HONEYCOMB BOND AND CORE DURABILITY ISSUES; EXPERIENCES WITHIN CREDP NATIONS

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F/A-18 Composite Repair Engineering Development Program (CREDP)

The Composite Repair Engineering Development Program (CREDP) is an international organisation established to address maintenance issues with composite structures on F/A-18 aircraft operated by the US, Canadian, Australian, Finnish and Swiss Forces, and Boeing St. Louis. This paper describes significant maintenance and possible flight-worthiness problems experienced by some of these operators with honeycomb core sandwich panels. Although the forms of degradation discussed have probably always been occurring in bonded sandwich panels, work at the US Naval Aviation Depot (North Island) has enabled a clearer identification of the damage types such that the significance to maintenance practices can now be more reliably assessed. Other member laboratories are assessing detection methods and damage significance, and developing preventative and corrective measures.

Two separate forms of degradation have been identified; **node bond failure**, where the adhesive bonds which join the core foils together are degraded, and adhesion type **fillet bond failure**, where the adhesive fillets forming the core-to-skin-bond separate from the core. In-flight loss of bonded panels has occurred on USN F/A-18 and RAAF F-111 aircraft due to fillet bond failure, and a number of panels have suffered severe node bond separation during repair heating procedures. Failures are usually associated with a moisture entry path such as drain holes and poorly sealed fasteners. Previous injection and potted repairs (which usually permit moisture diffusion) have been associated with both types of core bond failures on RAAF F-111. Free water has not been found in all cases, so the levels of atmospheric moisture normally absorbed by epoxies may be sufficient to initiate disbonding. While core corrosion may be associated with such failures, it is not the precursor to degradation.

Core bond defects have been detected in most forms of materials typically used for aircraft sandwich panel construction, including both composite and metal faced sandwich panels, and aluminium and Nomex™ core materials. Inspection for these defects is difficult, and only recently has an effective NDI method been found for detecting fillet bond failures. Conventional NDI has not been reliable because there is usually still sufficient contact between the core and adhesive, even when the interface is completely disbonded, to enable transmission of ultrasonic waves. Tap testing and some ultrasonic techniques will detect only a fraction of the size of the degraded area, even in severely disbonded panels. X-Ray and N-Ray techniques can detect moderate levels of moisture and corrosion in sandwich panels.

Most adhesion fillet bond and some node bond failures are interfacial between the core foils and the bond-line or node bond adhesives. In adhesion fillet bond failures, Flatwise Tension Strength has been shown to degrade by ninety percent. Similar strength losses occur in cell-to-cell peel strength for node bond defects, and degraded core cells can easily be peeled apart by hand. Although in most structures, core is usually only carrying low through-thickness shear loads, the loss of strength to the degree noted in tests may have structural integrity implications for critical components. RAAF F-111 and F/A-18 defect reports show that

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[1] The authors listed are reporting the considerable contributions to the subject by a number of researchers from various countries collaborating within the F/A-18 CREDP. The principal author is Max Davis, Aircraft Structural Integrity Branch, Amberley Detachment, 501 Wing, RAAF Base Amberley 4306 AUSTRALIA email <mjdavis@raaf.defence.gov.au>.

the problem may be widespread, and indicate that NDI inspectors and repair technicians are not aware of the significance of the defect type. This paper is intended to raise international awareness of the degradation problem, and to seek input on NDI, structural integrity management and repair procedures from other organisations who have experienced similar problems.

1. INTRODUCTION

The Composite Repair Engineering Development Program (CREDP) is an organisation established to address maintenance issues with composite structures on F/A-18 aircraft operated by the US Navy (USN), Canadian Forces (CF), and the Air Forces of Australia (RAAF), Finland (FAF) and recently Switzerland (SAF). Boeing St. Louis is also involved in the program. This paper is intended to highlight a potentially serious problem which has been raised at the recent meetings of the CREDP [1], relating to the durability of honeycomb sandwich panels on aircraft structures. The issue was raised after a number of failures during elevated temperature repair procedures. Some later in-flight failures of control surfaces fabricated from carbon/epoxy composite face sheets and honeycomb core highlighted the need for a clearer understanding of the problem. The various CREDP member nations have been aware of these forms of degradation for some time, and recent advances have identified a reliable inspection methodology for detection.
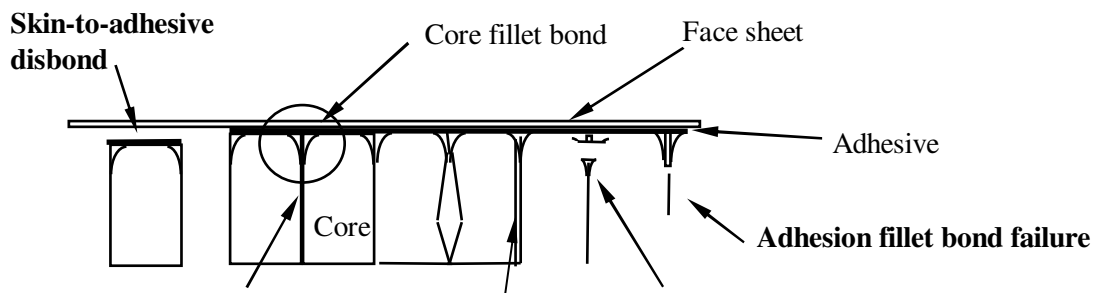
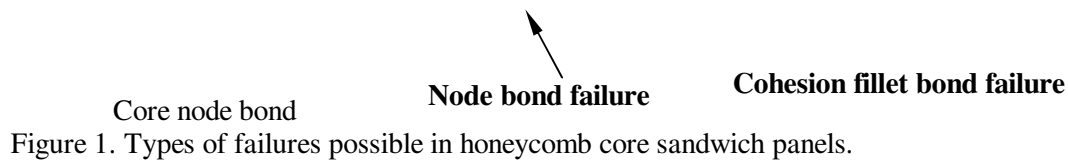## 2. HONEYCOMB CORE AND COMPONENT MANUFACTURE

