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Hot/Wet Environmental Degradation of Honeycomb Sandwich Structure Representative of F/A-18: Flatwise Tension Strength

T.C. Radtke, A. Charon and R. Vodicka

DSTO-TR-0908

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ABSTRACT

Aluminium honeycomb structure is widely used in the F/A-18 to save weight, however it is susceptible to degradation by water. The US Navy has experienced in-flight failures of honeycomb components such as the rudder which are believed to be due to moisture induced degradation. A long-term (52 week) environmental exposure trial was conducted to determine the effects on the flatwise tension (FWT) strength of honeycomb sandwich structure. A conditioning temperature of 70°C was chosen coupled with high-humidity exposure (85% and 95% R.H) to simulate a worst-case hot/wet environment. The trial simulated specimens in which moisture could freely enter the core (direct ingress) and those which were fully sealed and allowed only moisture diffusion through the epoxy matrix of the skins (diffusion ingress). The FWT strength was measured at 4, 9, 16, 32 and 52 weeks exposure. The FWT values decreased by about 40-50% when tested at 104°C and about 25% when tested at room temperature after exposure periods greater than 16 weeks. Both the direct ingress and diffusion ingress samples showed similar FWT strength losses but markedly different modes of failure. Diffusion specimens failed cohesively in all cases while the direct ingress samples failed predominantly adhesively after an exposure time of about 9 weeks. Subsequent drying of the samples exposed to the conditioning environment showed that diffusion ingress samples recovered most of their original FWT strength but direct ingress samples recovered only about 70% of their original baseline strength. This work shows that excluding water from within honeycomb sandwich structures is of primary importance in order to prevent permanent bond degradation and corrosion of the core.

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Executive Summary

The use of honeycomb sandwich structures is widespread on aircraft such as the F/A-18 and F-111. They provide stiff lightweight structures which are ideal for control surfaces and other exterior structure. In the case of the F/A-18 aircraft the sandwich panels are constructed using graphite-epoxy skins bonded to an aluminium honeycomb core with a high-temperature adhesive. The durability of these structures relies heavily on the integrity of the adhesive bond between the skin and core as well as the core itself. The environmental durability of graphite-epoxy skins is generally very good unless they are physically damaged.

The adhesive bond and core are affected in service by the presence of moisture. Moisture can enter the structure by a number of means. Free-water can enter the structure through damage to the skins as well as through damaged or degraded seals or bonds which can create corrosion as water fills the cells of the honeycomb core. Moisture can also diffuse into the epoxy matrix of the composite skins over a long period of time but moisture entering by this mechanism does not 'pool' in the core as 'liquid water'.

A good method of evaluating the skin to core bond is the flatwise tension strength test (FWT). This examines the strength of this bond under tension applied to the skin. A test trial was devised and implemented to allow the evaluation of the effects of hot/wet environments on the durability of the skin to core adhesive bond. Two types of specimens were evaluated, one to simulate direct ingress of moisture into the core (holes were drilled in the skins) and the other to simulate the effects of moisture diffusion as would be experienced for a perfectly healthy panel. Hot/wet conditions of 70°C and high humidity levels were used to simulate extreme tropical exposure. FWT strengths were then evaluated at periods of 4, 9, 16, 32 and 52 weeks.

The results show that FWT values decrease by about 40-50% for specimens tested at 104°C and about 25% for those tested at room temperature. For the diffusion ingress samples (simulating a healthy panel) these losses could be recovered if the samples were dried at 90°C for 4 weeks. The direct ingress samples (holes drilled in the skins) however recovered only about 70% of their baseline strength after drying. This shows that water entering the core, permanently degrades the adhesive bonds while diffused moisture can be removed by drying to restore original strength. The failure modes between the two samples types was also markedly different. The diffusion ingress samples show cohesive failure in all cases (ie: through the adhesive) while direct ingress samples failed at the adhesive to core interface.

The work highlights the damage caused to the adhesive bonds in honeycomb sandwich structures if water is allowed to enter the core. This degrades the adhesive bonds irreversibly and will corrode the core over the long-term. It is therefore vital that efforts are continued to minimise the possibility of moisture entering honeycomb sandwich structures by ensuring the skins are not damaged and that all seals and adhesive bonds are in good order.

Authors

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Tom Radtke graduated from Capricornia Institute of Advanced Education with an Associate Diploma in Mechanical Engineering (1986), from Swinburne University of Technology with a Degree of Bachelor of Technology (1993) and from the University of South Australia with a Graduate Certificate in Management - Scientific Leadership (1997). He has contributed to a broad range of propulsion system and structural composites programs for aircraft repair and life extension. The studies have included; the mechanics of scarf repairs for highly strained graphite/epoxy honeycomb structure, environmental durability aspects of adhesively bonded composite repair systems, fatigue and creep-fatigue interactions of various nickel-based superalloys, and fretting fatigue of titanium alloys. He currently works in the Aircraft Structural Integrity area where he manages the Division's Fatigue and Fracture Laboratory.

A. Charon

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Aaron Charon graduated from the Royal Melbourne Institute of Technology with a Bachelor of Aerospace Engineering (Hons.) in 1994. On completion of his degree he held several short-term contracts within the major airlines including Qantas and Ansett Australia as technical support engineer and with Australian Defence Industries (ADI) as project engineer working on the Minehunter project. He later joined the Aeronautical and Maritime Research Laboratory in 1997 as a contract engineer primarily with the task of developing a mechanical inspection tool for detecting moisture in honeycomb sandwich structures. He is currently involved in research into the environmental degradation of composite honeycomb sandwich structures and is particularly interested in developing tools for quantifying the level of degradation within these structures.

R. Vodicka

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Roger Vodicka graduated BSc. (Hons.) from Monash University and joined AMRL in 1990. He currently works in the area of composite materials and crack-patching repair technology. Current working projects include moisture diffusion properties of epoxies, battle damage repair, environmental certification of composite materials and composite manufacturing methods. He is currently the task manager for the Composite Repair and Engineering Development Program (CREDP).

Contents

1. Introduction

Environmental degradation of adhesive bonds within graphite-epoxy skinned aluminium honeycomb sandwich panels is of significant concern due to the implications for structural integrity and airworthiness. The focus of this work is to understand the nature of degradation of adhesive bonds by either liquid water or humid air in honeycomb structures relevant to the materials, structures and processes used on the F/A-18 aircraft.

Recent in-flight failures of honeycomb sandwich structure components on US Navy F/A-18 aircraft have created concern for RAAF aircraft fleets. These failures have been attributed to the presence of liquid water in the components leading to a loss of adhesive bond strength and corrosion of the aluminium honeycomb core. Degradation of the adhesive bonds in these structures has been severe in some cases with reductions in component strength of up to 90% reported by the U.S Navy (NADEP-NI) using PORTA-PULL tests. The RAAF has also reported the presence of corrosion damage in honeycomb sandwich structures on F-111 aircraft as well as poor bond-strength for affected areas. Replacement or repair of honeycomb sandwich structure is expensive and is unlikely to be a long-term solution if the root cause of the problem is not identified.

Work by QETE [1] found that 50% of F/A-18 rudders in Canadian Forces service contained moisture as liquid water. Work at Bombardier Aerospace Group by Vallerand [2] describes the entry points for water as being a consequence of poor seals around fasteners and other entry points on the control surfaces. The ingress of water into honeycomb sandwich panels on the F/A-18 aircraft has been the subject of Task S of the Composite Repair and Engineering Development Program (CREDP).

The repair of components that contain moisture as liquid water can also pose major problems for high temperature adhesively bonded repair operations. Water present in the honeycomb core can create high pressures at elevated temperatures (>100°C) which can seriously damage the component. A previous discussion paper [3] by DSTO-AMRL discusses issues related to moisture ingress into panels and the implications for elevated temperature adhesive bonded repair procedures.

A flatwise tension (FWT) test program was developed and initiated to investigate the integrity of the adhesive bond between the honeycomb core and the graphite epoxy face sheet (fillet bond) when exposed to an aggressive environment representative of the worst case service environment. This was designed to gain an understanding of the environmental durability of honeycomb sandwich structures and the type and levels of degradation, which have been observed under service conditions.

