IS FAILURE FORENSICS MORE IMPORTANT THAN DAMAGE TOLERANCE IN ASSESSING DEFECTS IN DISBONDING STRUCTURES?

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ABSTRACT: Fracture mechanics and damage tolerance analysis have proven to be effective tools for assessment of defects in aircraft structures. However, this paper will assert that the application of these technologies is of value for assessment of the structural significance of defects in adhesive bonded joints and structures in only very specific and restrictive conditions. Further, this paper will assert that the only defects for which damage tolerance is appropriate are those which are detected in post-production inspection. Defects which occur in structures after a period of service are usually those types which do not lend themselves to assessment by damage tolerance.

Central to this assertion is the difference in strength achieved when the failure is by cohesion (fracture of the adhesive layer) and adhesion (failure at the interface between the adherend and the adhesive). Without careful assessment of the failure mode, current attempts to correlate ground-air-ground cycles to damage propagation may be futile because there are documented cases where adhesion disbonding has occurred in the total absence of any flight loads.

In some cases where failure is away from the interface, extensive porosity may (as well as considerably weakening the structure) actually compromise the applicability of damage tolerance. Of importance, the primary tool for implementation of damage tolerance on aircraft bonded structures is Non-Destructive Inspection (NDI). This paper will assert that for structures experiencing adhesion failures or bond porosity, NDI and damage tolerance may in effect unwittingly compromise safety.

This paper will provide an explanation of the mechanisms of adhesion and adhesion failure, and will explain how the occurrence of such defects is driven by processing issues which are in turn driven by limitations in certification requirements. These explanations will also show that one disbond repair procedure in common use is totally futile and totally fails to restore bond strength.

Unless the first step in failure assessment is adhesive bond failure forensics, some analysis, inspection and repair regimes and research programs based on these are meaningless. Considerable improvements in flight safety and substantially reduced maintenance costs could be derived from eliminating adhesion failures and the causes of bond porosity. Ironically, an outcome of this would be the validity of damage tolerance for bonded structures.

INTRODUCTION:

Adhesive bonding as a method for joining and fabricating aircraft structures has been in use for decades. As the use of composite[1] structures increases, so does the usage of adhesive bonding. Service experience has shown that in some cases the structures have performed remarkably well,

[1] The author contends that the use of the terminology "composite" to refer to fibre-composite materials as well as adhesive bonding (composite construction) is inappropriate because the methods for design, analysis and testing and the failure modes are radically different.

but in contrast there have also been examples where bonded structures have performed well below expectations.

As reliance on adhesive bonding for principle structural elements increases, there is an obvious need for development of tools for management of the structural risks associated with disbonding in service. Historically the approach has been to rely on a combination of damage tolerance analysis and in-service NDI to manage structural integrity of structures exhibiting disbonds.

This paper will explain the significance of failure mode analysis (adhesive bond failure forensics) on the methodology for management of structural integrity by demonstrating that all adhesive bond defects are not correctly modelled by a simple “one-size-fits-all” approach to defect causes and methods of damage propagation. The paper will show that the applicability of damage tolerance is in fact restricted to only a few defects which occur in production and has very limited relevance to many defects which occur in service. In some cases, reliance on damage tolerance and NDI for management of the integrity of adhesive bonded structures may be a risk to flight safety.

BASICS OF ADHESION:

To understand why adhesive bonds fail, it is essential to first understand how adhesive bonds work. There are essentially four models for adhesive bonding [1]:

- Mechanical interlocking between the adhesive and the substrate.
- Diffusion of the adhesive into the adherend.
- Attraction due to molecular polarity.
- Chemical bonding at the interface (adsorption).

Without too much effort it can be easily demonstrated that mechanical interlocking does initially appear to provide added bond strength, but service history shows that such bonds may often fail. Given that the surface roughness has not altered, mechanical interlocking cannot be the primary mechanism of adhesion. Chemical diffusion may occur in such cases where solvents are used to bond surfaces on some plastics, the impermeable nature of metals negates the applicability of this model for metal bonded structures. Molecular attraction does provide a level of adhesion between adhesives and substrates, but analytical methods [1] demonstrate that the strength achieved from molecular attractive bonds is insufficient to explain the high strength of effective adhesive bonds.

The only reliable model for adhesion is the adsorption theory, whereby actual chemical bonds (mainly covalent) occur between the adhesive and the adherend at the bond-to-adherend interface. If this model is accepted, then the implications to bonding processes are significant.

It is readily understood that for adequate adhesion, surfaces must be clean. A clean surface is a necessary condition to enable chemical reactions to occur without the presence of contaminants inhibiting chemical reactions. However, a clean surface is NOT a sufficient condition for adhesion. For chemical reactions to occur to a level sufficient to generate adequate chemical bonds, the surface must also be chemically active.

Chemical activity may be generated by processes which remove inert (or relatively inert) surface molecules to expose fresh active surface material. Such processes include simple abrasion, chemical etching or anodising. If the surface is adequately active at the time of bonding (or application of primer) then the adhesive bond will probably demonstrate adequate strength. However, even if the surface is clean and sufficiently chemically active to form strong bonds, this may not be sufficient to assure longer term bond durability and failure in service may still occur, even though testing at the time of production exhibits ideal bond strength.

ADHESIVE BOND FAILURE MODES:

There are essentially two types of failure (see Figure 1): cohesion failure where the adhesive layer is fractured during the failure and adhesion failure where the bond fails along the interface between the adhesive and one of the substrates being bonded. Commonly, a third failure mode termed mixed-mode failure is described as a mixture of cohesion and adhesion failure.