Most honeycomb core is formed by the expansion process, where thin strips of adhesive are printed onto aluminium foils. The layers of foil are stacked and the adhesive is cured. The consolidated foils are expanded to form the common hexagonal core cell shapes. The aluminium foils may be treated with a corrosion inhibiting layer prior to application of the adhesive or the core may be treated after expansion by immersion in a corrosion treatment solution. The core is then machined to shape and bonded to the face sheets to form the sandwich panel. Apart from solvent cleaning, no surface preparation is possible for the core surfaces prior to bonding to the face sheets during the fabrication process.

3. IN-SERVICE CORE FAILURE MODES

A common form of failure of sandwich panels is due to a *skin-to-adhesive disbond* at the interface between the adhesive layer and the face sheet (see Fig. 1). Most aircraft operators experience this type of failure which typically results in a complete absence of adhesive on the separated skin material. Another common form of failure, *cohesion fillet bond failure,* occurs when the flatwise tension strength (FWT) of the adhesive fillet is exceeded, typically due to internal pressure generated during heating. The adhesive fractures, leaving the adhesive on the face sheet and core cell walls.

However, a number of CREDP members have experienced failures of sandwich panels which exhibit different failure characteristics. Two "new" forms of adhesive bond failures were first observed by Doug Perl at NADEP-NI. The first, termed *adhesion fillet bond failure* occurs at the interface between the core cell-walls and the adhesive used to bond the core to the face sheets during fabrication of the panel. The second form of failure, termed *node bond failure*, results in degradation of the core cell-wall bonds at the cell nodes formed during original manufacture of the core material. These two distinct forms of failure have been observed by the USN on F/A-18 aircraft, and have been detected on RAAF F-111 sandwich panels. Other CREDP members have similar experiences with F/A-18 fibre composite sandwich panels.

Core node bond   **Node bond failure**   **Cohesion fillet bond failure**

Figure 1. Types of failures possible in honeycomb core sandwich panels.

4. CHARACTERISTICS OF CORE FAILURE MODES

Adhesion fillet bond failures are identified by a "slick" separation of the core from the face sheet adhesive layer. There appears to be no damage to either the core or adhesive, with the core cells pulling neatly out of the adhesive layer (see Fig. 2 (a)). Damage to the adhesive layer and tearing of the core is minimal. In contrast, a strong bond between the core and adhesive fails by either fracturing the adhesive or by tearing of the core foils (See Fig. 2 (b)). In some cases of adhesion fillet bond failure, the skin has been removed so easily and the core appears to be in such good condition that technicians have attempted to bond a repair onto the old core (see Fig. 3).

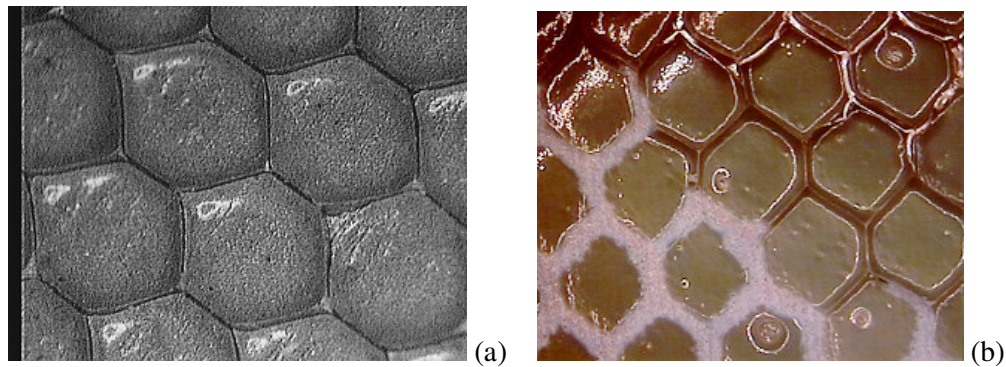(a)   (b)

Figure 2. (a) Photograph of an adhesion fillet bond failure surface from an F-111 glove panel failure, showing the clean separation of the adhesive from the core. (b) The failure surface after separation of an effective bond, with cohesion fracture of the adhesive (lower left) and tearing of the core foils (upper right).
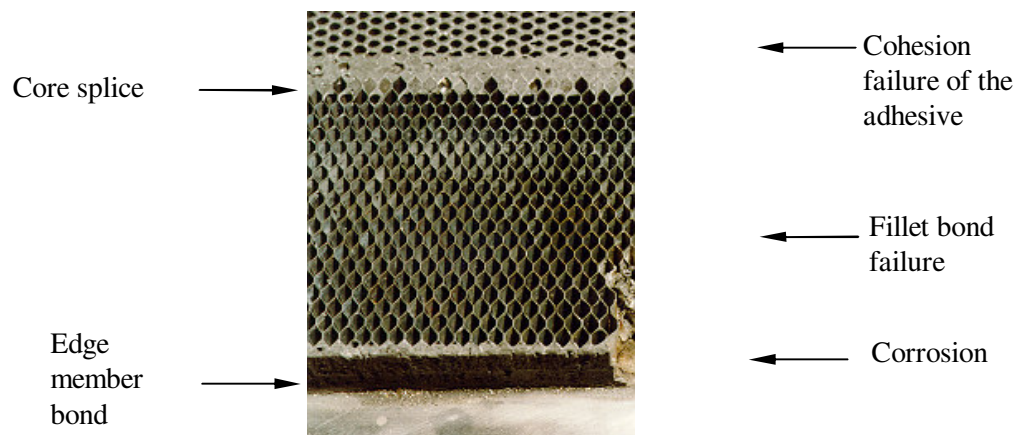

Core splice   Cohesion failure of the adhesive

Edge member bond   Fillet bond failure

Corrosion

Figure 3. Failed sandwich panel showing cohesion failure and adhesion fillet bond failure.