The aggressive environment was represented by either surface exposure of the honeycomb sandwich structure to humid air, or by exposure of the honeycomb sandwich structure core to a condensing environment to produce a liquid water exposure condition. This latter condition was termed direct moisture ingress. Under normal service conditions composite structures will absorb moisture from the service environment through the surface layers of the composite structure via the diffusion process. The humid air exposure condition was included in the study to quantify any degradation associated with moisture ingress by diffusion and to gain a broader understanding of the failure locus.

The FWT test is also identical in principle to the PORTA-PULL test which is used in the field to evaluate the skin to core fillet bond strength in honeycomb sandwich structure. Thus the results of this program will be comparable to results taken in the field using the PORTA-PULL technique.

2. F/A-18 Honeycomb Sandwich Construction

Composite-skinned honeycomb-sandwich panels are utilised for many stiff, light and structurally efficient aircraft components. Sandwich panels on the F/A-18 aircraft include the rudder, trailing edge flaps, horizontal stabilators as well as access doors along the fuselage undercarriage.

A honeycomb sandwich structure typically comprises three main elements. The facesheets, the core and adhesive layers. On a typical F/A-18 component the facesheets are manufactured from AS4/3501-6 graphite/epoxy composite and the honeycomb core is made of aluminium coated with a chromate based anti-corrosion layer. The adhesive that bonds the facesheet or skin to the core, known as the fillet bond, is Cytec FM300 adhesive, which cures at 177°C. The honeycomb core is constructed of ribbons of aluminium foil bonded at discrete locations with a phenolic-nitrile adhesive. The area of contact is termed the node and the bond between the ribbons is called the node bond. Once cured, the core is expanded into the final honeycomb core shape. Core cell sizes and densities vary across the aircraft. The aluminium honeycomb core used in this study is representative of that used in current RAAF F/A-18 aircraft. Figure 2 shows a schematic of a typical honeycomb sandwich structure.

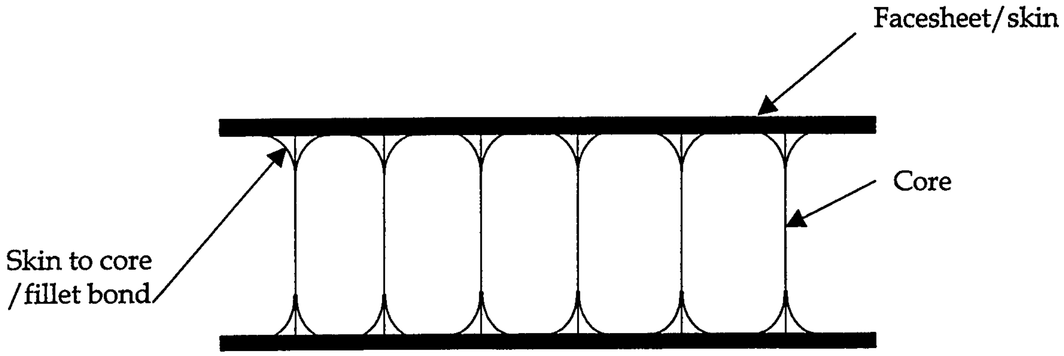
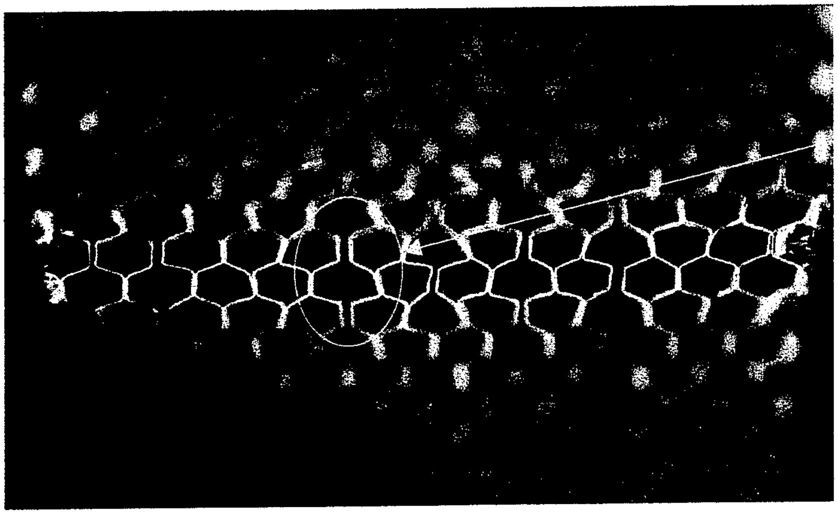


Figure 1 Schematic of honeycomb sandwich structure (side view)

3. Degradation of Honeycomb Structure

The durability of honeycomb sandwich structure components is of importance as many are used for control surfaces. Honeycomb-sandwich panels rely on the effective use of sealants and adhesive bonds to prevent water from entering the component. Service experience has shown that moisture can enter these panels potentially leading to corrosion of the aluminium honeycomb core and degradation of the adhesive bonds. The mechanism by which the moisture can enter the structure can only be either by direct ingress of liquid water, or by diffusion of moisture from the service environment.

Figure 3 shows the degradation of adhesive node bonds in a honeycomb sandwich beam exposed to a tropical environment for a long time period. The beam illustrates both node and fillet bond degradation. There is no skin to core (fillet) adhesive left on the honeycomb core indicating an adhesive failure mechanism. The gaps between many of the honeycomb nodes are a consequence of extensive node bond degradation.



Node bond degradation along core ribbon direction.

Also note lack of any residual skin to core adhesive.

Figure 3 Degradation of node and fillet bonds in aluminium honeycomb core structure

Moisture can enter the sandwich structure by a number of means:

1. poor or damaged or degraded seals around penetrations or the edges of panels
2. direct ingress through damaged facesheets (skins)
3. diffusion of moisture through the epoxy matrix in the composite skin

3.1 Moisture Diffusion Through Undamaged Sandwich Structure

Moisture in the form of humid air can transport into undamaged composite sandwich structure by diffusion through the epoxy matrix in the composite facesheets as well as through the adhesive which makes up the skin fillet bond and node bonds.

For NOMEX and other polymer-based honeycomb materials, moisture may diffuse through the honeycomb walls themselves. Recent work published by Cise and Lakes [4] examined the moisture ingress through three types of Korex honeycomb. Korex honeycomb is a paper pulp material dipped in liquid polymer. They found that moisture could diffuse through the structure if a small area of the core was exposed to high humidity. The diffusion rate was observed to be greater along the ribbon direction. This was due to the construction of the core material; the core being joined along the ribbon direction by adhesive which allows water to diffuse through it.

Little is known about the rate of diffusion through aluminium honeycomb sandwich structure. Although humid air cannot diffuse through the aluminium walls of the honeycomb, both the node bonds and skin-core bonds can allow the diffusion of moisture. Preliminary results from tests conducted at DSTO-AMRL using aluminium core with graphite/epoxy skins shows the bias of moisture transport along the core ribbon direction for a sample immersed in water at 70°C for four weeks (Figure 3).

Figure 3 illustrates the way moisture diffuses preferentially along the ribbon direction of the core causing adhesive failure (ie: areas where no adhesive remains on the core). The region of adhesive failure is up to 3 cells from the sample edge in the ribbon direction while in the transverse direction only about one cell shows adhesive failure. This demonstrates the diffusion of moisture through the adhesive which joins the nodes along the "ribbons". Note that the sample also shows signs of corrosion along the perimeter cells.