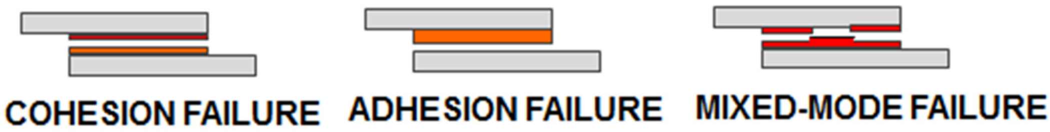

Figure 1. Types of adhesive bond failure.

BOND FAILURE MECHANISMS:

Cohesion Failure:

Cohesion failures result from a fracture of the adhesive layer. This is as a direct result of overloading of the bond.

Adhesion Failure:

For metallic surfaces, long-term bond durability depends strongly on the ability of the surface to resist the effects of moisture absorbed by the adhesive layer during service [2]. Most metals readily form oxides soon after fresh metal is exposed. With many metals and alloys, the surface oxides have a tendency to form hydrated oxides. For example aluminium forms the oxide Al_2O_3, which hydrates over time to form $Al_2O_3.2H_2O$. If an adhesive bond had been formed on the original oxide layer, the chemical bonds between the adhesive or primer and the oxide layer dissociate to enable the hydration process to occur. This results in interfacial (adhesion) failure of the bond.

In the same manner, corrosion of the interface is directly related to hydration of the surface oxide layer. The corrosion is not the cause of the disbond it is a consequence of degradation of the interface.

While there is no current data suggesting that a similar mechanism occurs in composite bonds, there have been suggestions that moisture may play a part in some composite bond failures [3].

Mixed-Mode Failure:

Some adhesive bond failures exhibit a mixture of cohesion and adhesion failure characteristics. There have been cases where such a finding has been interpreted in official investigative reports as being evidence of adequate bond strength because a failure through the interface has not occurred. This is not the case. The reason why mixed-mode failures occur is that the bond has been separated during the period where bond interface degradation is occurring, but before the interface has fully hydrated. The surfaces where hydration has occurred exhibit adhesion failure while the areas where hydration is not complete exhibit partial cohesion failure.

In cohesion failures in film adhesives, fracture usually migrates along the plane of the carrier cloth because that is the weakest plane in the joint due to the reduced bond area and stress concentrations associated with the carrier cloth. An important characteristic of mixed-mode failure is that the failure plane migrates away from the plane of the carrier cloth as hydration progresses. When the interface is fully hydrated, adhesion failure occurs along the interface [4].

EXAMPLES OF BOND FAILURE MODES:

Cohesion failures exhibit extensive separation at the plane of the carrier cloth and are usually high strength energetic failures (see Figure 2). Usually such failures result in catastrophic separation of the joint and are rarely the type of defect which is identified prior to failure, so NDI is of no value for detecting such defects prior to failure. The load to cause failure is usually high compared to other failure modes.

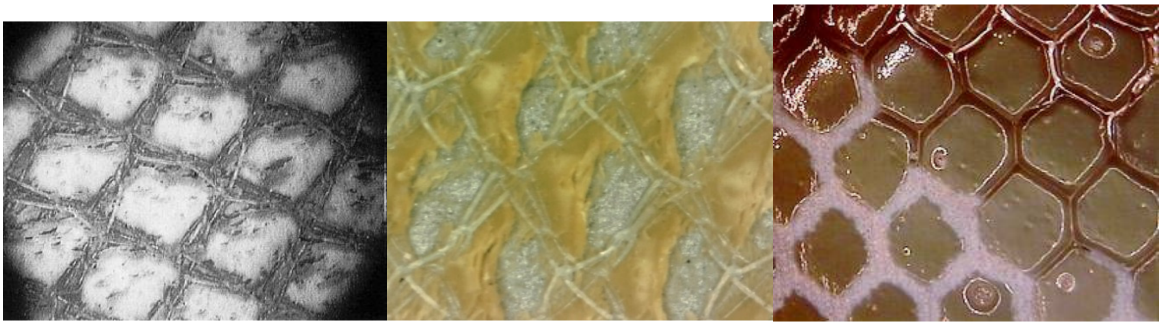

Figure 2. Cohesion failures in adhesive bonds for shear, peel and honeycomb core.

There are two exceptions to this assessment, where the overall strength in a cohesion failure is driven by the loss of bond overlap associated with macro or micro-voids in the bondline (see Figure 3). Macro-voids are large gaps in the bondline and are usually caused by poor fit-up of the joint, inadequate pressurisation and/or excessive evolution of volatile products during elevated temperature cure. Micro-voiding (porosity) is caused by evolution of gaseous materials during elevated temperature curing of adhesives, and the most common culprit is steam (water vapour) released from the adhesive or the surface of the adherend. All epoxy adhesives and composites absorb atmospheric moisture to some extent whenever exposed to the environment. When heat is applied to cure the resin or adhesive the water boils off creating steam bubbles which cause micro-voiding. Note that the application of high vacuum pressure in an attempt to eliminate these voids will exacerbate the problem by reducing the pressure around the bubble, thus increasing its size.

The effect of micro-voiding on shear strength can be significant but the effect on peel strength can be more substantial. Tests [5] have shown a 28% loss of T-Peel (ASTM D1781) for joints but even more significant loss of 53% for climbing drum peel (ASTM 1876).

Adhesion failures exhibit extensive interfacial separation and are low strength failures (see Figure 4). Usually such failures exhibit extremely low strength and in some cases failure has been reported with no externally applied service loads [6].

