode failure showing regions of adhesion failure and *apparent* cohesion failure.

To understand the significance of mixed-mode failures it must be understood that it is a transitional failure mode between cohesion and adhesion failure modes. As interfacial degradation progresses the locus of failure moves from failure through the carrier cloth (cohesion failure as in Figure 3) towards adhesion failure at the interface[6] as shown in Figure 7. Hence the absence of failure through the carrier cloth is a strong indicator of the onset of mixed-mode failure. Conversely, the presence of minor traces of adhesive on the surface of an adherend is NOT evidence that the joint has failed cohesively.

Because current NDI methods cannot detect the degradation of a susceptible interface until disbonding actually occurs and by that stage the joint load capability has already degraded, NDI and damage tolerance are ineffective for management of structural integrity for bonds experiencing mixed-mode failure.

5. STRESSES IN AN ADHESIVE BOND:

There is a common perception that adhesive bonds distribute the load evenly throughout the joint, resulting in a uniform shear stress. A survey[10] in 2004 found that 78% of US manufacturers used this approach to design their aircraft structures by keeping the average stress below a nominal "design allowable" average shear stress despite the fact that it has been known[11] since 1936 that the shear stress in bonded joints is not uniform because as load is transmitted into the adherends the strain in each adherend gradually changes, adding to the relative displacement of the adherends, and it is this relative displacement which causes shear in the adhesive. So the shear strains peak at both ends of the joint and decay in the middle of the joint [4]. If the joint is long enough, the shear stresses may decay to zero (see Figure 9).

The deficiency in the average shear stress design method can easily be demonstrated. If the shear stress was uniform and the overlap length was doubled, then the joint would nominally carry twice the load. In reality if the shear stress in a real joint decays to zero, then any additional overlap simply adds to the zero shear stress portion of the joint and the joint in reality cannot carry twice the load. In fact the average shear stress approach is only valid for overlaps less than the value at which the actual shear stress decays to zero[12] (see Figure 10). The only reason many bonded structures do not fail is because the "design allowable" stress is subjected to significant knock-down factors, and the designs are backed up by very extensive testing as part of the certification process. There are design methods[13] which provide a more accurate representation of adhesive bond shear stresses.

[4] *Note: For simplicity this paper will only discuss the conditions where the adhesive is loaded within the elastic limit.*

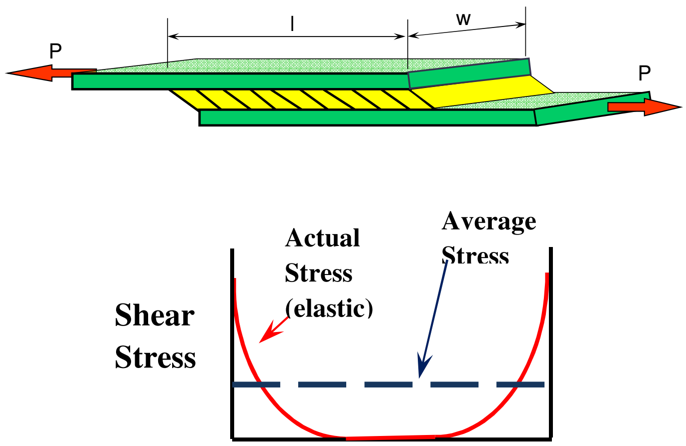


Figure 9: Elastic shear stress distribution in bonded joints.

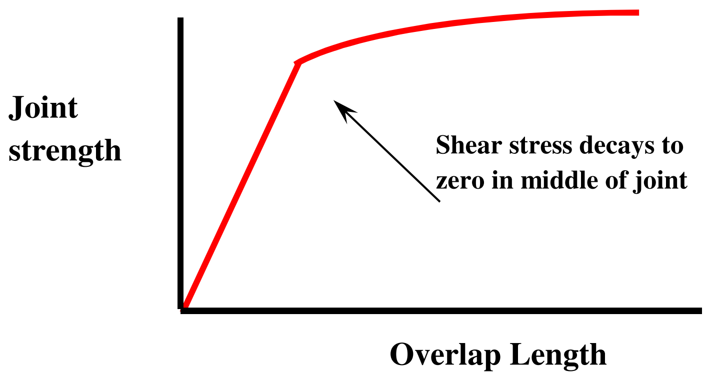


Figure 10: The effect of overlap length on joint load capability.