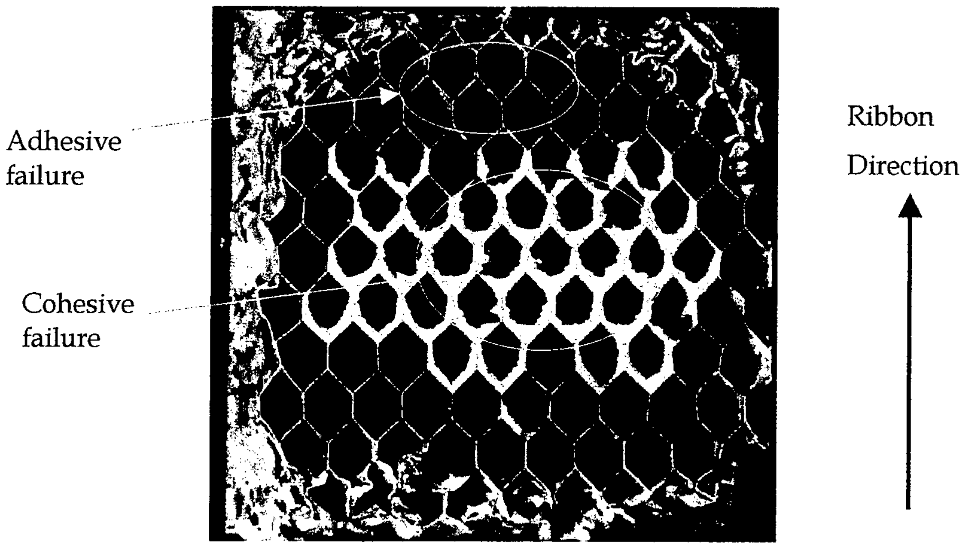


Figure 3 Degradation of fillet bonds (effect of ribbon direction)

3.2 Moisture Transport Through Damaged Structure

Damage to honeycomb sandwich structures can greatly increase the rate of moisture transport. The damage can involve:

Poor sealing: This is the ingress of water into a sandwich structure due to degraded or damaged seals. This allows liquid water to enter the structure.

Damage to facesheets: Impact damage to composite facesheets can create paths for liquid water to enter the sandwich structure. Typical aircraft flights can effectively drive liquid water into the structure due to the pressure differential between ground and high altitude. Work by Augl [5] has also shown that barely noticeable impact damage to composite face sheets can increase the effective transport rate of moisture compared to an undamaged laminate by about two orders of magnitude.

3.3 Numerical Modelling of Diffusion in Sandwich Structures

Numerical modelling of moisture transport in composite skinned honeycomb sandwich structures was performed in order to evaluate the best method to condition and dry honeycomb sandwich structures. A good model of this process allows the estimation of the time required to reach an equilibrium moisture content within all parts of the honeycomb sandwich structure (ie: both the composite facesheets and the adhesive bonds). It was also desired to establish whether the honeycomb sandwich structure could be effectively modelled by just considering the diffusion of moisture through only one side of the composite facesheet (ie: the core effectively insulates the inner side of the facesheet from humid air).

The diffusion of moisture through AS4/3501-6 composite has been studied extensively by Clark et al. [6] and these diffusion constants are used in this model. A one-dimensional FORTRAN code to solve this problem has been produced by Augl and Berger [7]. This code allows the modelling of diffusion through multi-layer sandwich structures under a range of exposure environments. Table 1 shows the parameters used to model a honeycomb sandwich structure comprised of 10 ply graphite epoxy skins (AS4/3501-6) bonded with FM300 adhesive (0.15mm thick) to 50 mm thick aluminium core. The core is modelled as a block of air as the aluminium in the core does not absorb moisture.

Table 1 Input parameters for numerical model of honeycomb sandwich structure

Material	Thickness (mm)	Diffusion Constant# (cm^2/s)	Solubility* (g/100g)	Density (g/cm^3)
AS4 3501-6	1.5	$3.7*10^{-9}$	1.6	1.5
FM300	0.15	$3*10^{-8}$	4.0	1.3
Al. Core	50	$>10^{-2}$	2.1	0.08
FM300	0.15	$3*10^{-8}$	4.0	1.3
AS4 3501-6	1.5	$3.7*10^{-9}$	1.6	1.5

* at 85% R.H

\# at 70°C

Figure 4 shows the results from the model for the panel exposed to 70°C and 85% R.H for time periods up to 120 days. It is clear that the rate limiting step in the diffusion process is that through the composite skins. Moisture content in the core is in equilibrium with the adhesive layer on the inner side of the facesheet ($x \approx 1.5$ mm) at all times. This is expected as the diffusion rate in the facesheets is over seven orders of magnitude lower than in the core. This demonstrates that the core does not significantly affect the diffusion through the facesheet and that the moisture content within the core can be effectively modelled by considering single-sided diffusion through the composite facesheet.

Therefore both the moisture levels on conditioning and drying of composite sandwich structures can be tracked using traveller coupons made of the same layup and material as the composite facesheets. For an undamaged sandwich structure a coupon of twice the thickness of the facesheet / skin, exposed on both surfaces and placed in an identical environment, is required to track the moisture content level.

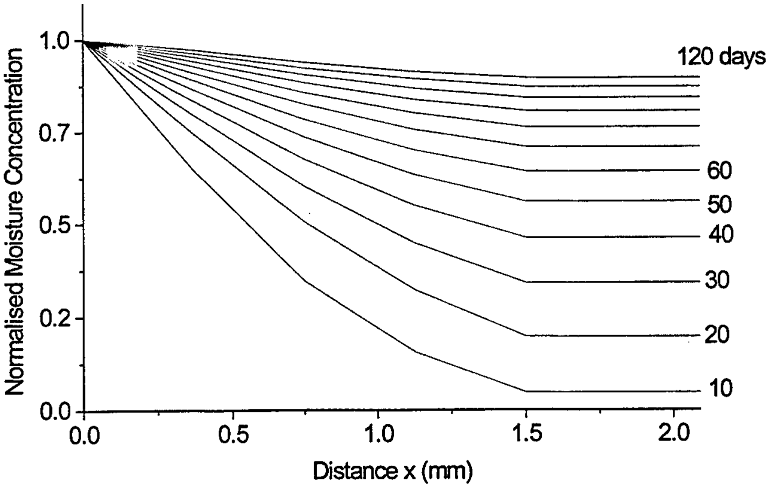


Figure 4 Diffusion of moisture into typical graphite/skinned honeycomb sandwich panel (Table 1). Only the first 2mm of the sandwich structure is shown. Values are symmetric about the core centre.

4. Experimental Approach

An experimenmtal program was designed to simulate environmentally induced failures related to degradation of the adhesive bond between the core and the composite facesheet (the skin fillet bond). The flatwise tension (FWT) test was chosen since it is economical and is a discerning test for the integrity of the skin to core fillet bond.

The experimental program undertaken at AMRL is detailed in Table 2. This defines the matrix for FWT testing. Testing was conducted both at room temperature and at 104°C (220F). Elevated temperature testing was designed to simulate maximum flight temperatures experienced on the F/A-18 during low altitude supersonic flight. Specimens consist of both the diffusion type simulating the effects of humid air on undamaged panels as well as direct ingress simulating liquid water ingress through damage to the composite facesheets or poor sealant integrity.

The basic philosophy of the test program was to simulate the durability of both damaged and undamaged graphite/epoxy skinned aluminium honeycomb sandwich structures.

4.1 Environmental Conditioning

Specimens were conditioned using two environmental conditions, direct and diffusion ingress.

Direct Ingress: This simulated the ingress of liquid water into a honeycomb sandwich structure which may occur due to poor sealing of the component or damage to the composite facesheets. This was simulated in the laboratory by drilling holes into one side of the facesheet above the centre of each honeycomb cell. A condensing humidity environment of 95% at 70°C was then applied simulating liquid water pooling into the damaged structure. This environment was provided by a TABAI climatic chamber. Specimens were conditioned in this environment for periods given in Table 2. Ten ply thick travellers were used to monitor the weight gain during the exposure period since diffusion in these samples can occur from both sides of the composite facesheets. A moisture uptake of 1.8% was observed in the composite skins over the exposure period.

Diffusion Ingress: This simulated a perfectly healthy panel subjected to an environment representative of a worst case tropical environment. A conditioning temperature of 70°C was chosen as a level representative of exposure to high ambient temperature in conjunction with high levels of solar radiation. A humidity level of 85% was chosen on the basis of a worst case tropical humidity level as defined by MIL-HDBK-17. Moisture ingress in these specimens was confined to diffusion by humid air through the composite skins only. After conditioning to moisture equilibrium this should represent the state of honeycomb sandwich panels which have been in service for many years. The conditioning environment was provided by a Heraeus Votsch climatic test cabinet (HC 4055). This gave a stable and accurate environment to within ±1 °C and ±3% R.H.

The moisture content of the coupons was tracked using a traveller coupon of twice the skin thickness (ie: 20 ply). A moisture uptake of 1.6% was observed in the composite skins over the exposure period. Initially diffusion ingress specimens were to be tested at time intervals after moisture equilibrium was established in the specimen. The numerical model of the problem estimated this to be about 120 days or 16 weeks (see Figure 4). It was later decided to begin testing prior to equilibrium at 9 weeks (see Table 2) in order to assess the effects of intermediate moisture content levels.