Node bond failures are characterised by separation of the cell wall node bonds along the ribbon direction (see Fig. 4). Although the separation may occur as simple disbonding of the cell walls, failures may also exhibit cell wall distortion due to pressure caused by moisture vaporising at elevated temperature (see Fig. 5). Node bond failures frequently occur during application of heat for cure of adhesive bonded repairs. The typical "freeze-thaw" cycle may also cause pressure on the cell walls if ice forms in the cells, although typically the amount of trapped water is usually insufficient to generate the required pressures.

5. CREDP EXPERIENCE WITH IN-SERVICE FAILURES

A number of in-flight failures have occurred due to adhesion fillet or node bond failures, resulting in severe damage and/or loss of control surfaces and structural panels on USN F/A-18. After the USN raised the issue of such damage mechanisms causing structural failures, a review of defect reports from other CREDP member fleets also identified the characteristics of these failures. Investigation of one failed F/A-18 graphite/epoxy skinned rudder (Fig. 6) shows that on a significant proportion of the failed surface there is minimal core fracture and negligible damage occurring to adhesive which was still bonded to the inner surface of the face sheet. Areas A and B show complete adhesion failure while areas C and D exhibits evidence of mixed cohesion and adhesion failures. The absence of adhesive on the ends of the core cells and the absence of fractured core are indicative of adhesion fillet bond failure. In contrast, the adjacent area (E) displays a typical cohesion peel failure, with fractured adhesive left on the cells.
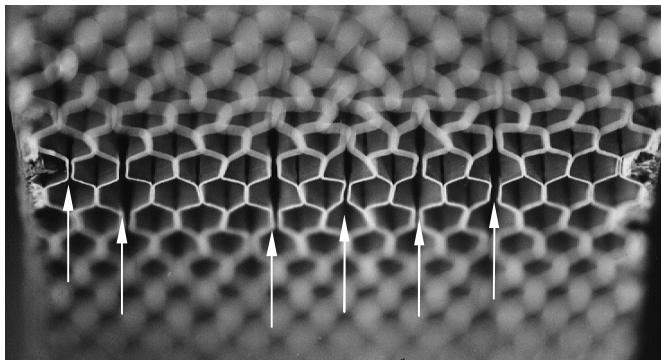

Figure 4. Node bond failures in aluminium core, showing the separation of the cell node bonds along the ribbon direction after exposure to slow cycle fatigue at a hot-wet tropical site.
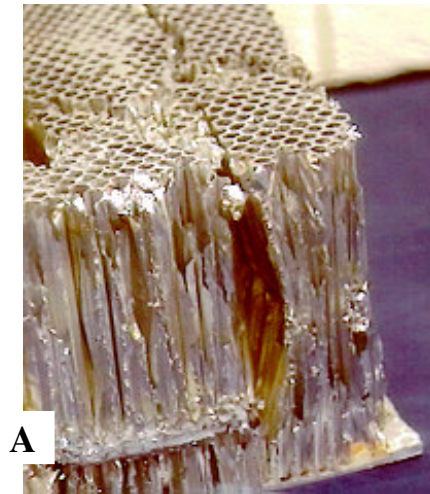

Figure 5. Node bond failure and cell wall distortion at "A" caused by internal pressure in aluminium core.
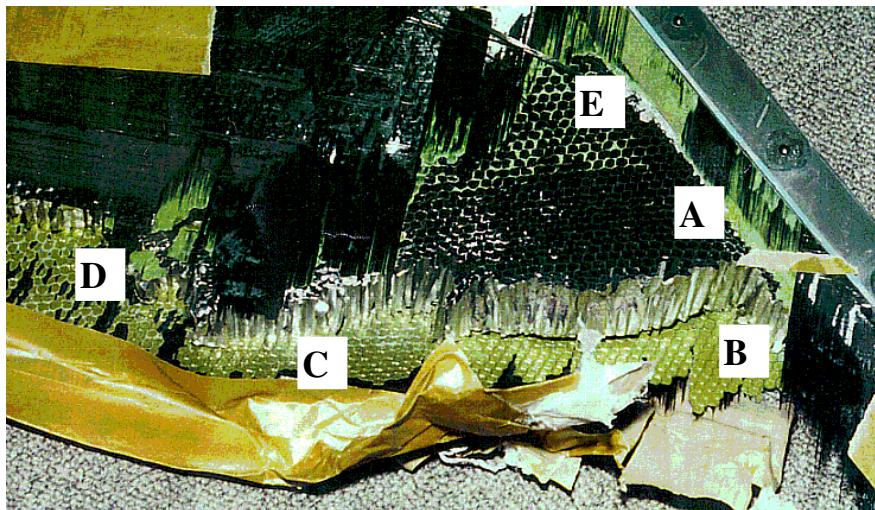

Figure 6. Photograph of a failed F/A-18 composite skinned rudder. A and B show complete adhesion failure while areas C and D exhibit evidence of mixed cohesion and adhesion failures, and peel failure (E). Note that protective tape has been applied for safer handling.

