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Damage mechanisms and non-destructive testing in the case of water ingress in CF-18 flight control surfaces

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Defence R&D Canada

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14. ABSTRACT

(U) Most service failures of adhesive bonded aircraft structures have been attributed to environmental degradation of bonded joints exposed to moist conditions. High humidity normally leads to plasticisation of the adhesive and an associated reduction of mechanical properties recoverable upon drying. Conversely, direct water ingress causes permanent adhesive bond degradation. Very little is known of the degradation mechanisms experienced with direct water ingress; however, this knowledge is required to establish the inspection requirements and for fielding nondestructive testing (NDT) techniques. This technical memorandum details the possible damage mechanisms and the results obtained with various nondestructive testing techniques tested during the course of the project.

(U) La cause première des défaillances de structures jointes par un adhésif est attribué à la dégradation environnementale des joints qui furent exposés à de forts taux d'humidité. Cette condition tend à plastifier l'adhésif et ainsi réduire ses propriétés mécaniques qui sont toutefois recouvrable après un séchage complet. Par contre, l'eau qui entre en contact direct avec l'adhésif cause une dégradation permanente. Les mécanismes de bris dû à la présence de l'eau sont très peu connus; cependant, ces connaissances sont nécessaires afin d'établir les besoins en inspection et de sélectionner une, ou des, technique(s) d'essai(s) non-destructif(s). Ce mémorandum technique identifie les divers mécanismes de bris et les résultats obtenus grâce aux diverses techniques d'essais non-destructifs durant le projet.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) nondestructive testing, nondestructive evaluation, damage mechanism, honeycomb structure, adhesive degradation, water ingress, flight controls.

Abstract

Most service failures of adhesive bonded aircraft structures have been attributed to environmental degradation of bonded joints exposed to moist conditions. High humidity normally leads to plasticisation of the adhesive and an associated reduction of mechanical properties recoverable upon drying. Conversely, direct water ingress causes permanent adhesive bond degradation. Very little is known of the degradation mechanisms experienced with direct water ingress; however, this knowledge is required to establish the inspection requirements and for fielding nondestructive testing (NDT) techniques. This technical memorandum details the possible damage mechanisms and the results obtained with various nondestructive testing techniques tested during the course of the project.

Résumé

La cause première des défaillances de structures jointes par un adhésif est attribué à la dégradation environnementale des joints qui furent exposés à de forts taux d'humidité. Cette condition tend à plastifier l'adhésif et ainsi réduire ses propriétés mécaniques qui sont toutefois recouvrable après un séchage complet. Par contre, l'eau qui entre en contact direct avec l'adhésif cause une dégradation permanente. Les mécanismes de bris dû à la présence de l'eau sont très peu connus; cependant, ces connaissances sont nécessaires afin d'établir les besoins en inspection et de sélectionner une, ou des, technique(s) d'essai(s) non-destructif(s). Ce mémorandum technique identifie les divers mécanismes de bris et les résultats obtenus grâce aux diverses techniques d'essais non-destructifs durant le projet.

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Executive summary

In November 1995, a cooperative effort between McClellan Air Force Base and the Canadian Forces Nondestructive Center resulted in X-ray and N-ray inspections of a CF-18. This inspection revealed indications of moisture ingress in the graphite/epoxy skin layers and aluminum honeycomb core structure of the left-hand rudder. This discovery and the subsequent in-flight disintegration of a rudder's structure led to the initiation of a corrosion/water ingress inspection program for the flight control surfaces of the CF-18 to assess the extent of the problem in the fleet.

The failure mechanisms are extremely complex and may be a combination of several different failure modes; however, the cause of failure is directly linked to water ingress in the flight control. Moisture (due to diffusion ingress) can have an adverse effect on the cohesive strength of adhesives, but the recovery of joint strength upon drying gives indirect evidence that the failure mechanisms encountered in flight control surfaces are not linked with moisture ingress. On the other hand, water ingress (or direct ingress) causes permanent degradation of the adhesive bond and degradation or loss of (adhesive) connection between the "chrome containing part" of the coating of the honeycomb core and the bonding system.

Various nondestructive testing techniques have proven to be effective in detecting the presence of moisture, the presence of water, the degradation of bond strength, the corrosion in honeycomb cells, and in verifying the control surface seal integrity to prevent water ingress. Currently, thermography is considered the best tool to rapidly screen flight controls with defects. After initial screening, a combination of techniques can be used to determine the stages or types of damage. Finally, preventing water to ingress the sandwich structure is considered the first line of defence against damage. To that effect, a helium mass spectrometer leak detection system can be used to assess the flight control seal integrity.