Table 2 FWT Test matrix

Exposure Condition	**Room temperature (20°C)**	**Hot (104°C)**
	Number of test repeats	
Dry Baseline tests	5	5
Direct moisture ingress by drilled skin and a condensing environment 70°C and 95% R.H		
4 weeks	5	5
9 weeks	5	5
16 weeks	5	5
32 weeks	5	5
52 weeks	5	5
Totals	25	25
Diffusion Ingress through skins in 70°C, 85% RH environment		
9 weeks	3	3
Equilibrium condition = 16 weeks	5	5
32 weeks	5	5
52 weeks	5	5
Totals	18	18

4.2 FWT Specimen Preparation

4.2.1 Panel Material & Manufacturing Process

Two nominally 700 mm x 600 mm graphite epoxy honeycomb sandwich panels were manufactured to simulate representative F/A-18 honeycomb sandwich structure.

The core material was 5/8" deep, 5056 alloy, CRIII coated aluminium honeycomb, of cell size 3/16" and density 5.7 pcf. The skins were manufactured 10 plies thick from AS4/3501-6 graphite/epoxy pre-preg and cured according to the manufacturer's specifications. The ply lay-up for the skins was (+45, -45, 0, 90, 0)$_S$. Cytec FM300 film adhesive was used to bond the skins to the aluminium honeycomb core using the manufacturer's recommended cure cycle.

Panels for room temperature testing were designated **R** while those to be tested at 104 °C (220 F) designated **H.**

4.2.2 Panel Cutting & Test Material Distribution

Each of the two manufactured panels were cut wet, with water, using a diamond tipped circular saw, into sections with dimensions as shown in Figure 5. These sections were further cut into 50mm by 50mm test coupons in accordance with the requirement for FWT specimen manufacture as given in ASTM C 297-94. Two sets of test specimens were prepared one for each of the room temperature (R) and hot (H) test conditions.

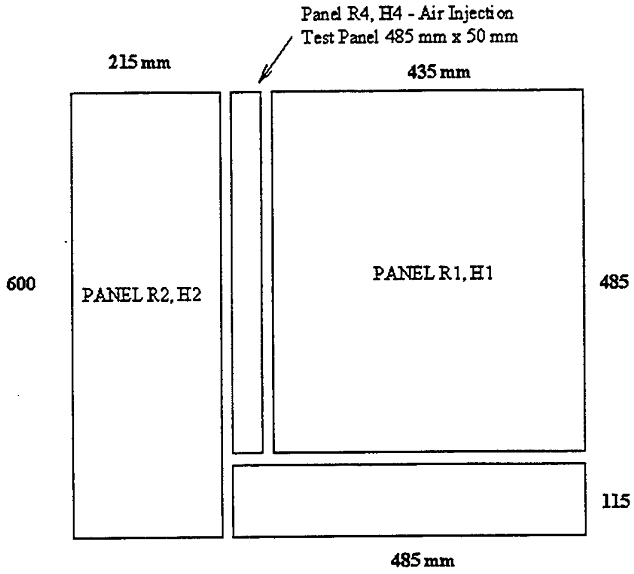


Figure 5. Panel breakdown. Two panels were cut identically for room temperature (R) and hot (H) tests respectively. These sections were then cut into 50mm square test coupons as per ASTM C 297-94.

4.2.3 Edge Sealing

All coupons were edge-sealed on all sides , as depicted in Figure 6, using Courtalds PR1422B2 sealant to minimise corrosion of the aluminium honeycomb core over the environmental exposure period. PR1422B2 sealant is a polysulfide rubber compound, which is typically used as a fuel tank sealant in the aviation industry.

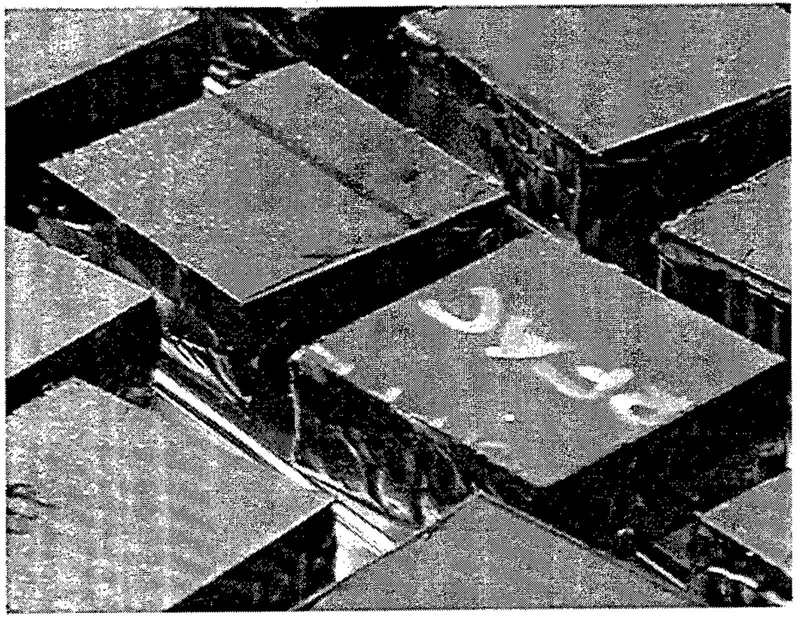


Figure 6 FWT coupons edge sealed using polysulfide rubber sealant compound. Diffusion ingress coupons are pictured; direct moisture ingress samples were treated identically.

4.2.4 Direct Moisture Ingress Test Coupons

Panels R1 and H1 were drilled wet from one side using diamond tipped drills of diameter 0.75 mm. Drilling was undertaken using CNC equipment to drill through the skin and ideally enter the core near to the centre of a cell. Figure 7 shows a typical direct moisture ingress sample. Skins were drilled from one side only to enable humid air to condense and pool in the core as liquid water.

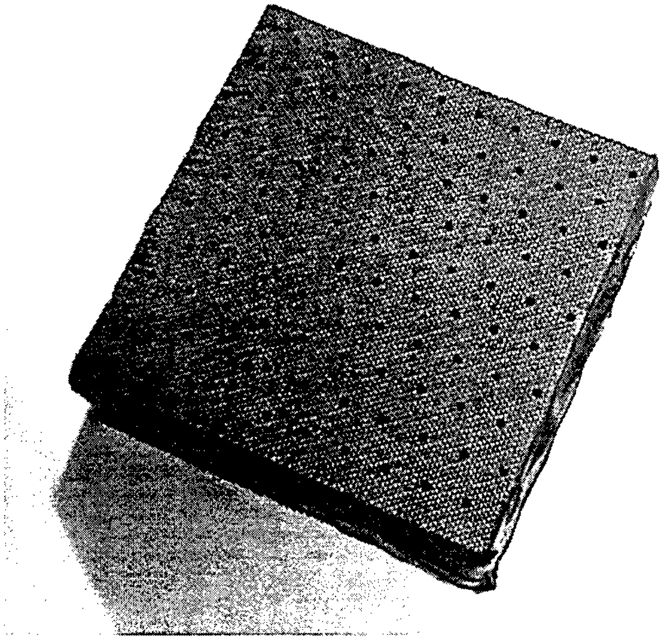


Figure 7 Direct moisture ingress FWT coupon showing the 0.75 mm holes drilled through the top skin into the nominal centre of each honeycomb core cell.

4.2.5 Diffusion Ingress Test Coupons

These coupons represent healthy honeycomb sandwich structure thus the 10 ply skins on these specimens were not drilled.

4.3 Flatwise Tension (FWT) Test Coupon Manufacture

On reaching the exposure period for the given condition, a batch of up to 5 coupons was removed from the conditioning environment, the loading blocks were bonded to the coupon and the assembly tested in its respective condition (room temperature or hot). Typically 3 or 4 coupons were tested and the "spare" coupons either continued conditioning or were removed and kept for other studies.

To enable tensile loads to be applied through the skins of the coupons, loading blocks were bonded to the FWT coupon skins using a suitable adhesive. The bonded assembly was then held in the loading fixture by pins and loaded to failure in a mechanical test machine to establish the FWT strength for the given exposure condition. Valid FWT tests were characterised by failure either of the adhesive bondline between the honeycomb core and the face-sheet or by tensile failure of the aluminium honeycomb core. Failure at the adhesive bondline between the loading block and the FWT coupon skin indicated the bond integrity at that interface was insufficient to evaluate the FWT of the skin to core bond or the FWT strength of the core.