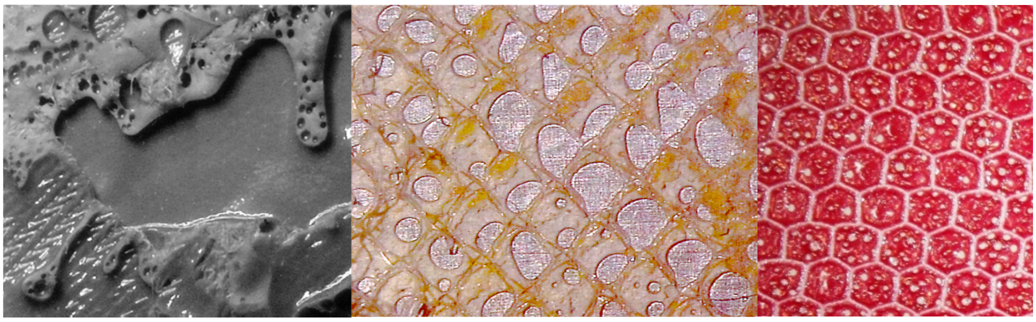

Figure3: Macro and micro-voids in adhesive bonds. A macro-void is shown left, micro-voiding in a bonded joint (centre) and micro-voiding in sandwich structure (right).

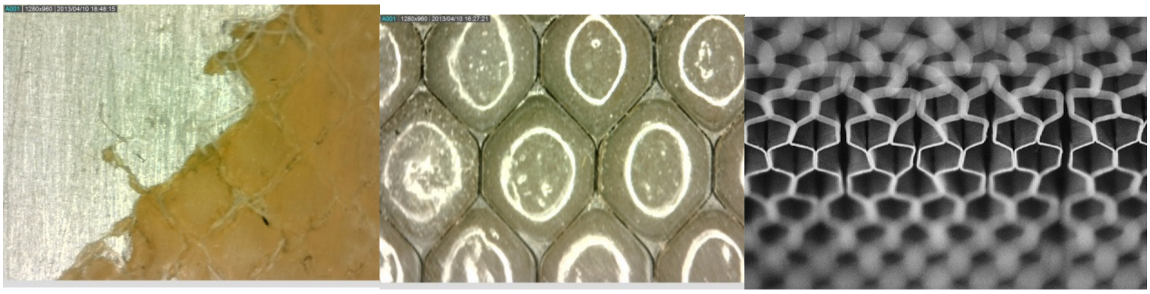

Figure 4: Adhesion failures in adhesive bonds. A bonded joint failure is shown left, and the second picture shows adhesion fillet bond failure for a sandwich structure. The last picture shows adhesion failure of the core node bonds.

Mixed-mode failures (see Figure 5) exhibit intermediate strength, but always below the strength which would be exhibited for cohesion failure. Failure may occur through the adhesive but away from the plane of carrier cloth with a proportion of failure being by adhesion.

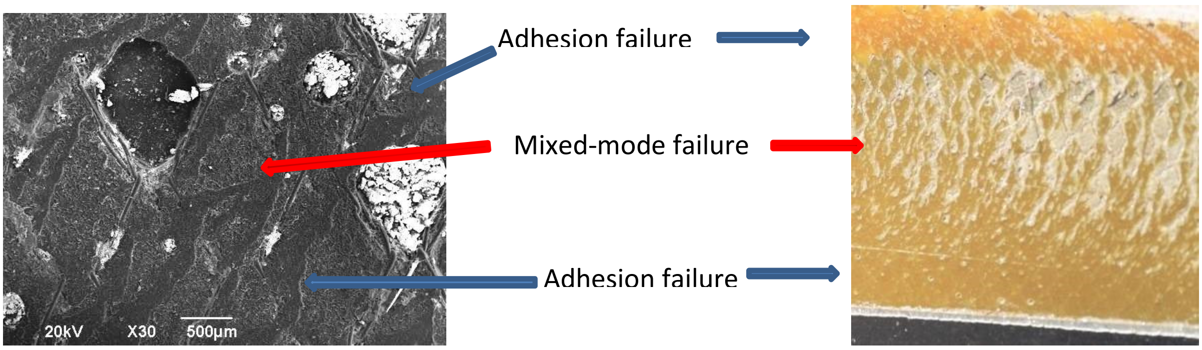

Figure 5: Mixed mode failures

THE SIGNIFICANCE OF BOND FAILURE MODES:

Cohesion failures in the absence of bondline defects exhibit high strengths (see Figure 6) with a slight loss of strength over time due to environmental effects on properties of the bulk adhesive as moisture is absorbed by the adhesive. Such effects are usually addressed by moisture conditioning of specimens prior to establishment of adhesive properties used for design.

The effect of macro and micro-voids is to reduce the bond strength initially, with the level of strength reduction dependent upon the residual bond overlap length. Typical values are shown, but for more severe cases, the strength loss may be more significant. Of importance, macro and micro-voids may be a significant risk under fatigue loading where the residual bond overlap is not sufficient to transfer loads.