The RAAF has also experienced core adhesion fillet bond failures on a fixed glove panel on F-111 (see Fig. 7). This defect became apparent when the inner skin separated from the core region during an attempt to perform a hot-bonded repair in the adjacent panel bay. The figure shows light corrosion around previous injection repairs (A) and a large area of adhesion fillet bond failure (B), where the skin simply lifted off the core. Less than 10% of the panel exhibited a cohesion peel failure through the adhesive (C) during break-down for rebuild. All of the remaining panels on this component displayed similar fillet bond degradation.
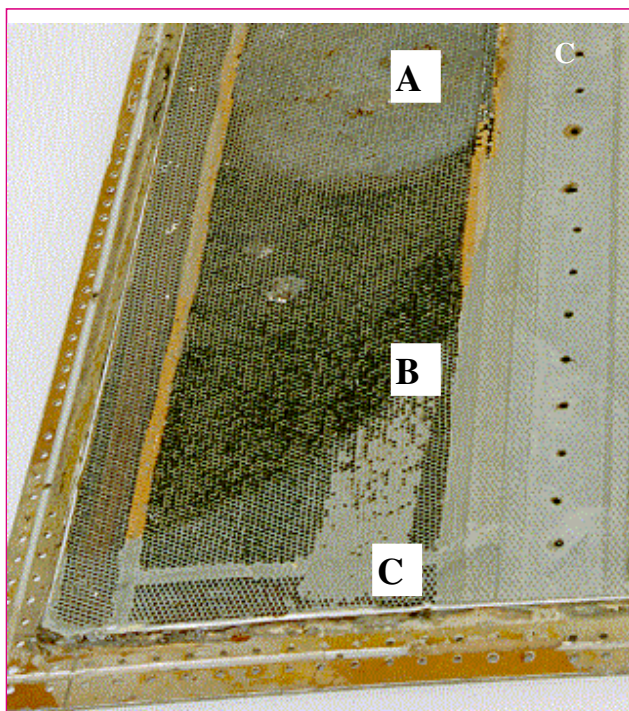

Figure 7. An F-111 fixed glove sandwich panel showing light corrosion at injection repairs (A), adhesion fillet bond failure (B) which occurred in service and peel failure (C) caused during break-down of the panel for rebuild.

Fillet bond failure is visible on the surface of an F-111 over-wing fairing recovered after an in-flight failure (Fig. 8). The adhesive shown on the surface is from injection "repairs". Note also that the cast impression at "A" of the matching bonding surface clearly show the core pattern. This indicates that the original defect, prior to injection repair was adhesion fillet bond failure. This large panel separated in flight causing extensive damage to the fin leading edge, rudder, horizontal stabilator and fuselage. In another USN in-flight failure, a trailing-edge flap upper-skin separated adjacent to a large repair. Core adhesion fillet bond failures were observed in conjunction with widespread node bond failures.
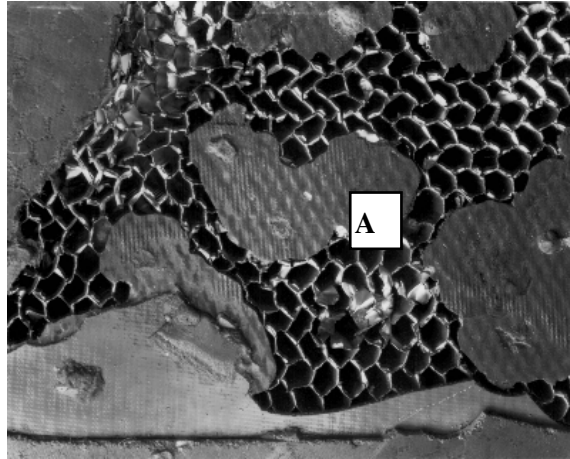
Figure 8. Failure surface from a recovered section of an F-111 over-wing fairing lost in flight.

Off-aircraft failures have been noted by the USN and RAAF during repair heating procedures to sandwich panels with both composite and aluminium skins. Under elevated temperature, the cell pressure increases due to the expansion of the air. Free moisture in the cells, or moisture which is de-sorbed from the adhesive or composite skins also greatly increases the pressure as the water turns to steam. Extensive measures have been undertaken to dry panels before heating above 100°C (250°F), with the USN experiencing failures even after a 48 hour drying cycle. The core pressure either forces the face sheet to disbond by adhesion fillet bond failure, or forces the cell wall bonds apart in a node bond failure. Similar panel damage has occurred on repairs on RAAF F-111. Failures are not restricted to older panels. The USN has experienced damage to sandwich structure on F/A-18 D model aircraft with less than five years service. Hence the degradation appears to be related more to service exposure time and high humidity environments than flight hours.

The USN has attempted to use lower temperature curing adhesive systems in order to minimise the pressure build up. By use of a 250°F curing adhesive, the cell pressure during repair has been reduced below the FWT strength of the fillet bonds. While this approach has eliminated adhesion fillet bond failures, node bond failures have still occurred. So far, the USN has experienced damage to two trailing edge flaps, a rudder and a number of horizontal stabilators. More extensive damage has occurred in panels which have been repaired by use of an autoclave, due to heating of the entire panel which may cause node bond failures at other sites where undetected moisture is present, with damage occurring over a metre from the repair site. The USN now perform 100% X-Ray on all autoclave repaired panels, and X-Ray a region of at least 12 inches around any site heated for local repair cure.