Significant consideration was given to both surface preparation and adhesive type for bonding the loading blocks to the FWT coupons. Of obvious concern was the influence of liquid water and its effect on the bond integrity to enable valid FWT assessment. For the direct moisture ingress specimens, it was evident that after conditioning, these coupons would contain liquid water that had condensed in the honeycomb cells. Similarly, for the diffusion samples the skins could contain moisture levels up to about 1.6% by weight at equilibrium. At high curing temperatures, these moisture sources could affect the bond integrity between the loading block and specimen face. Therefore the room temperature test coupons were bonded using low temperature adhesives to avoid potential boiling of water in the specimens as well as to avoid drying the coupons prior to testing. Elevated temperature test coupons needed to be bonded using an adhesive that could withstand the test temperature after absorbing some moisture from the composite skins during cure.

After a series of trials Hysol EA9320NA was selected to bond the loading blocks to the specimen for the room temperature tests. This adhesive was cured at room temperature for 8 hours then post-cured for a further 2 hours at 50 °C. For the hot tests (104°C) Cytec FM 300-2 structural adhesive was cured at 120°C for 90 minutes.

4.4 FWT Bonding Jigs

To obtain the true FWT strength of a bond, eccentricity in loading should be eliminated and a purely tensile load applied. For this reason, the bonding jig shown in Figure 8 was developed to ensure the bonding surfaces between the loading blocks and specimen remained parallel during the curing process. A spring was used to maintain a constant pressure on the adhesive during the cure cycle. Both room temperature and elevated temperature cure cycles were accommodated using this jig.

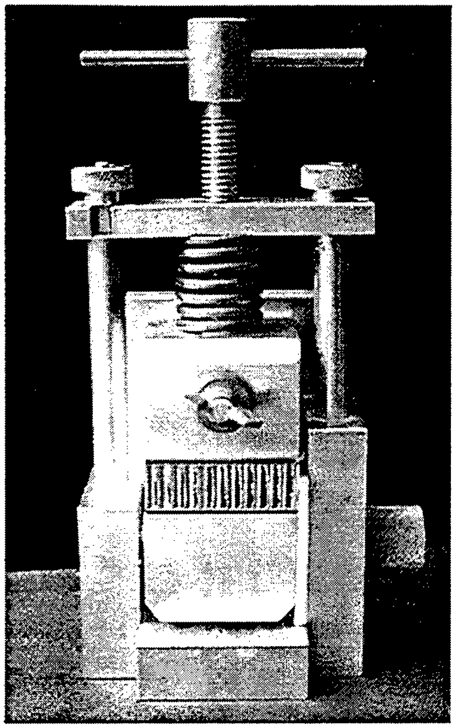


Figure 8 FWT loading block bonding jig

4.5 FWT Test Procedure & Equipment

All testing and manufacture of the FWT samples was in accordance with ASTM C 297-94. The flatwise tension specimen complete with loading blocks was loaded into a self-aligning loading fixture. Tensile load was applied using an Instron Model 1185 electro-mechanical test machine. Data was recorded using a PC-based data acquisition system. Some initial testing was conducted using a cross head displacement rate of 0.5 mm/min. Using this rate, the failure load was reached in under 3 minutes and this was not in accordance with the ASTM standard. All subsequent tests were conducted using a crosshead displacement rate of 0.2 mm/min with failure occurring between 3 and 6 minutes in accordance with the ASTM standard. Figure 9 shows a typical FWT test setup within a heater cabinet.

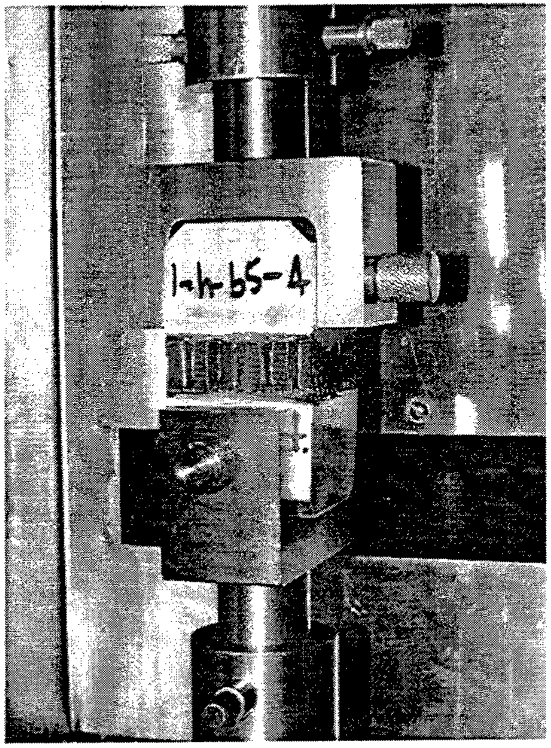


Figure 9 FWT Test set up in mechanical testing machine

4.6 FWT Hot Testing Procedure

The hot (104°C) test environment was achieved using an Instron model 3111 heater cabinet mounted in the Instron 1185 test machine load frame. In order to maintain an accurate test condition of 104°C at the FM300 skin to core adhesive bondline, a spare FWT coupon (dummy specimen) was used to calibrate the operation. The dummy specimen complete with loading blocks was fitted into the loading fixture along with two thermocouples, one located at the centre of the specimen at the core to skin interface (in the FM300 bondline), and the other located at the top loading block surface. A temperature calibration curve was established as shown in Figure 10. The typical specimen soak time was approximately 30 minutes for the FM300 bondline to reach the test temperature of 104°C. All hot FWT tests were monitored by one thermocouple at the loading block surface and commenced when the temperature of this surface reached 104°C (220F) as shown in Figure 10.

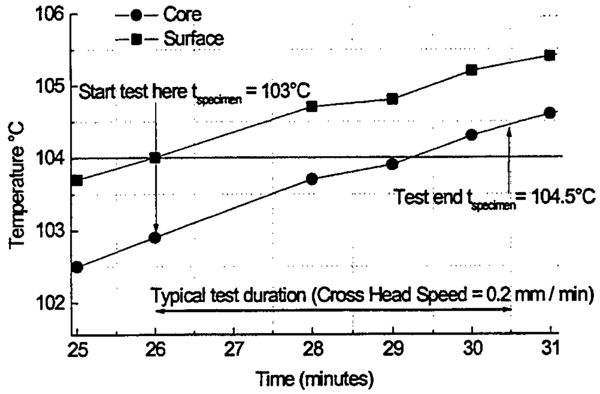


Figure 10: Adhesive bondline temperature calibration curve for hot FWT tests at 104°C

5. Dry Recovery of FWT Strength

The dry recovery of FWT specimens was investigated to ascertain whether any reduction of flatwise tension strength, attributed to environmental degradation or plasticisation of the adhesive, could be recovered by the application of a drying cycle. The assumption was made that complete dry recovery would occur when the composite facesheets were fully dried as predicted by numerical diffusion models or traveller coupons.

Two methods of dry recovery were investigated. Firstly, one based on a Structural Repair Manual (SRM) drying procedure and secondly one based on numerical modelling of the diffusion process.

1. A 'water removal' cycle as per F/A-18 SRM-250 WP 005 consisting of drying the specimen for 6 hours at 70°C. The FWT strength after applying this drying cycle for a specimen which saw 9 weeks of direct moisture ingress was then evaluated.
2. A more aggressive drying cycle using 90 °C was applied to diffusion ingress FWT coupons having had 16 weeks exposure. The FWT strength was then assessed after the specimens were dried at 90°C for time periods of up to four weeks. A temperature of 90°C was chosen as it is below the boiling point of water and unlikely to create significant steam pressure.

Utilising the diffusion model developed earlier the time taken to dry the composite skins was calculated at 4 weeks at 90°C. Samples that had been exposed to direct and diffusion ingress environments for up to one year were dried at 90°C for 4 weeks.

6. Results

The results of the FWT tests are shown in Table 3 and Table 4. Results are shown as an average value from the test batch together with the standard deviation.