An understanding of the effects of overlap length is important for NDI considerations because the presence of bond line defects effectively reduces the overlap length. As may be seen from Figure 10 the presence of a bond defect does not necessarily mean the joint is significantly weaker until the size of the defect reduces the overlap length below a length necessary for the development of the zero shear stress trough at which time the joint load capability reduces rapidly.

Because the rate of load capability loss is significant, it is improbable that NDI and damage tolerance will be effective in managing airworthiness for short overlap length joints unless the inspection intervals are short and the failure is fatigue related. If adhesion or mixed-mode failure is involved, NDI and damage tolerance are ineffective for managing airworthiness.

6. REGULATORY ASPECTS:

Current regulations and design methodologies assume that failure will be by cohesion, achieving the maximum load capability for the joint. The role of processes in the development of bond load capability is addressed by FAR 2x.605 where the requirement is that the process used must be known to produce a "sound" structure. However, adhesive bonds which are susceptible to interfacial degradation actually present as a "sound" structure at the time of manufacture which would pass strength testing, but would later be susceptible to failure in service once the interface degrades.

FAR 2x.605 does not preclude the production of an adhesive bond which demonstrates adequate short term load capability but is susceptible to interfacial degradation.

Given that hydration is a primary cause of interfacial degradation[3, 4] and hydration is directly related to moisture absorbed from the environment, the requirements of FAR 2x.603 should address the issue:

> *2x.603 (a) The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must-*
>
> - *(3) Take into account the effects of environmental conditions, such as temperature and humidity, expected in service.*

Traditionally environmental effects on adhesive bonds are assessed by "moisture conditioning" where specimens are exposed in a humid environment until the adhesive absorbs moisture until saturated. While such tests may address the effects of the environment on the bulk adhesive properties, the effect of hydration on the interface would not be obvious for such short-term tests. One test which provides good correlation between accelerated test results and service history is the wedge test ASTM D3762. RAAF and USAF experience[14] with processes validated with this test shows that the test can identify processes which provide excellent long-term durability. The FAA has sponsored a program to revise that standard[15].

Unless certification testing interrogates the resistance of the *interface* to environmental effects, FAR 2x.603 will not prevent loss of load capability due to environmental effects on the interface.

The damage tolerance of adhesive bonds is regulated by FAR 2x.573 paragraph 5:

- *Limit load capability must be substantiated by one of the following methods:*
  - *(i) The maximum disbonds of each bonded joint determined by analysis, tests, or both. Disbonds 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.*

With regard to paragraph (i) above, tolerable defect sizes are determined by analysis and testing and the airworthiness of the structure is managed by inspecting for defects which are larger than that critical size. The approach used to determine the tolerable defect size assumes the adjacent bond is pristine, whereas for cases where the interface is degraded the bond is NOT pristine and hence the load capability is reduced. Therefore the use of NDI and damage tolerance as specified in para (i) is ineffective for management of airworthiness.

If the bond load capability degrades in service then established procedures for assessing bond integrity based on NDI defect size and defect testing will not be able to substantiate the ability of the bond to sustain limit load throughout the life of the structure.

The alternative approach of reliance on proof-testing at the time of manufacture as stipulated in para (ii) above again will not interrogate the potential for the degradation of the interface in service.

The third alternative of direct reliance on NDI is currently unsustainable because current NDI methods are incapable of "ensuring the strength" of bonded joints. Present NDI methods can only provide assurance of the absence of critical defects and cannot currently provide assurance of bond load capability. Research in the development of a capability to use NDI to assess bond load capability will be discussed on page 14.

It may be concluded that the regulatory structure may be interpreted in a manner which fails to prevent mixed-mode and adhesion failures of bonded structures.

However, the regulations are supported by Advisory Circulars which provide guidance on how to interpret and apply the regulations, and the primary document for bonded structures is AC20-107-B. Recent amendments to this document (from –A to –B status) addressed the issue of adhesion failures by advising that adhesion failures during certification testing must be addressed before certification proceeds, and that adhesion failures detected in service require that the component be withdrawn from service until engineering disposition addresses the integrity of the structure. However to date no provision has been made for addressing mixed-mode failures by either regulatory or advisory documents.