6.   CIVIL AVIATION EXPERIENCE

There is evidence of similar failure modes on civil aircraft, although there is no clear identification of the damage types. The FAA has issued an Airworthiness Directive AD 90-12-13 for the inspection of Airbus A310 rudders for disbonds, with the description of the problem being very similar to that experienced by the CREDP members. Inspection of Airbus elevators from one Australian civil airline revealed skin-to-core disbonds which when investigated under a low power microscope revealed core node and adhesion fillet bond failures. Concerns were expressed by the airline when the size of a disbond identified using the recommended NDI procedures was found to be less than 20% of the actual size of the core fillet bond failure found during damage removal. A later draft AD to update disbond inspection procedures was issued under Rules Docket No. 96-NM-65-AD. These Airbus elevators are fabricated with graphite/epoxy skins on Nomex™ core. Elevator core samples were inspected by the RAAF and found to have similar failure modes to those experienced in aluminium cored sandwich panels (see Fig. 9).

7. FAILURE INVESTIGATIONS

Post failure analysis has revealed that the node bond adhesive from at least one core supplier is applied to the aluminium during manufacture of the core as a series of discrete dots rather than as a continuous film (see Fig. 10). Should the cell wall node bonds not form a complete cover, leaving gaps in the core adhesive, these gaps would increase the rate of moisture progression through a sandwich panel. Node bond failures on one particular brand of core, although appearing to be adhesion node bond failures, are in fact cohesion failures. Optical and electron microscopical examinations have revealed the presence of adhesive on both failure surfaces (see Fig. 11). On other core material, node bond adhesive is peeling from the surface interfacially. Aeronautical and Maritime Research Laboratories (AMRL) (Melbourne) showed that the different forms of failure correlate with two core manufacturing companies. The manufacturers use different core node bond adhesives, and one appears to have a lower durability than the other. Different surface preparation procedures prior to bonding the foils together may also contribute to the interfacial failure mode.
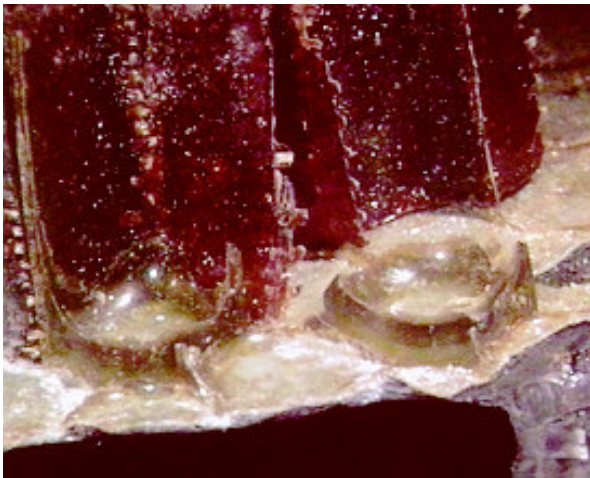

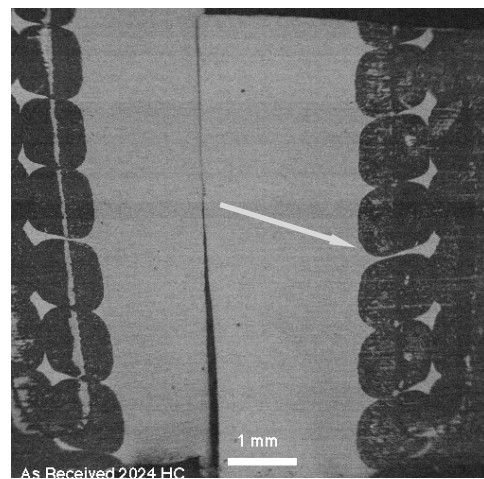Figure 9. Adhesion fillet bond failures in Nomex™ core from an Airbus elevator.

Figure 10. Magnified view of an adhesive strip used to bond the foils together at the nodes.
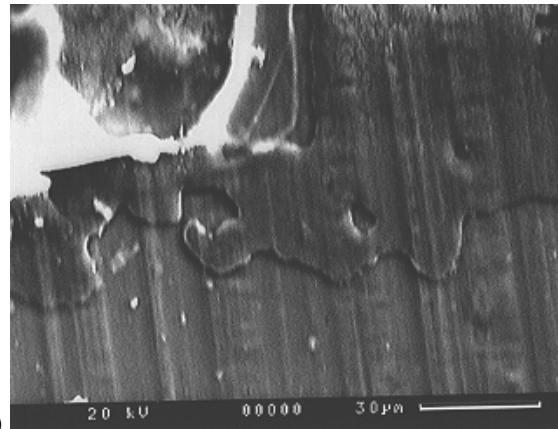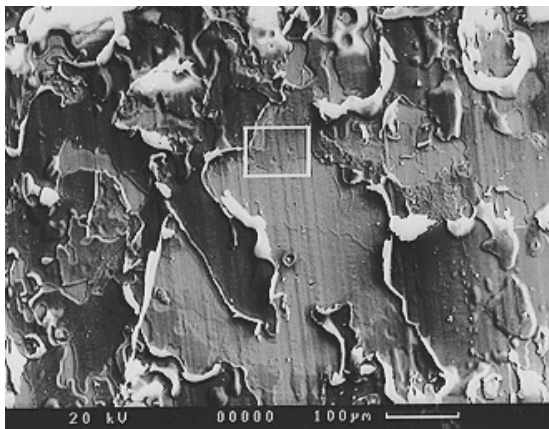

(a)

(b)

Figure 11. Close-up photograph of a core node bond region taken from the F-111 glove panel. Note the core node bond adhesive peeling off the surface of the cell walls. The magnified region in Fig. (b) shows the presence of what appears to be residual adhesive on the core surface.