Table 3 FWT test result matrix for direct ingress specimens

		FWT Strength (MPa) Room Temperature		FWT Strength (MPa) Elevated Temp. (104°C)	
Identifier	Exposure	**Average**	s.d	**Average**	s.d
a	Dry **Baseline**	7.27	0.52	4.88	0.23
b1	4 weeks	7.1	0.40	3.46	0.50
b2	9 weeks	5.43	0.42	2.09	0.20
b3	16 weeks	4.97	0.72	2.15	0.23
b4	32 weeks	4.91	0.47	2.43	0.17
b5	52 weeks	4.77	0.31	2.36	0.22

Table 4 FWT test result matrix for diffusion specimens

		FWT Strength (MPa) Room Temperature		FWT Strength (MPa) Elevated Temp. (104°C)	
Identifier	Exposure	**Average**	s.d	**Average**	s.d
c2	9 weeks	6.44	0.46	2.68	0.29
c0	Equilibrium = 16 weeks	5.73	0.33	2.74	0.12
c3	32 weeks	5.81	0.26	2.56	0.15
c4	52 weeks	5.94	0.20	2.86	0.04

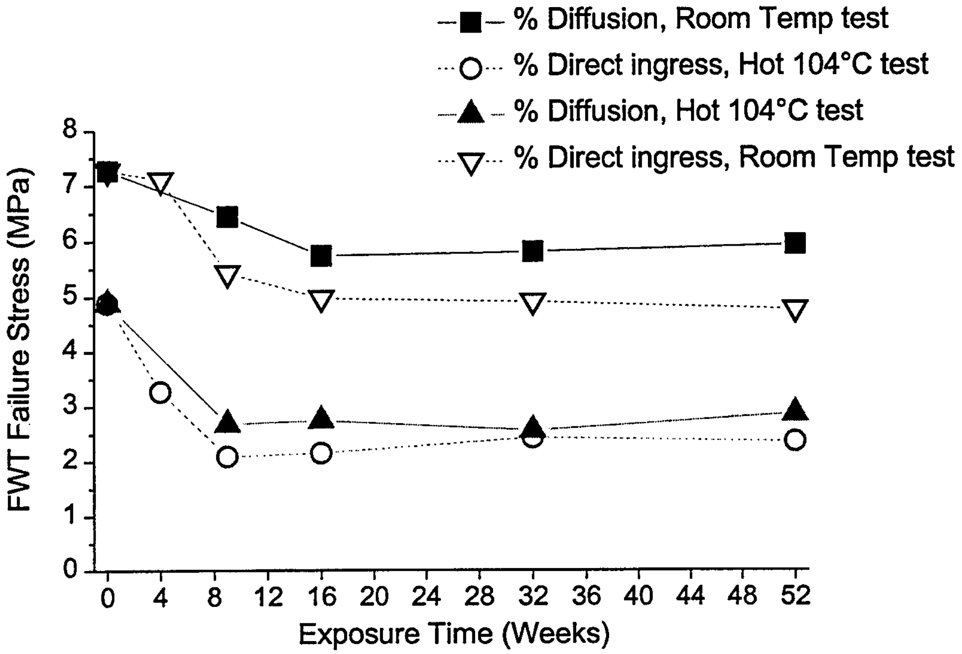


Figure 11 FWT test results for direct moisture ingress and diffusion moisture ingress tested under room temperature and hot 104 °C test conditions.

Figure 11 plots the FWT failure stress (MPa) against the exposure time in weeks. Figure 12 shows the FWT data normalised against the dry baseline result for each of the two test temperatures considered.

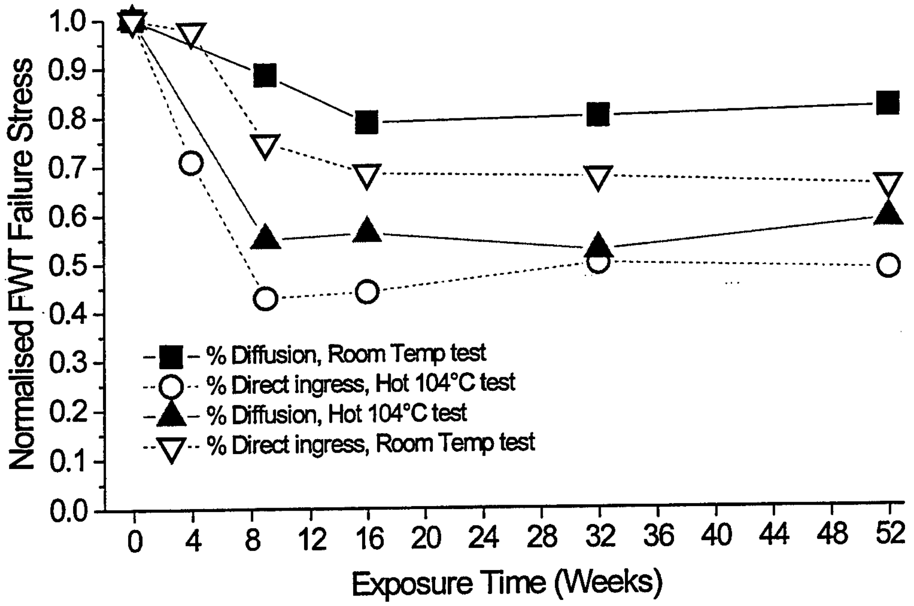


Figure 12 Normalised FWT test data for direct moisture ingress and diffusion moisture ingress tested under room temperature and hot 104°C test conditions

6.1 Fractographic Observations on FWT Coupons

Preliminary fractographic observations have been undertaken on the failed FWT test articles. Table 5 shows the change of fracture mode for test temperature and exposure time for the direct ingress specimens. For the direct ingress coupons, tested in either the room temperature or hot condition, there are clear indications of a change from cohesive, through mixed cohesive/adhesive to adhesive fracture surface appearance which corresponds to a decrease in FWT strength as shown in Figure 11. The diffusion ingress specimens showed cohesive failure in all cases even though decreases in FWT strength of similar magnitude to the direct ingress specimens were observed.

Table 5 FWT Failure Modes for Direct Ingress specimens.

Exposure Time	Room Temperature	Elevated Temperature (104 °C , 220 F)
Baseline	Cohesive	Cohesive
4 weeks	Cohesive	60% Cohesive
9 weeks	60% Cohesive	Less than 20% cohesive
16 week	60% Cohesive	Less than 20% cohesive
32 week	60% Cohesive	Less than 20% cohesive
52 week	60% Cohesive	Less than 20% cohesive

The skin to core fillet was biased in distribution around the perimeter of the core cells in some specimens as shown in Figure 13. Figure 14 shows the degradation of a direct ingress coupon; adhesive failure predominates. Figure 15 clearly shows cracking at a core node bond after being tested to failure in a FWT test. Figure 16 shows further levels of extreme degradation on exposure to liquid water for a period of 16 weeks.

The fillet form was also skewed in some cases as seen in Figure 17. The ideal fillet form would be that of an 'equilateral' triangle, distributed equally around all edges of the cell. The fillet skew identified (Figure 17) shows an uneven distribution of adhesive depth and shape from the top of the cell to the fillet depth. The skew may be due to the cleaning procedure used to prepare the honeycomb material for bonding. Vapour degreasing of honeycomb material may cause impurities to collect on certain sides and to differing depths within the honeycomb cells. This effect has not yet been fully investigated and will receive attention in future testing trials.

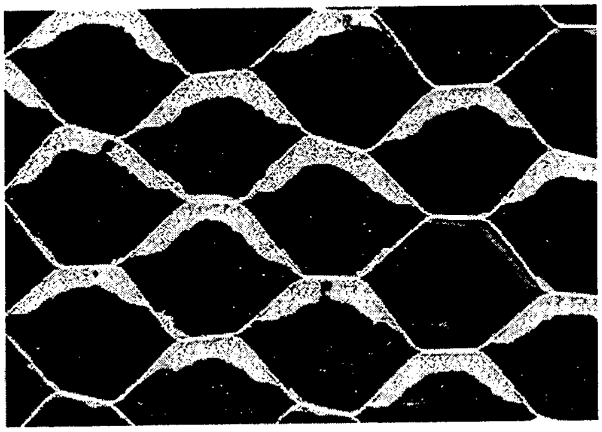


Figure 13 Bias of the amount of adhesive remaining on the core of an environmentally degraded FWT coupon.