The third level involved in managing airworthiness of bonded structures involves the publication of Policy Statements and it at this level that PS-ACE100-2005-10038 provides the first guidance on how to prevent the onset of adhesion failure by direct reference to the wedge test.

At a meeting of the FAA Bonded Structures Working Group in Salt Lake City UT 16-18 July 2014 the FAA announced the proposed development of a new Advisory Circular on adhesive bonding which will specifically address an appropriate methodology for production of adhesive bonds with adequate resistance to interfacial degradation.

7. THE IMPLICATIONS OF MIXED-MODE FAILURE TO DAMAGE TOLERANCE:

There are significant implications of the understanding of mixed-mode failure for management of continuing airworthiness of bonded structures. The flaw in reliance on damage tolerance to manage bonded structures is that the tests and analysis infer that the adhesive surrounding the defect maintains its original strength (see Figure 11(a)) whereas for a bond experiencing progressive interfacial degradation the region adjacent to a disbond will be weak (see Figure 11(b)).

Note that Figure 11 shows ***local*** adhesive strength, i.e. the shear stress at that location at which the adhesive bond would exceed the local strength of the bond. It should be understood that if a load is applied which causes failure at a given point it does not necessarily mean that the entire joint will fail, it means that the failure may exhibit itself as progression of mixed-mode failure. Total failure may not occur because the adhesive ahead of that point may exhibit a higher local strength. The actual load at which the joint would fail (termed the joint ***Load Capability***)[5] is indicated by the area under the curve and this load capability is the value used to assess the structural integrity of the joint.

In Figure 11 it may be seen that the load capability of the joint with a degraded interface is significantly lower than for the defect within a pristine joint, ***despite the fact that the disbond and artificial defect are the same size***.

8. THE EFFECT OF SHORT OVERLAP LENGTH:

A further consideration in this discussion is to combine the interfacial degradation issue with the effects of bond overlap length as shown in Figure 11. If the bond overlap is long, then provided the remaining un-degraded length is large enough then the joint should be capable of sustaining the required loads at the time of inspection, but it must be realised that further degradation is inevitable and will progress until eventually the load capability will reduce to a level which is no longer capable of sustaining limit load.

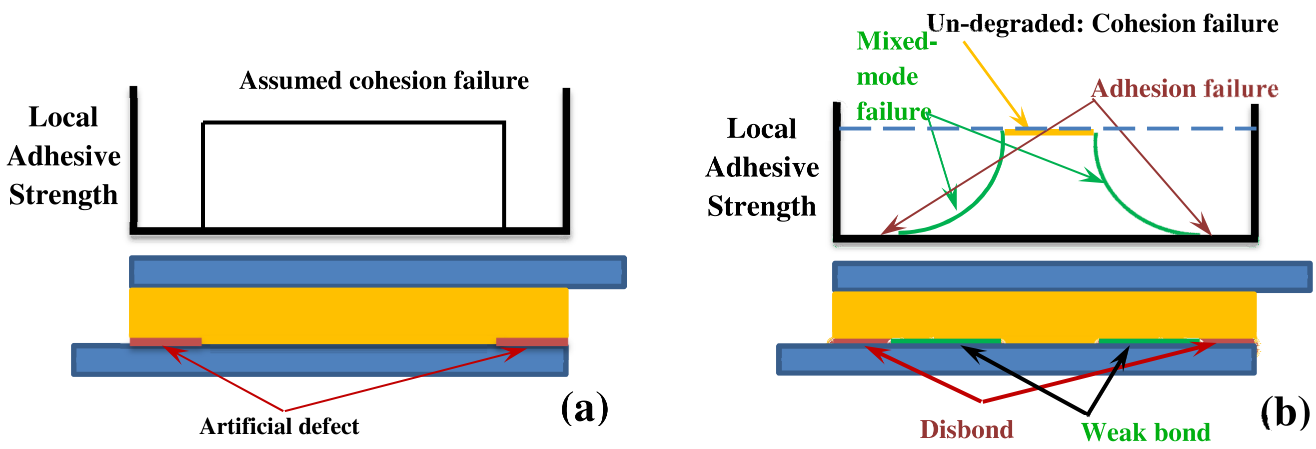


Figure 11: The difference in local bond strength over the length of a bonded joint for (a) artificially created disbond defects which represent production voids, and (b) the same size disbond defect which occurs in service as the interface degrades. *The **load capability** of each joint is given by the area under the curve.*