Giguère, J.S.R.. 2000. *Damage Mechanicsms and Nondestructive Testing in the Case of Water Ingress in CF-18 Flight Control Surfaces*. DCIEM TM 2000-098. Air Vehicle Research Section.

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Sommaire

En novembre 1995, un effort coopératif entre le personnel de la base aérienne américaine McClellan et le personnel du Centre d'essais nondestructifs des Forces canadiennes a permis d'inspecter un CF-18 par radiographie conventionnelle et par radiographie à neutron. Cette inspection a révélé la présence d'humidité et d'eau dans le gouvernail gauche, soit dans le revêtement en composite de fibre de carbone et dans l'âme en nid d'abeilles. Cette découverte, suivie par la désintégration d'un gouvernail lors d'un vol, a mené à la mise en oeuvre d'un programme d'inspection afin de détecter la corrosion et la pénétration de l'eau à l'intérieur des surfaces de contrôle du CF-18 et de déterminer l'étendue du problème.

Les mécanismes de bris sont extrèmement complexes et peuvent être dûs à une combinaison d'un grand nombre de modes de bris; cependant, la cause du bris est directement relié à l'entrée d'eau dans la surface de contrôle. L'humidité (présente par le phénomène de diffusion) peut avoir un effect négatif sur la force de cohésion des adhésifs, mais le recouvrement des propriétés mécaniques lors du séchage donne une preuve indirecte que le mécanisme de bris des surfaces de contrôle ne sont pas reliés à l'humidité. Par contre, l'eau (présente par entrée directe à l'intérieur de la construction sandwich) cause une dégradation permanente du lien adhésif et une dégradation, ou perte de connexion, entre la partie contenant le chrome pour l'enduit sur l'âme en nid d'abeilles et l'adhésif.

Plusieurs techniques d'essais nondestructifs se sont prouvées comme étant efficace pour détecter la présence d'humidité, la présence d'eau, la dégradation de la force adhésive, la corrosion de l'âme des nids d'abeilles, et vérifier l'intégrité de l'étanchéité de la surface de contrôle afin de prévenir la pénétration de l'eau. Présentement, la thermographie s'est avérée le meilleur outil afin d'identifier rapidement les surfaces de contrôle présumées défectueuses. Après cet examen sélectif, une combinaison de techniques d'essais nondestructifs peut être utiliisée afin de déterminer les divers stages et types de dommages. Finalement, la meilleure méthode pour protéger les surfaces de contrôle est d'empêcher l'eau de pénétrer à l'intérieur de la structure de construction sandwich. À cet effet, une technique utilisant un spectromètre de masse peut servir à déterminer l'intégrité de l'étanchéité des surfaces de contrôle.

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Table of contents

List of figures

List of tables

Acknowledgements

Active thermography results were obtained during trials and demonstration conducted by Thermal Wave Imaging, Inc. . Their contribution and sharing of inspection results are greatly appreciated. The author also wishes to thank NDT inspection technologists at the Quality Engineeering Test Establishment (QETE), the Canadian Forces Nondestructive Test Centre, and the Royal Military College of Canada for conducting the various NDT inspections on CF-18 flight controls.

Introduction

In November 1995, a cooperative effort between McClellan Air Force Base and the Canadian Forces Nondestructive Center resulted in the X-ray and N-ray inspection of a CF-18. The ability to correlate the results for both inspections gave a picture of both the moisture ingress and the structural integrity of the flight controls inspected. This inspection revealed indications of moisture ingress in the graphite/epoxy skin layers and aluminum honeycomb core structure of the left-hand rudder. Subsequently, a full range of tests were performed on the rudder including all nondestructive inspection methods readily available through the Canadian Forces. The results indicated that the FM-300 adhesive layer had disbonded at the interfaces between the honeycomb and the adhesive and that water was present in the cells; however, corrosion products were not found. This discovery and the subsequent in-flight disintegration of a rudder's structure have justified the initiation of a corrosion/water ingress inspection program for the flight control surfaces of the CF-18 to assess the extent of the problem in the fleet. The cause of failure is directly linked to water ingress in the flight control; however, little of the damage mechanism is known. This information is essential for the successful implementation of a nondestructive technique.