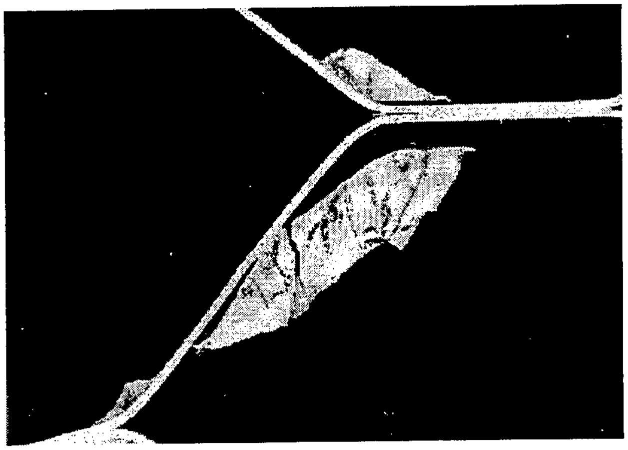


Figure 14. FWT direct ingress test coupon showing the fillet to core bond separation after 16 weeks of exposure (test conducted at room temperature).

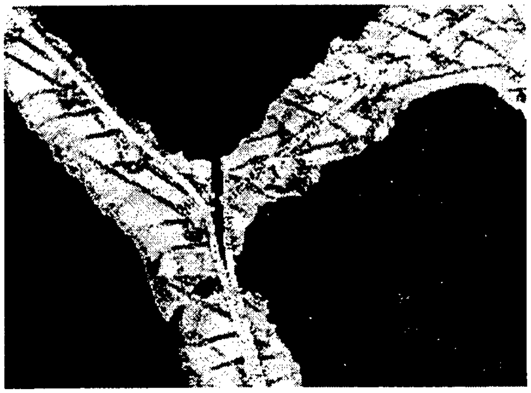


Figure 15. Cracking through the skin to core fillet and into the node bond in a direct moisture ingress sample after 16 weeks exposure.

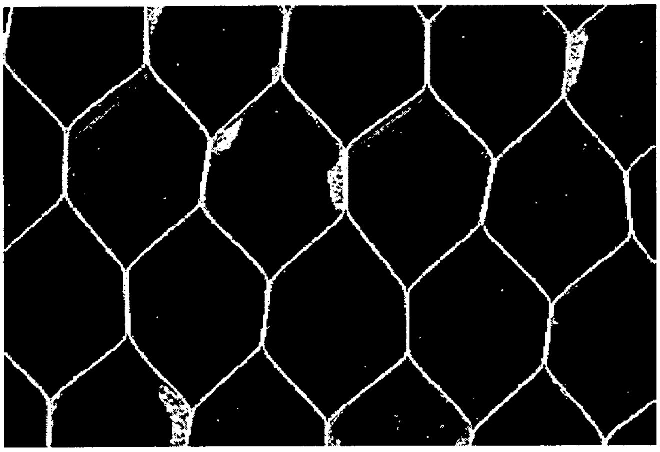


Figure 16. Core cells of a failed FWT test coupon exposed via direct moisture ingress for a period of 16 weeks. The failure surface is virtually purely adhesive.

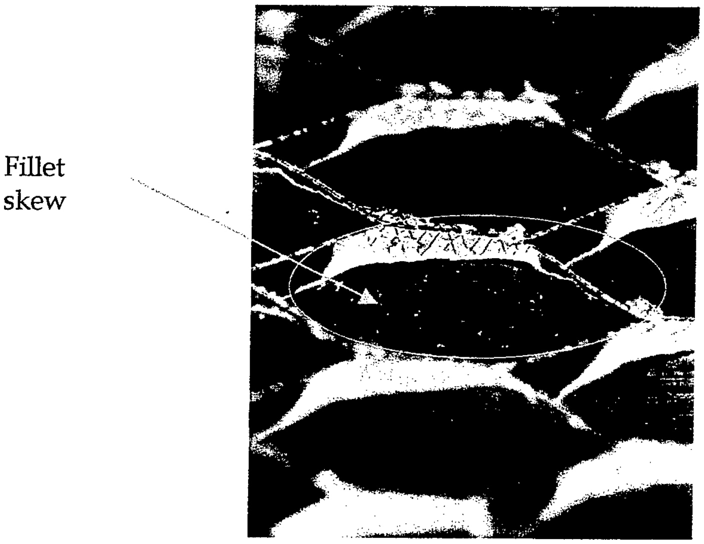


Figure 17. Skew and bias in skin to core fillet adhesive.

6.2 Dry Recovery of FWT Strength

6.2.1 SRM Dry Recovery

This dry recovery procedure (6 hours at 70°C) was applied to one direct ingress (ie: drilled skin) FWT test coupon which had previously seen an exposure environment of 9 weeks at 70°C and 95% R.H. The specimen was then tested at room temperature. The average FWT strength of coupons exposed to this condition (9 weeks at 70°C and 95% R.H.) was 5.43 MPa. The FWT strength for the coupon that had been "dried" using the SRM method was 4.74 MPa, hence dry recovery was not successful using this procedure.

6.2.2 Diffusion Based Dry Recovery

Results of FWT strength versus various drying times at 90°C are shown in Figure 18. All tests were conducted at room temperature on diffusion ingress FWT coupons (ie: non-drilled) which had previously seen 16 weeks exposure to 70°C and 85% R.H. This shows that full recovery of FWT strength is achieved after a period of time required to fully dry the composite skins (ie: 4 weeks).

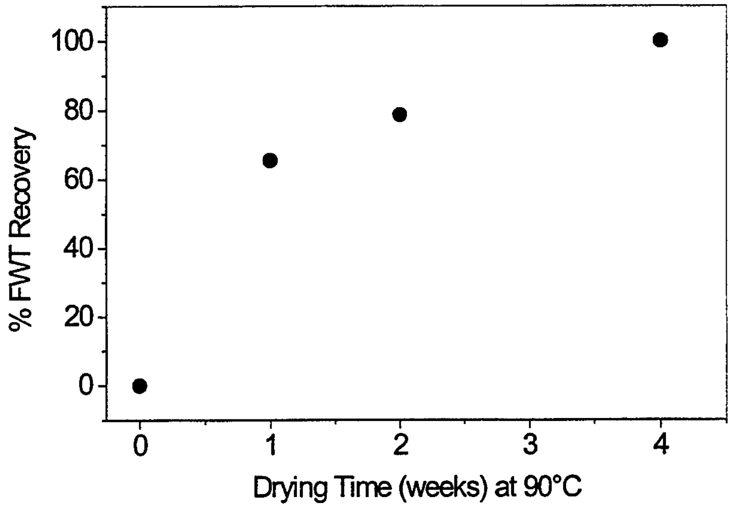


Figure 18 Dry recovery of FWT strength (dried in oven at 90°C)

Specimens exposed to both diffusion and direct ingress for a period of one year were evaluated using a dry recovery procedure of 4 weeks at 90°C to determine the amount of recovery possible. Results are shown in Table 6.

Table 6 Dry recovery of specimens after one year of hot/wet environmental exposure

Exposure Type	Average Dry Recovery (%)
Diffusion Ingress – Room Temp.	86 (single result)
Diffusion Ingress – Elevated (104°C)	97 ± 3.2
Direct Ingress - Room Temp.	71 (single result)
Direct Ingress - Elevated (104°C)	72 ± 11.5

This shows a very good level of recovery for most of the diffusion ingress samples but only partial recovery in the direct ingress cases.

7. Discussion

Exposure of honeycomb sandwich structure to hot/wet environments has been shown to decrease flatwise tension strength by up to 50% (Figure 12) at elevated temperature and 25% at room temperature. The loss in FWT properties occurred in the first 16 weeks after which the values remained constant up to the end of the trial at 52 weeks. Also, the difference between the FWT strength values of direct ingress and diffusion ingress specimens is not great. This is a particularly interesting observation since the failure mode of the diffusion coupons remains cohesive during the entire exposure period while the direct ingress samples exhibit gross adhesive failure after long-term exposure. Typically adhesive failure surfaces are associated with failure through the aluminium oxide layer resulting in poor bond strength. Some preliminary surface analysis on direct moisture ingress specimen fracture surfaces has been undertaken to better understand the failure locus. Visually, the failure surface looks very much like an adhesive failure however, surface analysis has indicated that the failure is through the thin layer of adhesive containing the CR III chromium coating. The CR III layer appears to have similar strength to the adhesive layer which may explain the similar FWT values to the diffusion ingress samples but with markedly different failure mode. Further analysis is required in order to adequately explain this observation.