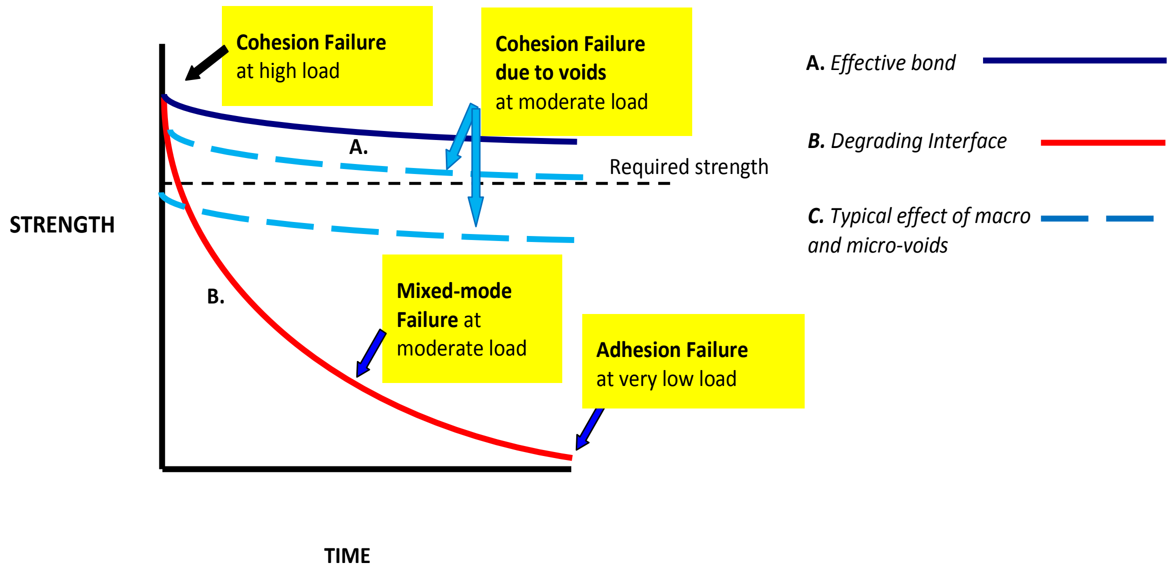

Figure 6: The influence of failure mode over time for a degrading bond. As the failure transitions from cohesion to adhesion failure, the strength decreases as the proportion of adhesion failure increases.

In contrast, the effects of interfacial degradation result in an ongoing loss of bond strength with time. As the interface degrades, there is a transition from cohesion failure to mixed-mode failure and eventual adhesion failure. The proportion of cohesion/adhesion failure gradually decreases as degradation progresses, and there is a matching loss of bond strength. Initially a high level of cohesion failure and a small amount of adhesion failure will result in a small loss of bond strength, but after degradation has progressed, the level of cohesion failure reduces and the level of adhesion failure increases and there is a corresponding loss of bond strength. Eventually the entire interface may fully degrade resulting in complete adhesion failure and a total loss of bond strength. Cases exist [6] where disbonds have been reported even though the component had never been fitted to an aircraft.

The locus of failure is an important indicator of the strength of the joint. High strength cohesion failures occur in the plane of the carrier cloth. Weak adhesion failures occur at the interface and moderate to poor bond strength is exhibited by mixed-mode failures and these usually involve failures between the plane of the carrier cloth and the interface.

It is therefore of critical importance to determine the type of failure which is occurring before any attempts are made to manage the flight safety of structures exhibiting disbonds. This assessment must be based on physical investigation based on principles of adhesive bond failure forensics.

LIMITATIONS OF NDI:

In management of structural integrity of adhesive bonded structures, there is extensive reliance on Non-Destructive Inspection (NDI) to provide assurance of structural integrity for both post-production and in-service defect occurrences. In many cases such a high level of reliance is unfounded. It must be recognised that NDI can only detect air gaps, such as occur in macro-voids. NDI has limited capability in detecting micro-voids (porosity) unless fatigue damage is already occurring and negligible capability for detecting "kissing" disbonds. NDI can NOT indicate bond strength, especially in cases of adhesion or mixed mode failure. NDI is ONLY effective after disbonding has already occurred, because it can only detect air gaps due to disbonding. Therefor NDI cannot find defects in bonds which are susceptible to mixed-mode failure until disbonding actually initiates, or adhesion failure occurs (See Figure 7).

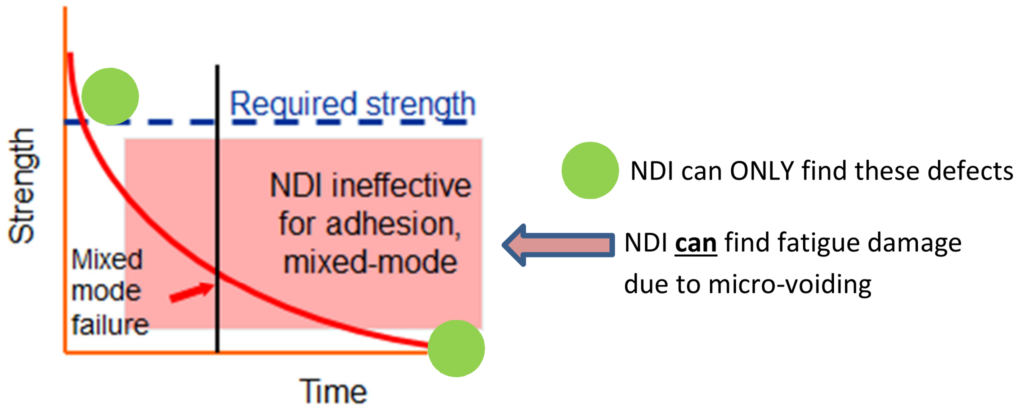

Figure 7: This figure shows the limitations of NDI in managing adhesive bond defects.

It must be clearly understood that only a negative NDI report is valid, because it indicates that disbonding has occurred. A positive NDI report does not necessarily indicate that the bond integrity is sound. It simply means no air gaps were found. It definitely does NOT imply that the bond strength is adequate. The fundamental fact is that NDI is only of value in detecting post-production macro-voids and fatigue damage associated with voids in the bondline.

DAMAGE TOLERANCE FOR MANAGEMENT OF DISBONDS:

Frequently, adhesive bonded structures are managed by damage tolerance. Most analyses and tests for damage tolerance involve the use of artificial defects embedded in the bondline. Testing often involves non-bonding inserts, and FE analyses often disconnect elements to replicate a disbond. **The implication of these approaches is that the adhesive surrounding the defect maintains full strength.**

It must be clearly understood that these methods are ONLY valid for production macro-voids, or with extreme care, localised interfacial failure where there is absolute certainty that the disbond was caused by production contamination. **Every other type of disbond or bond defect is NOT represented by this approach** because the defect type will result in reduced bond strength around the defect (See Figure 8).

Because the adjacent adhesive bond is NOT maintaining full strength, damage tolerance analysis is NOT applicable for:

- Cohesion failure due to micro-voiding.
- Adhesion failure, or

- Mixed-mode failure.