In contrast, if the overlap length is very short the load capability of the joint may already be inadequate at the time of inspection, even though the detected defect size is less than the defect size permitted by a damage tolerance analysis (see Figure 12). For very short overlap lengths, even the local adhesive strength may be degraded well below the local strength exhibited in a pristine bond. As shown in Figure 12, the load capability may be so low that mixed-mode failure occurs at a low load, ***even though there is no disbond at all***. Therefore for principal structural elements with a short overlap length which are

[5] **Terminology:** Because the actual local strength of a bond changes with position along the bondline, it is necessary to delineate between that local bond strength and the overall strength of the total bond. This can be achieved by referring to the load at which the joint fails as the ***Load Capability***. It is the load capability which is required to exceed limit load.

fabricated using processes which may be susceptible to interfacial degradation there is a real risk to flight safety in managing these structures by current damage tolerance methods. Given that for short overlap lengths, NDI and damage tolerance may not provide adequate assurance of bond strength, the only remaining method for compliance with FAR 2x.573 is proof testing on an on-going basis.

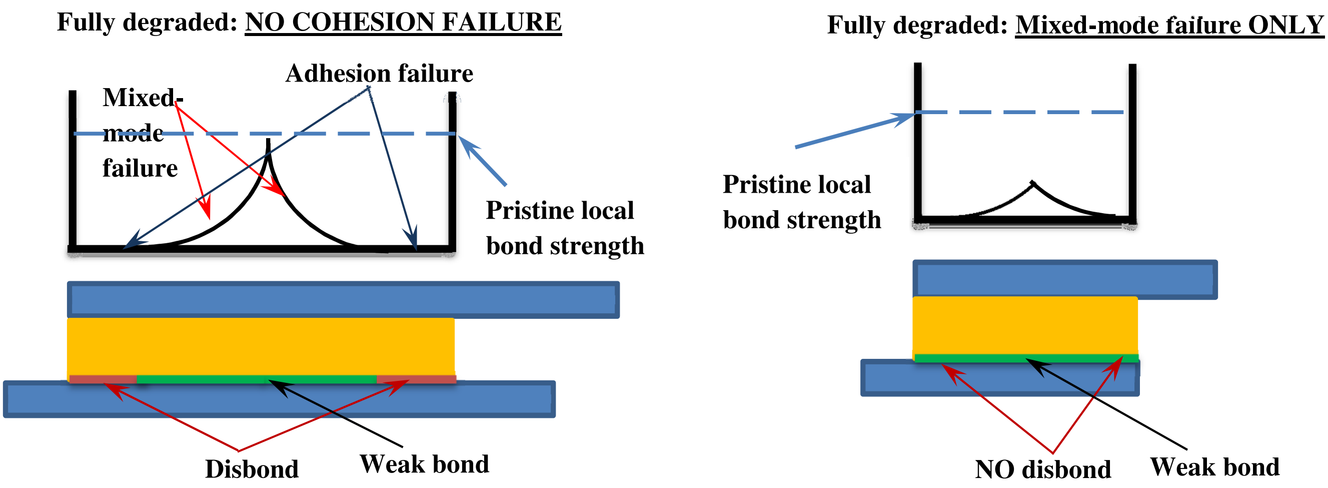


Figure 12: The effect of short overlap length on the load capability of joints exhibiting extensive interfacial degradation. The load capability of each joint is given by the area under the curve.
Note the loss of local strength shown and the possibility of bond failure even when there is no disbond.

Current NDI methods and damage tolerance are ineffective for management of structural integrity of short-overlap bonded joints that are susceptible to interfacial degradation because the load capability of the joint may be exceeded before any disbond occurs.

9. LIMITATIONS OF NDI AND DAMAGE TOLERANCE:

A primary limitation of current NDI methods is that defects can only be detected in cases where an air gap interrupts a return or transmitted signal. Even the simple tap-test is susceptible to this limitation because joints which are fabricated using simple low strength double-sided adhesive tape give the same response as those which are well bonded. Air gaps only exist in *production bonds* if trapped air causes voids. Air gaps only exist in *in service adhesive bonds* once adhesion failure has initiated, and by that stage the bond load capability for short-overlap joints may already be compromised.