This indicates that the adhesive bonds in this structure are able to withstand direct moisture exposure for extended periods without losing significant bond strength compared to a fully sealed structure. Thus the absolute value of flatwise tension strength itself may not be an ideal guide to the integrity (in terms of liquid water sealing) of the structure. This is an important point if proof tests such as PORTA-PULL (which is essentially a field version of the flatwise tension test) are used to determine the 'soundness' of a honeycomb sandwich structure. The locus of failure must be an integral part of any such test.

Differences in the degradation mechanisms between direct and diffusion ingress cases become apparent when the dry recovery of the specimens is considered (see section 6.2). The diffusion specimens dry out and recover much of their original properties which indicates that any reductions in FWT strength are due to moisture in the adhesive causing plasticisation and not due to any permanent degradation of the adhesive bond. The direct ingress specimens however did not recover their full FWT strength (only about 70% of original baseline) which indicates that some level of permanent adhesive bond degradation has occurred. Once the failure mode of the component changes from cohesive to adhesive it is unlikely that dry recovery procedures will restore full FWT strength.

Using dry recovery procedures to restore FWT strength in healthy components in RAAF service is not likely to be productive as the moisture content of the skins will re-establish again during normal service. For damaged components or those which contain liquid water the danger with using elevated temperature heating (> 100°C) to perform dry recovery is that any trapped liquid water may cause damage to the structure through steam pressure and may even accelerate the degradation of surrounding adhesive bonds and promote corrosion.

The results reinforce the need to ensure that liquid water is prevented from entering a honeycomb sandwich structure. Results up to one year of exposure indicate that well-sealed honeycomb sandwich structures show no noticeable permanent bond degradation. However, once liquid water has entered a structure, moisture will transport through the adhesive at the nodes, the adhesive fillet bond and through damage caused by corrosion. This highlights the need to ensure that all seals on honeycomb sandwich structures are in good order and that the skins are not damaged in such a way that liquid water may enter the structure. The detection of liquid water within honeycomb sandwich panels is of great importance to ensure that degradation similar to that demonstrated with the direct ingress coupons shown here does not create permanent bond degradation.

Fractographic analysis has shown that the adhesive fillet which forms during manufacture of honeycomb components is not always uniform in shape. The fillet is often skewed or biased towards one side of the cell. The reason for this is not fully explored here but may be associated with cleaning procedures applied to the core prior to bonding.

No corrosion of the core was noted for any of the tests performed here where specimens were exposed to humid air. The chromium coating on the honeycomb (CRIII) was quite effective when exposed to high humidity levels and elevated temperature (70°C and 95% R.H). Note that for samples tested fully immersed in water at 70°C (Figure 3) significant corrosion damage was seen after a period of only 4 weeks. This is quite a severe test case and would suggest that quite a long period of exposure to humid air is required to cause significant corrosion damage.

Some evidence of node bond degradation has been observed using optical microscopy (Figure 15). The level of node bond degradation was not under investigation in this study and is thus not quantified. Future work will be aimed at examining the level of node-bond degradation and the implications for structural integrity.

8. Summary

A long-term (52 week) hot/wet environmental exposure trial was conducted to determine the effects on the flatwise tension (FWT) strength of honeycomb sandwich structure.

In service, moisture in the form of either humid air or liquid water can enter a honeycomb sandwich via 3 primary means:

- poor or damaged or degraded seals around penetrations or the edges of panels
- direct ingress of liquid water through damaged facesheets (skins)

- diffusion of moisture from humid air through the epoxy matrix in the composite skin

The trial exposed specimens to environments in which (1) humid air could freely enter the core and condense as liquid water (direct ingress) and (2) specimens were fully sealed and allowed only moisture to enter by diffusion through the epoxy matrix of the skins (diffusion ingress).

Moisture transport in the honeycomb core has been observed to be directional and biased along the ribbon direction due to the presence of adhesive node bonds.

The FWT values were seen to decrease by about 40-50% when tested at 104°C and about 25% when tested at room temperature.

The FWT strength reduction associated with exposure to an aggressive environment plateaus after approximately 16 weeks for periods of up to one year.

Both the direct ingress and diffusion ingress samples showed similar FWT strength losses but markedly different modes of failure.

Diffusion ingress specimens failed cohesively in all cases while the direct ingress samples failed predominantly adhesively after exposure periods of longer than about 9 weeks.

The fracture surface appearance alone may not be a reliable indicator of the bond strength, however a cohesive failure is still an indication of good adhesive to core interface bond integrity.

The F/A-18 SRM water removal procedure did not restore the FWT strength of environmentally degraded test coupons.

Subsequent drying of the exposed samples at 90°C for periods of up to 4 weeks showed that diffusion ingress samples recovered most of their original FWT strength however direct ingress samples recovered only about 70% of their original baseline strength.

For the diffusion exposure case, up to 52 weeks of exposure to an aggressive environment representative of the worst case service environment does not appear to permanently degrade adhesive bond strength.

Absorbed moisture (either liquid water or humid air) does reduce FWT strength. In this study moisture levels of up to 1.8% in the composite skins were achieved over the exposure period. The maximum expected moisture uptake level in RAAF composite aircraft components has been previously measured to be of the order of only 1.0% maximum. Therefore the results of this study are somewhat conservative and represent a worst case exposure scenario. Although the moisture content examined was conservative it is not possible to reliably simulate the effects of long-term (many years) exposure in such a laboratory based trial. Although the exposure conditions here are used to accelerate any degradation processes the exact time dependent nature of any degradation processes on RAAF aircraft is not known.

In the case of diffusion ingress, this is due to adhesive plasticisation, while in the direct ingress samples permanent bond degradation was noted by change to an adhesive failure mode. This work shows that excluding water from within honeycomb sandwich structures is of primary importance in order to prevent permanent bond degradation and corrosion of the core.

9. Recommendations

- Honeycomb sandwich structures need to be maintained stringently to prevent water from entering the structure through damaged seals or cracked composite skins. Work in this report has showed that liquid water inside honeycomb structures can result in failure of the adhesive bond to the core. This does not appear to be the case for diffused moisture through the composite skins; for periods of exposure up to one year.
- Drying panels to increase or recover FWT strength is not advised as a routine maintenance procedure especially if it is not clear whether the structure contains any water. Drying or bonding operations above 100°C need special consideration since at these elevated temperatures liquid water can generate high steam pressures that can damage components.
- Porta-Pull strength results (which consist of a test similar to FWT) taken from aircraft structure should be treated with some caution. High Porta-Pull strength values combined with a cohesive failure mode are required in order to establish that a structure is sound.

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Representative of F/A-18: Flatwise Tension Strength

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19. ABSTRACT

Aluminium honeycomb structure is widely used in the F/A-18 to save weight, however it is susceptible to degradation by water. The US Navy has experienced in-flight failures of honeycomb components such as the rudder which are believed to be due to moisture induced degradation. A long-term (52 week) environmental exposure trial was conducted to determine the effects on the flatwise tension (FWT) strength of honeycomb sandwich structure. A conditioning temperature of 70°C was chosen coupled with high-humidity exposure (85% and 95% R.H) to simulate a worst-case hot/wet environment. The trial simulated specimens in which moisture could freely enter the core (direct ingress) and those which were fully sealed and allowed only moisture diffusion through the epoxy matrix of the skins (diffusion ingress). The FWT strength was measured at 4, 9, 16, 32 and 52 weeks exposure. The FWT values decreased by about 40-50% when tested at 104°C and about 25% when tested at room temperature after exposure periods greater than 16 weeks. Both the direct ingress and diffusion ingress samples showed similar FWT strength losses but markedly different modes of failure. Diffusion specimens failed cohesively in all cases while the direct ingress samples failed predominantly adhesively after an exposure time of about 9 weeks. Subsequent drying of the samples exposed to the conditioning environment showed that diffusion ingress samples recovered most of their original FWT strength but direct ingress samples recovered only about 70% of their original baseline strength. This work shows that excluding water from within honeycomb sandwich structures is of primary importance in order to prevent permanent bond degradation and corrosion of the core.