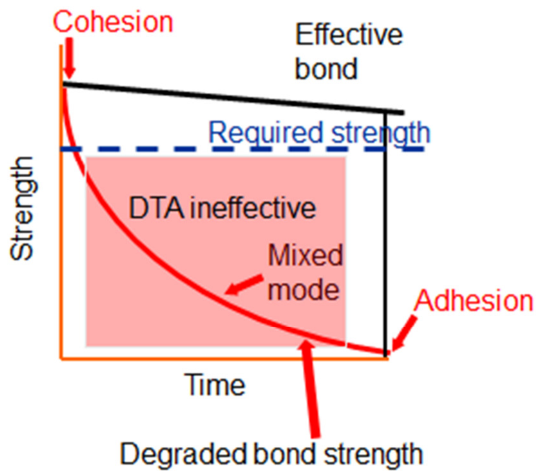

Figure 8: For adhesion and mixed-mode failures, damage tolerance is ineffective for the prevention of bond failure where there is bond strength degradation adjacent to the defect.

For micro-voiding it is impossible to determine by NDI the total size of the overlap length lost by the sum of the micro-void area in a manner which will provide any reliable assessment of the actual defect size after production. Without that information, damage tolerance analysis cannot be used to manage the structural integrity of adhesive bonds experiencing micro-voiding. NDI is a valuable tool in finding propagation of fatigue damage in service but only after the damage has initiated. However, because the strength of the adjacent adhesive bond is significantly lower than for pristine adhesive, damage tolerance analysis is only of value if some allowance has been made for that reduced bond strength.

For adhesion and mixed-mode defects, the bond strength is reduced by interfacial degradation, and therefore an assumption that the adhesive adjacent to any defect maintains full strength it totally invalid.

Unless the type of disbond occurrence is considered in damage tolerance analysis, the outcomes may be grossly unconservative and may constitute a significant risk to flight safety. Therefore adhesive bond failure forensics must be used in conjunction with damage tolerance analysis to manage flight safety of adhesively bonded structures.

BOND FAILURE FORENSICS:

One of the reasons that deficient adhesive bonding processes have not been addressed is that the level of knowledge of adhesive bond failure forensics is relatively low. Even at the highest level of crash investigation, errors are evident in official reports in interpreting bond failure characteristics. Several examples will be presented here. Note that the reports are not referenced. The objective for presenting these examples is to show the level of understanding of adhesive bond failure forensics, not to pillory the authors.

In the first example, artefacts ahead of a disbond were incorrectly identified as evidence of fatigue of the adhesive bond (see Figure 9). Note that the artefacts are located within the adhesive layer roughly in the plane of the carrier cloth. Note also that the actual disbond front was propagating along the interface between the adhesive and the adherend because there is no adhesive on the adherend. It is physically impossible for these artefacts to be of any relevance to the disbond because they are not occurring in the same plane as the disbond.

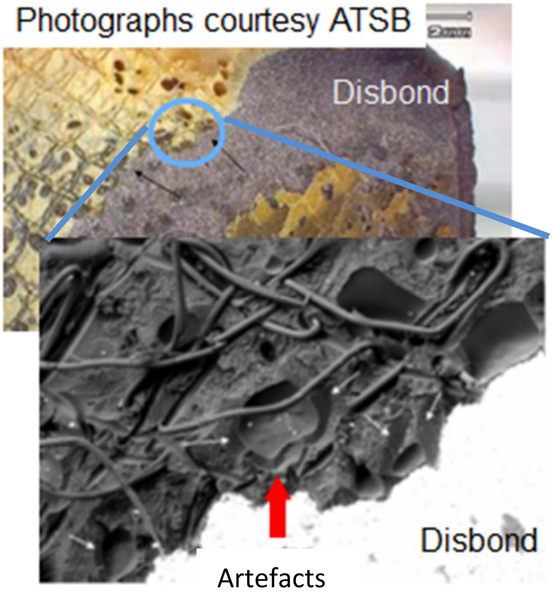

Figure 9: Artefacts in an adhesive bond failure which were incorrectly attributed as evidence that the bond failed due to fatigue.

In a second example from the USA, regions of slight adhesive residue were identified only by use of a microscope, and the failure mode was changed to mixed-more to imply that the bond strength was higher. In reality, if the failure occurs so close to the interface that a microscope is required to find the traces of adhesive, the difference in strength exhibited by the bond would be marginal.

In a third example from New Zealand, examination of a bond failure (see Figure 10) classified the adhesive as a "good" bond, despite the fact that the bond exhibited extensive micro-voiding which would have substantially reduced the bond strength.

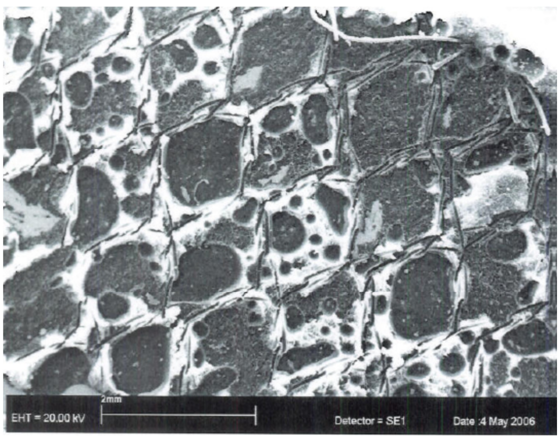

Figure 10: This failure was classified as a "good" bond despite the presence of extensive micro-voiding.

These examples and several others exhibit the fact that the level of understanding of adhesive bond failure forensics is relatively low, even in organisations responsible for high level crash investigations. The lack of effective assessment of the nature and causes of adhesive bond failures is a primary reason why the exceptionally low performance of some adhesive bonded structures has not been corrected before now.