The inference from this discussion is that adhesive bond defects can only be detected immediately after production, or once adhesion failure has actually initiated and the adjacent bond is already degraded, and damage tolerance only assumes that cohesion failures occur in otherwise pristine bonds. These limitations are shown in Figure 13.

Current certification methodologies and damage tolerance analysis assume that the bond around the defect site is effective and the failure of the adhesive adjacent to the defect will be by cohesion. It is also assumed that all significant defects can easily be identified by post-production NDI. Because NDI can only detect air gaps, NDI is only of value late in the service life once adhesion failure initiates. *In between these limits, no defect is detectable* so NDI is ineffective even though the load capability of the bond is decaying with time. There is a risk is that the load capability of the bond may decay with time to a degree that flight loads cannot be sustained even though no in-service defect can be detected.

The significance of Figure 13 is that for most of the life of the structure, neither current NDI methods nor damage tolerance procedures can actually address the loss of load capability for the joint. In the meantime, actual service loads can exceed the load capability of the joint before any defect may exist to a size which can be detected by NDI.

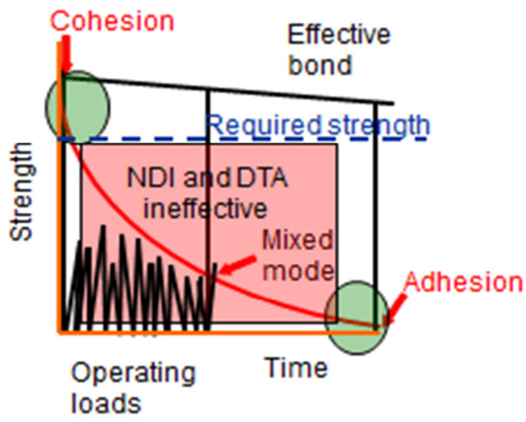


Figure 13: The limitations of NDI and damage tolerance in managing failure of bonded structures.

10. NDI ASSESSMENT OF BOND LOAD CAPABILITY

Research is progressing into methods for providing a measure of relative bond strength, using specialised ultrasonic inspection techniques[16], laser ultrasonics, guided waves, ultrasonic spectroscopy, and resonance methods as well as holographic methods[17]. These methods show potential for addressing the issue of bond load capability in the absence of air gaps. A significant limitation of these methods is that the approaches appear to assume that the *entire* joint exhibits a specific level of weakness, whereas for real joints, the local bond strength varies through the joint. If these methods could be calibrated against the samples of known reduced strength, and then the joint was scanned over the bond length, these procedures could indicate *local* adhesive bond strength which could be integrated along the overlap length to provide an estimate of the load capability of the structure (see Figure 15). Hence it may be possible to correlate the predicted joint load capability based on the total signal output over the length of the joint. Such a development would probably meet the requirements of FAR 2x.573 paragraph 5 (iii) above. This would represent a significant advance in NDI technology.