Objective

The main objective of this paper is to examine applicable degradation mechanisms and review the results obtained with various nondestructive techniques.

Construction

The CF-18 aircraft bears 12 flight control surfaces (Figure 1) with a honeycomb sandwich structure that provides a stiff lightweight structure. The flight control structure consists of an aluminum or graphite-epoxy composite (AS4/3501-6) bonded to an aluminum honeycomb core with a high-temperature adhesive.

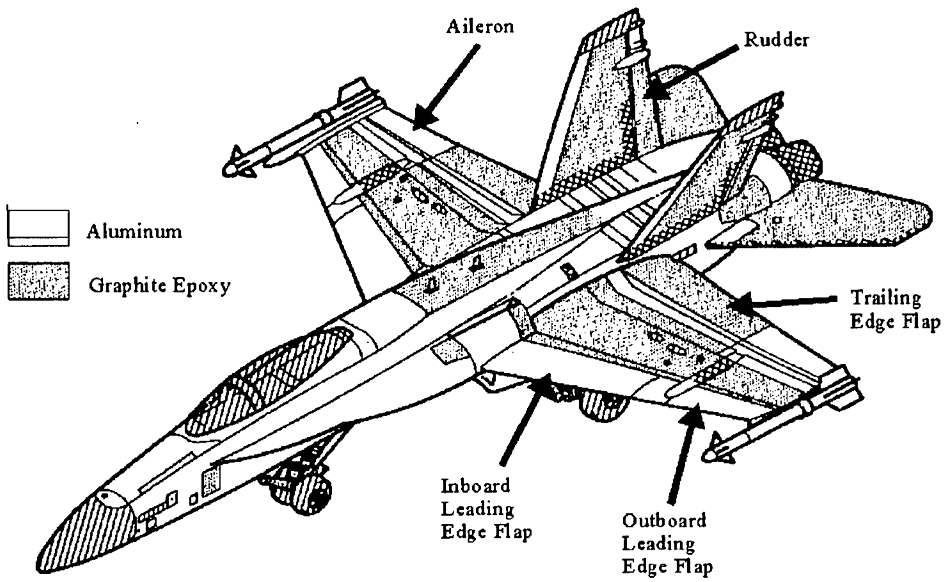


Figure 1. CF-18 material distribution and flight controls from [1].

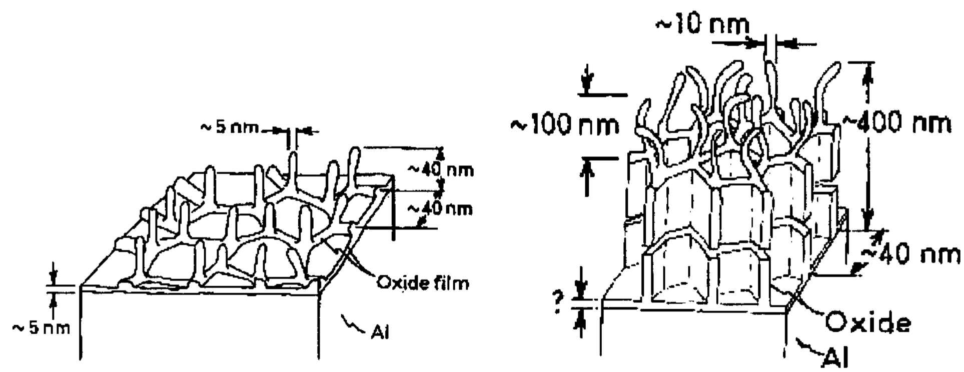
Honeycomb core

The honeycomb core (0.125 and 0.188 inches hexagonal cell) is 5056-H39 aluminum alloy [2]. It is constructed of ribbons of aluminum foil bonded at discrete locations (nodes) with a phenolic-nitrile adhesive. Once cured, the core is expanded into the final honeycomb core shape [3]. The durability of this type of structures relies heavily on the integrity of the adhesive bond between the skin and core as well as the core itself i.e., a strong interfacial bonding at all interfaces is required.