The author has been addressing this subject since 1997 [7] and for a long time the official response has been that there were no reported cases of crashes associated with adhesive bond failures. To place such responses in context, every one of the above examples relate to failures in main rotor blades of helicopters. Main rotor blades are just one example of principal structural elements which rely totally on adhesive bond structural integrity to maintain flight safety.

DEFINING THE ISSUE:

The above discussion shows that for a significant proportion of the life of a bonded structure, both NDI and damage tolerance are not capable of managing structural integrity if the bond is suffering from degradation of strength from interfacial degradation. Figure 11 shows that in cases where the strength decays below the strength required for sustaining operating loads, failure may occur. Note that even at these reduced strengths, NDI may not be capable of detecting any defects, even though the bond strength is well below that necessary to sustain flight loads. As may be seen in Figure 5 the regions of adhesion failure may be intermingled with areas of mixed-mode failure, making NDI detection impossible.

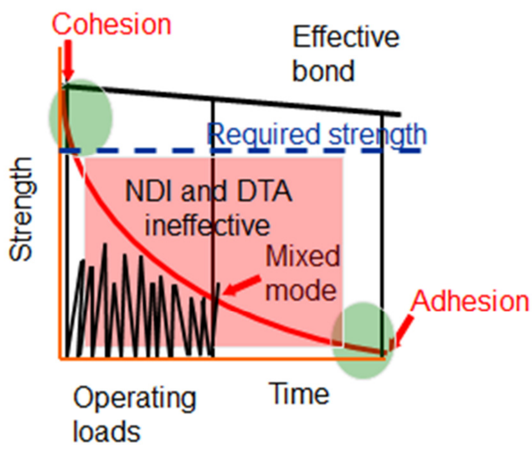

Figure 11: If the operating loads exceed the strength of the bond, failure may occur within the regions where damage tolerance and NDI are ineffective in managing bond defects.

Hence for bonds susceptible to interfacial degradation, if NDI cannot find defects of a size which risks structural failure, and damage tolerance analysis cannot predict bond failure because it is based on the assumption that the adhesive strength is not degraded in service, then it is invalid to rely on NDI and damage tolerance analysis for managing structural integrity of bonded structures.

For micro-voiding whilst it may be possible to find fatigue damage using NDI, the deficiency in the application of damage tolerance analysis is due to the assumption that the adhesive strength adjacent to the defect is the same as the pristine bond. Hence, reliance on NDI and damage tolerance for managing micro-voiding is also invalid.

THE ROLE OF BOND OVERLAP LENGTH:

Environmentally driven bond interface degradation in bonds susceptible to hydration is driven by moisture diffusion through the bulk adhesive material. Therefore disbonding usually occurs adjacent to the edges of joints or other features where moisture may enter the bond. Unfortunately these regions also experience high shear and peel stresses, so disbonding will occur at these locations.

Provided the bond overlap length is large enough, the low stress and low moisture region in long overlaps may enable a joint to carry load even in the presence of a small disbond. It may be possible to detect a disbond before it reaches a critical size (see Figure 12(a)). Such structures can be monitored in service by NDI, but it must be realised that the actual critical defect size may be significantly smaller than that estimated by damage tolerance analysis based on the pristine strength of the bond.

For short overlap bonds there is no margin available and failure may occur before any disbond achieves a detectable size (See Figure 12(b)). Therefore while the current approach based on NDT backed up by NDI may capture disbonds in long overlap joints before critical conditions arise, this is not the case for short overlap joints. Therefore the application of DTA and NDI for short overlap joints is a risk to flight safety.

(a) (b)

Figure 12: The effect of overlap length on moisture diffusion, shear and peel stresses. (a) Long overlap and (b) Short overlap.

LONG-TERM MANAGEMENT OF ADHESIVE BOND INTEGRITY:

If damage tolerance is to be a valid tool for management of adhesive bond structural integrity, then it will be essential to eliminate the occurrence of adhesion and mixed-mode failures and micro-voiding in adhesive bonds. Management of structural integrity of adhesively bonded structures requires a long-term approach to address deficiencies in current processes for structures yet to be manufactured. The objective of this approach would be the elimination of the primary causes of bond degradation in service. This requires management of two issues:

- Elimination of the causes of micro-voiding (porosity) in adhesive bonds, and
- Use of surface preparation processes which prevent the occurrence of interfacial degradation.

Managing micro-voiding:

Micro-voiding is best managed by diligence in avoiding exposure of adhesives, composite materials and adherends only in controlled environments as described in the FAA AC 21-26 Para 8 a 2 (a):

(a) Unless otherwise validated for the material system in use, the area should be temperature and humidity controlled such that the minimum temperature is 65 degrees F with a corresponding relative humidity not greater than 63 per cent and the maximum temperature is 75 degrees F with a corresponding relative humidity not greater than 46 per cent.

Note that the guidance in AC 20-107B Para 6 a (7) b (1) is less prescriptive:

The environment and cleanliness of facilities are controlled to a level validated by qualification and proof of structure testing.

This does leave room for interpretation in a manner which can result in micro-voiding unless the production environment is controlled to the specific conditions used to manufacture the components for certification testing. Regrettably the interpretation often applied amounts to "If I made the test article in my garage, then I can make the parts in my garage" and the temperature and humidity during manufacture are ignored.

There are other issues which can result in exposure of materials to humid environments, for example transport or storage of materials in a manner which fails to prevent moisture ingress. Guidance on minimisation of humidity effects is available at Reference [8].

Prevention of interfacial degradation in service:

For metals, interfacial degradation is primarily driven by hydration of oxides on the surface of the metal. In the process of hydration, the chemical bonds formed with the adhesive during manufacture of the bond will dissociate to enable the hydration reaction to occur. Therefore to prevent adhesion failures it is essential that the process for preparing the interface for bonding must include a process to prevent later hydration in service. The long-term bond durability is established at the time the bond is first manufactured.