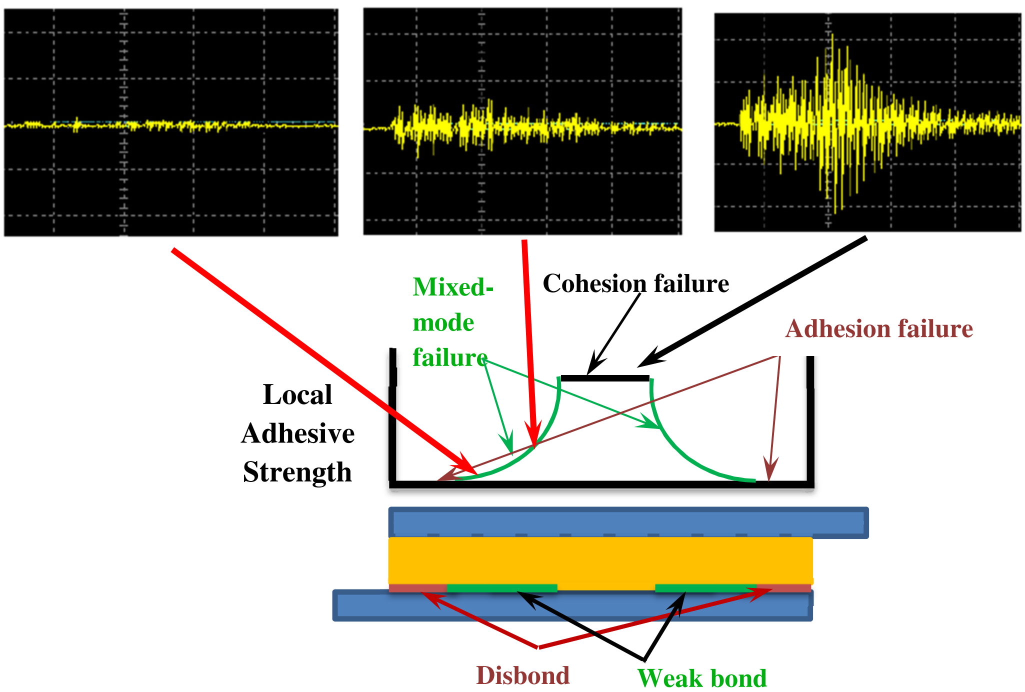


Figure 14: The variation of anticipated through transmission ultrasonic A-scan signal with location along a degrading adhesive bond. (Images courtesy Dennis Roach, Sandia National Labs. [Error! Bookmark not defined.])

11. PREVENTING ADHESION AND MIXED-MODE FAILURES:

For metallic structures the mechanism that drives interfacial degradation is hydration of the oxide layer on the surface of the adherends. There are methods for surface preparation of adhesive bonds such that the potential for hydration of oxide layers is minimised and may even be prevented. *Such bond will be highly resistant to development of mixed-mode and adhesion failures.*

Service experience with the USAF and the RAAF[14] has shown that for on-aircraft bonded repairs the bond failure rate over extensive service exposure is almost zero. Hence, it is possible to produce adhesive bonds which can deliver extended service lives without mixed-mode or adhesion failures.

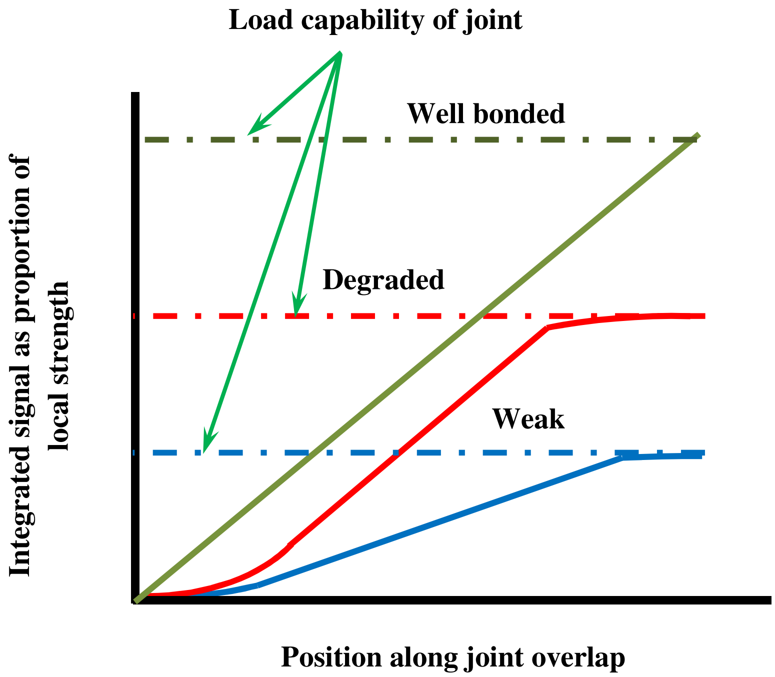


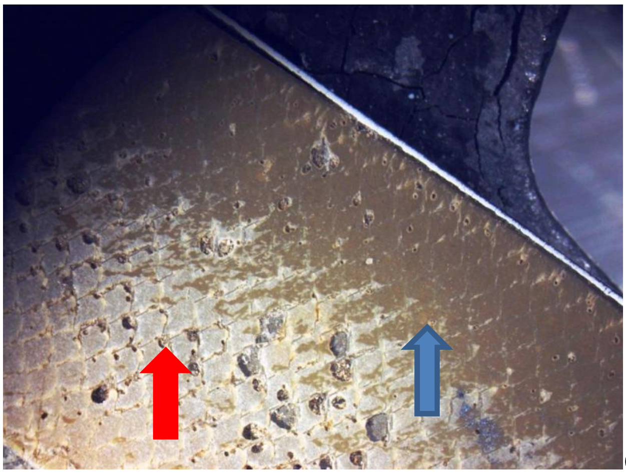
Figure 15: How the integrated local strength of a joint as interpreted from UT through transmission (or any other NDI method) could be used to determine the load capability of a bonded joint.