Observations by the RAAF indicate that adhesion fillet bond degradation is typically interfacial (see Fig. 12). The shiny appearance of the fillet bond region of the core foils suggests the region had been

experiencing fretting abrasion due to relative movement between the core foil and the adhesive on the face sheet. Such interfacial (adhesion) failures are usually associated with bonding surfaces with a low resistance to hydration [2]. This appears likely with the fillet bond because there is no available method for preparation of core material prior to bonding to the face sheet adhesive (apart from solvent cleaning which does not affect the oxide layer). The inadequately prepared surface will be susceptible to hydration of the chemical bonds between the metallic surface and the adhesive.

In a significant number of honeycomb panel failures there is a moisture entry path adjacent to the defective area which, as well as causing the core bond degradation problems discussed, may also cause corrosion. Two failed F/A-18 rudders exhibited corrosion or the presence of water which had entered through a poorly sealed fasteners. In Canada, Bombardier has found a extensive corrosion in metal faced sandwich structure on CL-41 Tutor aircraft. Similar corrosion frequently occurs on RAAF F-111. In many cases a breakdown of the panel sealing leads to the moisture entry.
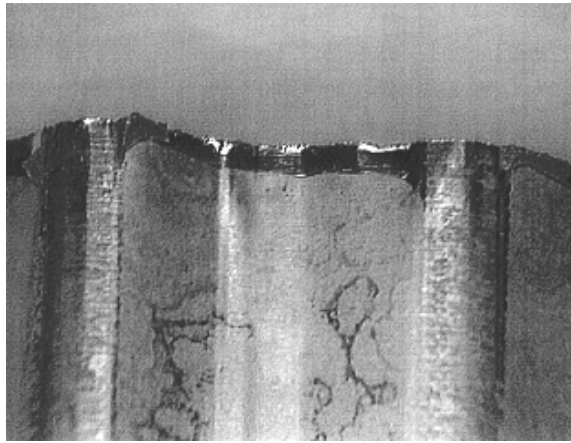

Figure 12. Photograph of a honeycomb core foil showing light surface corrosion which does not extend into the fillet bond area (top of photograph).

Many of the metal faced RAAF F-111 sandwich panels which exhibited core corrosion and core and node bond failures had been "repaired" using adhesive injection procedures or potted repairs. Injection repairs attempt to rebond disbonded face sheets by squeezing fresh liquid adhesive into disbonds. Because the surfaces which have disbonded are no longer chemically suited to adhesion, this form of repair has very little success. Moisture may then enter the sandwich panel through the injection holes. In potted repairs, disbonded skin material is cut away and core removed. The cavity is then filled with a resin and glass flock mixture. In the past there was no requirement to cover injection or potted repairs with a moisture barrier and consequently, moisture entered panels by diffusing through the potting material.

8. STRUCTURAL INTEGRITY IMPLICATIONS AND ASSOCIATED RESEARCH

The USN (NADEP-NI) have tested core node bonds by cutting individual nodes from core sections and then performing a micro T-peel test. Node bond T-peel specimens were cut from a sample of Hexcell CRIII core and exposed to 60°C (140°F) at 95% RH in a humidity cabinet. After 6 weeks of exposure specimens exhibited a loss of strength from a baseline value of 6.2 pounds per inch width (piw) to 4.2 piw and began to exhibit an adhesion failure mode. For specimens cut from failed node bond areas on repaired parts T-peel strengths were reduced to approximately 1 piw. Fillet bonds have experienced similar reductions in strength following moisture exposure. Climbing drum peel tests after exposure to 35°C (95°F) and 95% RH for over 20 months by the CF [3], exhibited a significant loss of strength and a change from cohesion to adhesion fillet bond failure. The USN (NADEP-NI) have also shown a similar loss in FWT strength for specimens subjected to a 7 day exposure to boiling water [4]. Such substantial losses in strength, combined with a

history of in-flight losses of components, suggests that there is a risk to structural integrity of aircraft components from these forms of defects. Safety-of-flight will depend upon the criticality of the individual component, flight loads and the extent of damage.

Despite the prevalence of honeycomb degradation in aircraft honeycomb panels and the possible effect this could have on the structural integrity of the aircraft, there appears to be little in the literature on systematic studies of the effect of such degradation on the structural integrity of sandwich panels.

In Canada, as part of CREDP, Canadair are preparing to develop a computer model that will look at the effects of reduced FWT strength on structural integrity of honeycomb sandwich assemblies. They are planning on using input values based on the "wet" FWT test data generated experimentally as well as test data derived using a "Porta-Pull" device used to measure the tension load necessary to pull a sandwich panel face sheet from the core. Boeing St. Louis has undertaken to review the implications for structural integrity of a reduction in FWT strength to the levels detected on the basis of the available test data.

In Australia, AMRL plan to study the effect of sandwich panel defects on F-111 structural integrity by use of a specimen representative of typical aircraft structure to validate a Finite Element (FE) model of the aircraft. The flight loads required to cause skin or fillet bond failure will then be able to be calculated and measured for different initial defect sizes. Finally using a global/local FE model, the influence of a local failure will be investigated by examining the way in which load is shed into adjacent structure. The effect of this load increase will be evaluated to see if further failures in neighbouring structures could be expected. This information will enable an assessment of the significance of honeycomb defects and will assist in establishing maximum tolerable defect sizes for inspection requirements.

9.   SUPPORTING RESEARCH

The USN (NADEP-NI) and AMRL have undertaken programs to develop methods of conducting rapid tests to produce the failure modes detected on aircraft components. The principal aim of these programs is to develop a relatively quick test (compared to actual service exposure) which can be used to evaluate different materials or processes. The program will attempt to correlate a reduction in FWT strength (which is not a design number) with a reduction in beam shear strength (which is a design number).