So why do bonds formed using procedures which comply with regulations and meet certification testing still exhibit adhesion or mixed-mode failures in service? The reason is that there is no specific requirement to demonstrate long-term bond durability as part of the certification basis for bonded structures. Current regulations require demonstration of static strength and fatigue performance, and the use of processes "known to produce a sound structure". *None of these requirements address the TIME dependent degradation of the bond interface.*

The most significant change which could make a fundamental difference to adhesive bond structural integrity would be to amend FAR 2x.603 to require demonstration that processes used to manufacture bonded structures "*produce a sound **and durable** structure".*

It is possible using rudimentary processes to produce a bond which exhibits initial strength if tested soon after manufacture. The same bonds may still exhibit adequate strength after short-term "environmental conditioning" ostensibly meeting certification requirements, but may still fail in service because of the time necessary for hydration to progress. In essence, current testing methods do not interrogate the durability of the bond interface, but rather focus on bond strength at the time of testing.

Clearly hydration is environmentally driven and it is known that hydration effects are more pronounced in tropical environments. While there are regulatory requirements to address the effects of environment, these are usually interpreted as assessing the impact of adsorbed moisture on the properties of the bulk adhesive, where adsorbed moisture causes a depression of glass transition temperature and leads to a minor reduction in adhesive properties. The significance of these effects is only a small fraction of the strength loss associated with interfacial degradation, yet the focus of environmental testing is on assessing moisture-conditioned specimens which have been conditioned to enable assessment of the effect on bulk adhesive properties but exposure is for such a short period of time that hydration effects have not had time to manifest themselves.

Unless the Designated Engineering Representative responsible for assessing certification testing is clearly aware of the difference between the effects of moisture on bulk adhesive properties and the effects of hydration on the long-term degradation of the bond interface, current regulatory controls on assessment of environmental effects will be inadequate.

An accelerated test exists which can assess the effects of bond surface preparation processes on bond durability within a few days. The test is the wedge test ASTM D3762, where samples cut from a coupon are wedged apart using a standard wedge whilst exposed in a hostile environment. However, the acceptance criteria in the current standard have been shown to be inadequate, and an FAA sponsored program at the University of Utah is proposing amendments to the test standard to establish more acceptable criteria. Practical experience with the RAAF and USAF has shown that processes which meet modified criteria have a demonstrated service history with near-zero bond failures or the occurrence of corrosion for twenty five years [9, 10].

Adhesive bonding primers:

Many manufacturers rely on the use of adhesive bonding primers as a principal element of their preparation processes for bonding. While primers may enhance the performance and corrosion resistance of bond interfaces, they are not a panacea for adhesive bond durability problems. Unless the primer itself can form a hydration resistant chemical link with the oxides on the surface of the metal then they too will fail by adhesion at the interface.

Sealing adhesive bond edges:

Many manufacturers and repair stations place heavy emphasis on the use of a sealant barrier around adhesive bonds to prevent moisture degradation. Such measures only slow down the hydration process; they do not prevent it. Moisture already adsorbed by the adhesive prior to the application of sealant, and any moisture which may diffuse through the sealant are usually sufficient to initiate hydration of susceptible bond interfaces. Sealants alone will not prevent eventual hydration and consequent bond failure.

THE COST OF IMPROVED BOND INTEGRITY MANAGEMENT:

In these days of economics-driven engineering decisions, one must assess the impact of improved bond integrity management on the cost of certification of an aircraft structure. In reality the cost is quite small provided adequate assessment of candidate processes is undertaken prior to testing. Clearly if one persists with proving the current approved process is valid in spite of early contrary evidence, then the number of tests and the cost will be extensive. If however evaluation is based on sound knowledge then the number of tests to demonstrate bond durability could be as low as 100 samples. Once that data base is established, only a limited number of tests will be required to establish equivalence for other adherend and adhesive combinations.

Of importance, these tests must be undertaken before any other tests are undertaken as part of the certification process. Unless bond durability is established as the first step in certification then the remaining tests may need to be repeated.

THE PAY-OFF FOR IMPROVED BOND INTEGRITY MANAGEMENT:

To offset the cost of the additional testing it is necessary to assess the value of the outcomes of the establishment of reliable bond durability. Firstly, if adhesion and mixed-mode bond failures are eliminated and micro-voiding is controlled, then the need for frequent and repetitive NDI assessment will be significantly reduced, principally because the only bond failure mode should be by cohesion failure, and that failure mode is amenable to the application of damage tolerance analysis. There will be consequent and significant improvement in component reliability and service life as well as a major improvement in flight safety for bonded structures.

For companies who invest the relatively small effort in *correctly* validating their processes and implementing the outcomes, the return from a reputation as a company that produces reliable bonded structures will be immeasurable.

HOW TO MANAGE EXISTING STRUCTURES WHICH ARE SUSCEPTIBLE TO DEGRADATION

The proposals presented here will address the performance of components manufactured after the production processes are improved. However, the issue of management of bonded structures currently in service must be addressed.

If reliable adhesive bond failure forensics has confirmed that the failure is not due to adhesion or mixed-mode failure and has confirmed that the failure is not related to micro-voiding, then the structure can be managed by application of damage tolerance analysis and NDI.

If reliable adhesive bond failure forensics has confirmed that the failure is adhesion failure at the interface and there is irrefutable evidence of localised contamination, then the structure can be managed by application of damage tolerance analysis and NDI. Evidence to support such circumstances would, for example, be the presence of foreign material included in the bond. In contrast, if adhesion disbonds are occurring at other locations in the same structure (or even other identical parts) then that is evidence of a potential deficiency in the production process and such components must be managed in the same manner as for parts experiencing mixed-mode or adhesion failure.