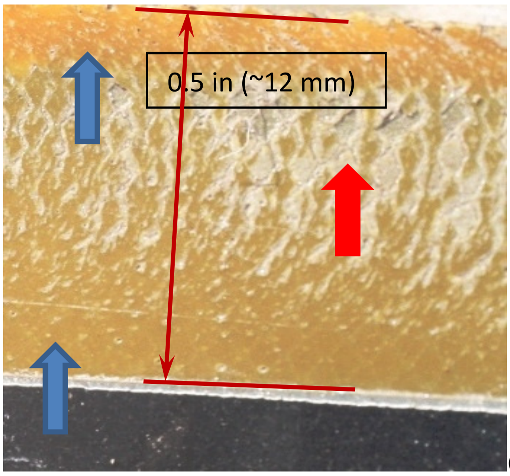
One of the issues in assessing the resistance of interfaces to hydration degradation is that the effects are time related, and hence unless a reliable short-term test can be identified, realistic evaluation of production processes will take the life of the part. The work of the USAF and RAAF identified that the wedge test ASTM D3762 is an effective short-term test which differentiates between poor processes and those which can provide longer-term bond longevity, provided the standard is amended to more adequately identify reliable processes. The FAA has a program underway to prepare such amendments[15].

12. CASE STUDY:

To demonstrate the short-comings of current management practices for adhesive bonded principal structural elements an example of a fatal helicopter crash is discussed. In this case, a well maintained helicopter with an experienced pilot was flying in calm, sunny conditions when one of the main rotor blades broke up in flight causing the aircraft to crash into the sea. The Investigator in Charge (IIC) concluded that the most probable cause of the crash was disbonding of one of the main rotor blades. Examination of the failure surfaces revealed extensive adhesion and mixed-mode failure (see Figure 16) with very little evidence of cohesion failure. In one case the failure exhibited total adhesion failure, (see Figure 17).

The aircraft underwent a scheduled 100 hour service just under 80 hours prior to the crash. The blade was inspected and tap-tested. The blade had been re-examined and again tap-tested about 17 hours after the service when a pilot reported some flight aspects that could not be properly characterised


(a)



(b)

Figure 16: Failure surfaces from bond surfaces of the helicopter blade salvaged after a crash.
Mixed-mode failure is indicated with the red arrow and adhesion failure with blue.
There is no cohesion failure exhibited anywhere on the failure surfaces.

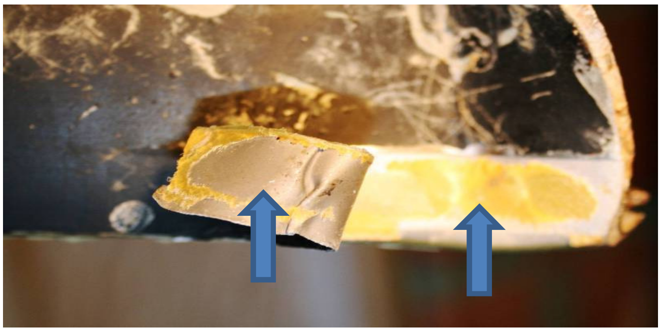


Figure 17: Bond failure surfaces from the crashed helicopter blade showing (arrowed) total adhesion failure.

One bond defect which was within manufacturer's limits was located in a skin-splice area but this defect had not propagated when inspected in a further scheduled 50 hour service, and during the crash the adhesive joint containing that disbond did not fail. No other defects were found in the blade tip or the skin-to-spar bonds when the blade had been inspected visually and by tap-hammer inspection in accordance with the manufacturer's manual in the initial servicing, the unscheduled 17 hour inspection or in the scheduled (visual) inspection approximately 20 hours prior to the crash. Despite being inspected three times within 80 hours prior to the crash (see Figure 18) and no defects being detected in the areas which later exhibited mixed mode and adhesion failures, the IIC concluded that the most probable cause of the crash was that the adhesive bonds in the blade failed, resulting in the crash.