The need for these programs to develop such a test is significant because a limiting factor in studying adhesion fillet bond failure is the ability to reproduce the failure modes under laboratory conditions. Simple approaches using release agents and sprays to simulate adhesion fillet bond failures do not produce acceptable fillets due to the hydrophobic nature of the core surface. The only reliable fillet reproduction method found so far is to form the fillets as a normal bond and then to expose the specimen to a high humidity environment. To reduce environmental exposure times prior to testing, AMRL are evaluating two methods for moisturising specimens. For metallic-skinned specimens, only one skin is bonded to the core initially and the specimen exposed to the hot/wet environment in this state. After drying to remove excess water, the bare core surface is bonded directly to the load block for testing. This test configuration gives a slightly stiffer specimen than one with two skins and initial results for non-degraded specimens indicate that failure loads are higher (11.7MPa) than comparable double skinned specimens (9.6 MPa).

For composite skinned specimens, the graphite/epoxy laminates have been drilled with a diamond coated drill to create approximately 100 holes in each 2500 mm^2 face sheet. This is to enable moisture to rapidly degrade the interior of the structure during the hot/wet exposure. An obvious difference between composite and metal face sheets is that moisture can diffuse through the composite skin over time, whereas for the metal skin, moisture can only gain access to the interior of the structure through a leakage point. To investigate possible differences in the failure modes, some of the composite skinned specimens will not be drilled and the moisture will be forced to diffuse through the face sheets to attack the fillet and node bonds.

NADEP-NI is performing "Porta-Pull" testing and node bond T-peel testing on an F-18 rudder inducted for repair that had X-Ray indications of water in the core and attenuated ultrasound. Porta-pull testing has indicated some correlation between strength loss, percent of adhesion fillet bond failure and attenuation of ultrasound. In addition, honeycomb sandwich panels are planned to be fabricated, moisture conditioned, and subjected to Porta-pull testing, ultrasonic inspection, and beam shear testing in an attempt to correlate FWT strength, ultrasonic inspection response, and beam shear strength.

Canadian research at QETE on water damage to in-service components shows that the water has little or no effect on the actual laminate. The water can degrade the adhesive's properties but these same properties can usually be restored by drying out the adhesive. The water absorbed by the epoxy plays the role of a plasticiser, reducing the tensile modulus and lowering the glass transition temperature (T_g). There appears to be a critical water concentration below which no permanent water induced damage to the joint will occur. Initial results from the CF tests indicate that, if an epoxy-metal joint is conditioned in a humid environment and the water concentration is below 1.35wt%, then any loss in the joint strength due to the absorbed water can be recovered by drying out the epoxy-metal joint. This will usually restore the original modulus and T_g of the epoxy adhesive suggesting that the water damage is reversible below the critical water concentration.

Water has a significant effect on the aluminium core, or more specifically on the oxide layer at the core/adhesive interface. Typically, there is a loss of adhesion which can be identified using ultrasonic C-scan. Some recent work in Canada (yet to be reported) has identified regions which are neither completely disbonded nor completely bonded. What the partially bonded region represents, beyond a lower tensile strength region, is still to be determined. Two possible causes for the partial bonding have been identified:

(1)   The reduction in tensile strength is due to the conversion of the oxide layer on the "as manufactured" aluminium honeycomb, typically amorphous Al_2O_3, to a hydrated form of aluminium oxide with a chemical composition between boehmite ($Al_2O_3 \cdot H_2O$) or pseudoboehmite ($Al_2O_3 \cdot 2H_2O$) or

(2)   The reduced tensile strength is due to microcracking in the hydrated oxide layer.

The hydration of the original "as manufactured" oxide layer is believed to be the cause of the weakened bond. Failure analysis reveals that the adhesion of the boehmite (or pseudoboehmite) layer to the aluminium substrate is weak. When the bond fails, this hydrated layer is usually found on the adhesive and not on the substrate. Because of the weakness of the hydrated oxide layer, and the fact that the exposed surface of the core would probably form a hydrated oxide, attempts to rebond to the surface will always be ineffective.

A new technique is being developed at AMRL in an attempt to obtain some quantitative information on degradation present in fillet and node bonds on panels in service. The technique involves measurement of internal pressure in an individual honeycomb cell (see Fig. 13). By measuring pressure in the cell as the temperature is increased, the presence of water can be detected by a pressure increase due to the partial vapour pressure of the water. However, the presence of water in itself cannot confirm degraded bondlines, as this is related to the time the water has been in the cell and the types of interfaces present.
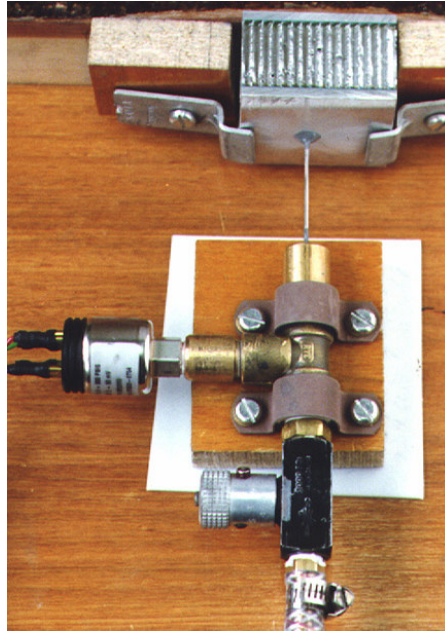
Figure 13. The gas injection tube system, pressure sensor and needle valve for pressure regulation used to detect moisture and to determine cell node bond strength.