In cases where mixed-mode or adhesion failures have been identified and in the absence of mitigating factors such as foreign material inclusion in the bondline, then there is no question that the overall strength of the component is degrading or has already degraded to unacceptable levels and there is a real risk of failure at loads below the anticipated service loads. The FAA Advisory Circular AC 20-107B recognises the significance of adhesion failures and advises that structures exhibiting adhesion failures should be isolate, inspected and repaired and immediate action taken to restore the aircraft to an airworthy condition. This approach fails to recognise that adhesion failure is the final stage of a degradation process and mixed-mode failure is almost as significant a risk to flight safety. So is the occurrence of excessive micro-voiding.

Repair of disbonds:

If the reader understands that chemically active surfaces are essential for adhesion, then it is clear that the “standard” practice of injecting paste adhesive into disbonds or voids is totally futile. For production voids, the entire surface of the defect has been fully reacted, so the surface cannot form any meaningful bond to the fresh adhesive. In the case of service disbonds, the failure is almost certainly adhesion or mixed-mode failure, in which case an adequate chemical bond can also not be formed. Figure 13 shows an example of an injection repair to “fix” an adhesion failure between a sandwich panel skin and the adhesive layer. It is obvious that the injected adhesive also failed by adhesion. Note that two attempts to use injection repairs have been made on the right of the picture as indicated by the different adhesive colours. The repair has been undertaken twice because the first repair did not work. The adhesion failure exhibited by all repairs clearly shows that this procedure is totally ineffective.

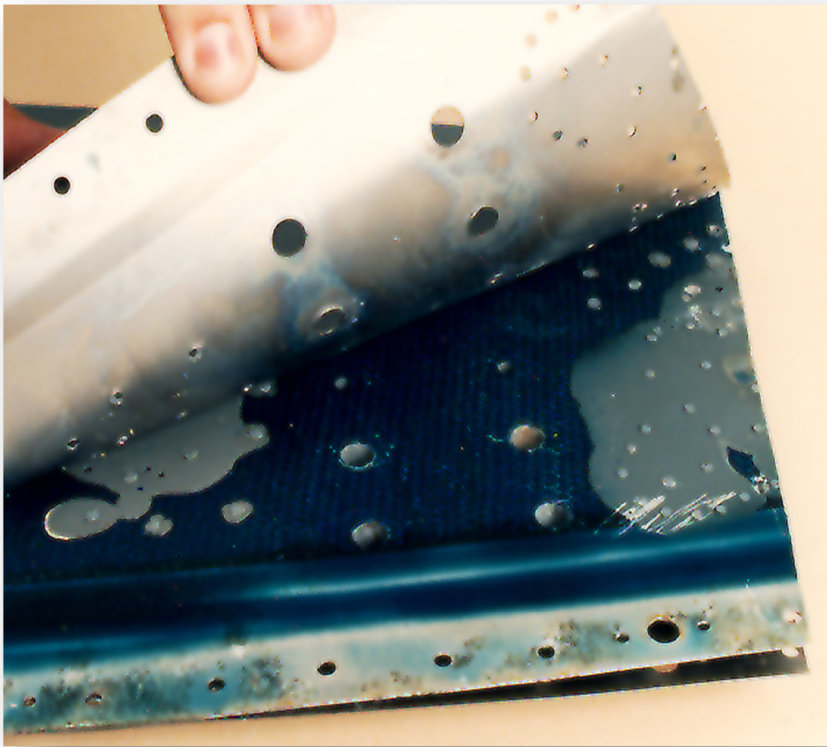

Figure 13: Injection repairs to “fix” adhesion failure of the bond between the skin and adhesive in a sandwich structure.

There are only two outcomes of an injection repair at any stage of the life of a component: the air gap caused by the defect is filled so that NDI can no longer detect a defect and the technician gets a warm fuzzy feeling because he/she has complied with the engineering order. Structurally, this “repair” activity has not changed the strength of the structure at all. *Absence of evidence (NDI can’t find the defect) is NOT evidence of absence.*

There is only one valid applications of injection repair; to hide structurally insignificant macro-voids detected in post-production inspection provided that a damage tolerance analysis has been undertaken to demonstrate that the structure maintains sufficient residual structural integrity. The sole purpose of this “repair” is to prevent repeated reports from in-service inspection. It will not change the strength of the structure at all!

Of importance, injection repairs are often (incorrectly) implemented to address disbonds which occur in service. This practice is a significant risk to flight safety. The author has for over twenty-five years challenged anyone to produce any experimental evidence *whatsoever* (apart from NDI reports) to verify the effectiveness of injection repairs. To date no one has responded.

CONCLUSIONS:

NDI can only find defects which present an air gap. Damage tolerance is based on the fundamental assumption that the surrounding adhesive bond maintains full integrity. The only circumstances where these conditions are valid is for production macro-voids. For all other defects, especially those which initiate in service, NDI and damage tolerance analysis are invalid and may well be unconservative. The only way that some bonded structures are currently managed by damage tolerance and NDI is that the overlap lengths are sufficiently large that defects are detectable by NDI before they become critical to flight safety. For structures with short overlap lengths, there is no margin of safety built into the overlap length such that structural failure may occur before it is possible for NDI to detect any defect.

The specific applicability of damage tolerance and NDI to only macro-voids and under extreme conditions to localised contamination disbonds means that for any bond defect it is essential that the actual defect type is clearly identified before any attempt is made to apply damage tolerance for management of structural integrity of adhesively bonded structures.

Repair of disbonds by injection of fresh adhesive is totally ineffective and this procedure must be prohibited with the only exception being for hiding production defects smaller than the tolerable defect size as determined by damage tolerance analysis.

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