It is significant to note that the nominal overlap length for this bond is 0.5 inches and the tolerable defects size was 20% of the bond. Examination of the failure surface of many bonds such as shown in Figure 16 and Figure 17 clearly shows that the bonds exhibit characteristics which are consistent with substantially reduced load capability (i.e. mixed-mode and adhesion failures) yet all of these bonds actually passed three inspections.

In fairness, there is no way to definitively state if these specific bonds failed as part of the initial blade failure which probably caused the crash, or if the bond failures occurred subsequent to the initiating event, but what can be definitively stated is that there is no question that these bonds would exhibit a load capability well below the original certification load capability. In particular, the region of the bond that exhibited complete adhesion failure (see Figure 17) the load capability would have been substantially lower than the original certified load capability.

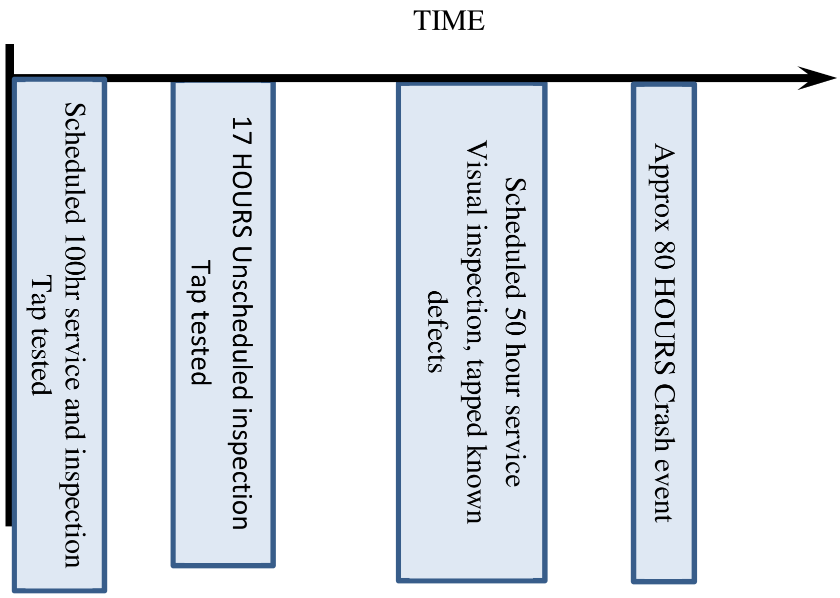


Figure 18: A timeline showing the sequence of three inspections of the blade over the last 80 hours service prior to the crash.

There is no doubt that the forensic assessment of the bond failure surfaces indicates that the bond load capability was significantly lower than the qualified bond load capability. There is also no doubt that the approved NDI methods intended to manage airworthiness failed to identify the significant loss of load capability of these bonds, whether or not they played a part in the actual cause of the crash.

13. CONCLUSIONS:

- The conditions for which NDI and damage tolerance may be unable to prevent failure of a bonded joint are:
  - Adhesive bonds in which extensive porosity is present.
  - Adhesive bonds in which interfacial degradation may occur and where the bond overlap is not sufficient to provide a sufficient reserve of load capability to enable detection of the occurrence of disbonds before the reduced joint load capability is exceeded by flight loads.

  For such conditions, regular and on-going proof testing at limit load in accordance with FAR 2x.573 Paragraph 5 (iii) may be the only method for assurance of continuing airworthiness.

- Current procedures for establishing tolerable defect sizes based on artificial defects in otherwise pristine bonds do not adequately represent the actual strength conditions which exist in adhesive bonds which are experiencing interfacial degradation. As a consequence, NDI based on artificial defects may fail to meet the substantiation of limit load capability requirements of FAR 2x.573 after the part is in service and the interface begins to degrade.
- Both porosity and interfacial degradation are directly related to production processes and can be prevented by:
  1. Elimination of the sources of moisture absorption prior to bonding to prevent porosity.
  2. Selection of surface preparation processes which provide resistance to interfacial degradation, especially by hydration of surface chemical bonds.
- If current research programs actually achieve the "holy grail" of being able to accurately assess the load capability of weak bonded joints in a structure, it may be possible to more accurately manage damage tolerance of bonded structures. If the fundamental causes of adhesion and mixed-mode failure and bond porosity were eliminated at manufacture, the need for a methodology to assess weak bonds would be limited to post-production assessment of contaminated joints. *There would be a significantly reduced requirement to continually inspect adhesive bonds in service.*

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