A second measurement techniques is being investigated to obtain information as to the degree of bondline degradation. Using the same equipment, the temperature is kept constant, and pressure is increased by injecting nitrogen gas into the cell, creating a mode 1 stress in the node bond joints of that cell. If the joints are not degraded, the pressure should continue to rise as nitrogen is admitted until the cell fails at a high pressure (dependent on the type of core and adhesive). A sudden drop in pressure at an early stage indicates that the node bond was degraded and has failed, allowing gas to escape into neighbouring cells. This result would suggest that core replacement may be required together with an investigation to determine how the moisture entered the core. However, this technique involves drilling a small hole in the skin and so is not strictly speaking a non-destructive technique. The damage involved is however very minor, although it will be important to ensure that the hole can be effectively sealed to prevent future water ingress.

10. NON-DESTRUCTIVE INSPECTION

Extensive NDI examinations of scrap honeycomb components from both F-111 and F/A-18 aircraft are being correlated with destructive investigations to determine the exact nature of the failures detected. This will enable determination of the resolution and accuracy of various NDI methods used. Results to date indicate that NDI methods such as X-Ray radiography and conventional ultrasonics are only capable of detecting severe damage to either fillet or node bonds. These techniques have also been successful in detecting deliberate defects in a calibration test panel such as artificial disbonds or cut nodes.

Both conventional and innovative inspection methods are being tried to see if it is possible to detect the early onset of disbonding of degraded honeycomb structures. Thermography, ultrasonics and X-Ray radiography have all been tried on both degraded components as well as NDI standard specimens. Good results have been obtained with some of the more conventional techniques as well as newer methods such as ELCH (Elasticity Laminate CHecker) and the Bondmaster instrument, although the key lesson learned is that no one technique applies equally well to all defect types. Because of the need to obtain a vacuum seal, the ELCH was found to have limited practical application for panels with even moderate curvature. In the short to medium term, it is clear that a range of NDI methods will be required to obtain good quality information from a range of different damage types.

With adhesion fillet bond failures, while the interface between the adhesive and the core at the fillet may be weak, sufficient contact remains to enable transmission of sound and so precludes the use of simple ultrasonic inspection techniques and the coin-tap test. Extensive fillet bond failures become easier to detect using simple techniques after the core has separated from the adhesive on the face sheets. The RAAF is investigating the use of laser holography to inspect for reduced core fillet bond stiffness, which may enable identification of potentially defective surfaces. Research at QETE in Canada has developed an optimised ultrasonic C-scan through-transmission method. The technique appears to be capable of finding disbonds as well as partial bonding. It has identified regions on an F/A-18 rudder which are different from the obvious disbonds and good portions of the rudder. Tests have confirmed these regions as having lower tensile strengths through the use of the "Port-a-Pull" testing equipment. The CF have also found moisture degradation during an N-Ray examination of a composite rudder. The USN (NADEP-NI) have also had some success using ultrasonic C-scan to identify areas of partial fillet bonds on an F-18 rudder. The cause of the signal attenuation is unknown, but in those areas where the C-scan indicates about 80-90% attenuation, "Porta-Pull" tests show a large loss of strength (to approximately 80 psi compared to the minimum value of 625 psi) and an adhesion fillet bond failure. Adjacent to the indication (in an "acceptable" area by C-scan) "Porta-Pull" strengths are near 600 psi and 5% adhesion/95% cohesion fillet bond failures are observed.

Detection of node bond failures is relatively easy using X-Ray, provided the core cell walls have been distorted by pressure during heating procedures. However X-Ray examinations are slow and expensive, and not all node bond failures cause cell wall distortion.

11. COMPONENT MANAGEMENT

Localised repairs using high temperature curing adhesives may be relatively ineffective, depending on the extent of degradation and the pressures generated during such cure cycles. Localised high temperature repairs may cause more significant damage than the defect being repaired, due to the low bond strength of the nodes and fillets near the defective region. Where possible, lower temperature curing adhesives should be used for repair to reduce the build up of internal pressures during heating to the cure temperatures.

If moisture continues to degrade the core node and fillet bonds, the FWT strength will eventually degrade to zero, resulting in a loss of panel integrity and also making repair impossible. An obvious measure for reduction of the occurrences of adhesion fillet and node bond failures in existing panels is to pay particular attention to sealing moisture entry paths. Epoxy based fillers should not be used for this purpose due to the moisture adsorption characteristics of these materials.

NADEP (NI), Boeing St Louis and Naval Air Warfare Centre (NAWC) Patuxent River are investigating the use of Phosphoric Acid Anodised (PAA) core for use on the F/A-18E/F as well as for production of current model F/A-18 spares. Comparison testing is under way between standard core and PAA core to evaluate fatigue response as well as fillet bond strength, node bond T-peel strength and core delamination strength following environmental exposure. Testing should be completed by mid 1999. Published data [5] suggests that PAA core performs significantly better than conventional core materials under hot-wet exposure.

12. CONCLUSIONS

The problem of fillet and node bond degradation in honeycomb sandwich panels appears to be widespread and has structural integrity implications. The consequences to flight safety will need to be evaluated for each individual component. Existing NDI techniques appear to be adequate for detection of large area disbonds and some recently developed methods show promise for development of effective inspection measures for service components. One short term measure for prevention of these defect types is to ensure

all moisture entry paths are adequately sealed. Longer term, the use of PAA core may present the best method for prevention of core degradation problems.

The objective of this paper is to alert the aviation industry to the nature and significance of adhesion fillet and node bond core degradation problems, and to seek industry input on inspection techniques, structural integrity assessment, and procedures for repair and prevention. The authors would welcome discussion.

ACKNOWLEDGMENTS

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