There is conflicting information pertaining to the honeycomb core treatment for CF-18 flight control surfaces. It is suggested that the honeycomb core is unprotected [4]. If commercially pure aluminum foil were to be used, it would produce honeycomb with excellent resistance to corrosion; however, higher strength alloys (e.g., 5056-H39) can provide the same structural performance for a lower core density but they have a much lower resistance to corrosion. Investigations conducted by the Quality Engineering Test Establishment revealed that flight controls with water ingress did not exhibit conventional corrosion [5]; hence, it should be assumed that the honeycomb core has some form of corrosion protection. An investigation [6] confirmed this assumption and detailed the various layers coating the aluminum honeycomb core to be an oxide layer, a chromate conversion coating, and a top coat.

Oxide layer / conversion coating

In order to obtain a durable bond, the aluminum honeycomb core is generally pre-treated. Possible pre-treatment processes include: surface treatment with chromic oxide and sulfuric acid, chromic acid anodizing, and phosphoric acid anodizing. For these three methods, the air formed aluminum oxide layer is removed using acid or alkaline solutions prior to pre-treatment and the result after pre-treatment is a new aluminum oxide structure having a particular morphology (Figure 2). These pre-treatment processes take relatively long (30-60 minutes) and the aerospace industry has taken advantage of a faster pre-treatment process (10-120 seconds), namely the application of conversion coatings [7,8].



(a) (b)

Figure 2. Oxide morphology produced on aluminum by (a) chromic acid anodizing (b) phosphoric acid anodizing from [9].

Conversion coatings are adherent surface layers of low-solubility oxide, phosphate, or chromate compounds produced by the reaction of suitable reagents with the metallic surface. They differ from anodic coatings in that conversion coatings are formed by a chemical oxidation-reduction at the surface of the aluminum, whereas anodic coatings are formed by an electrochemical reaction. Although anodic coatings are stronger than conversion coatings for adhesive bonding applications [10], chromate conversion treatment ("Alocrom", "Alodine", etc.) provide protection against corrosion of the core [3,7]. The coating is placed on the foil before the node adhesive is applied, thereby ensuring corrosion protection over the full foil surface area.

The high corrosion resistance offered by chromate films is attributed to the presence of trivalent (Cr(III)) and hexavalent (Cr(VI)) chromium in the coating [10]. The trivalent chromium is believed to be present as an insoluble hydrated oxide, whereas the hexavalent chromium (when present) imparts a "self-healing" character to the film during oxidative (corrosive) attack by species such as chloride ion. The Cr(VI) is reduced during corrosion to form an insoluble chromium species that terminate the oxidative attack. Cr(VI) is not necessarily present for all types of chromate conversion coatings [8,10]. In fact, there is no indication of its presence on honeycomb core used for CF-18 flight control surfaces [3,6].

Top coat

The exact nature of the top coat is unknown; however, aluminum honeycomb is sometimes coated with a thin film of organic resin, which results in improved environmental resistance of bonded honeycomb structures [11]; however, no organic resin can be truly hydrophobic and water will ultimately penetrate the top coat [12].

Adhesive

The structural film adhesive that bonds the facesheets (or skin) to the core is Cytec FM-300. It is an epoxy film, supported by a tightly knitted scrim cloth, which cures at 177°C [3]. FM-300 is a one part system that has a curing system already incorporated into the adhesive. Heat and pressure are then required to get full and useful cure. This adhesive provides better than average moisture resistance [13] i.e., it has a low level of uptake water or high saturation level. The selection of FM-300 was also dictated by its thicker scrim which prevent electrical contact between graphite fibre and aluminum honeycomb, a situation that would lead to galvanic corrosion of the core [14].

Effect of moisture

Adhesive properties

Moisture can have an adverse effect on the cohesive strength of adhesives [15]. The effect of absorbed moisture on epoxy resins is one of plasticisation that leads to a reduction in glass transition temperature and of mechanical properties at elevated temperatures [16].

a. The glass transition of a material is the reversible change into an amorphous polymer from (or to) a viscous rubbery condition to (or from) a hard and relatively brittle condition. This glass transition generally occurs over a relatively narrow temperature range known as the glass transition temperature (T_g). Below the glass transition region, most of the energy put into the material for deformation is recovered when the load is removed.

b. In warm, moist environments, an adhesive will absorb moisture and swell until it is in equilibrium with its environment. Imposition of a load upon the adhesive produces additional stress, which causes the adhesive to deform until a new equilibrium is reached. The decrease in stress observed under constant deformation is known as stress relaxation, and the reduction in strength (Figure 3) it induces is detrimental to most adhesive systems [17].

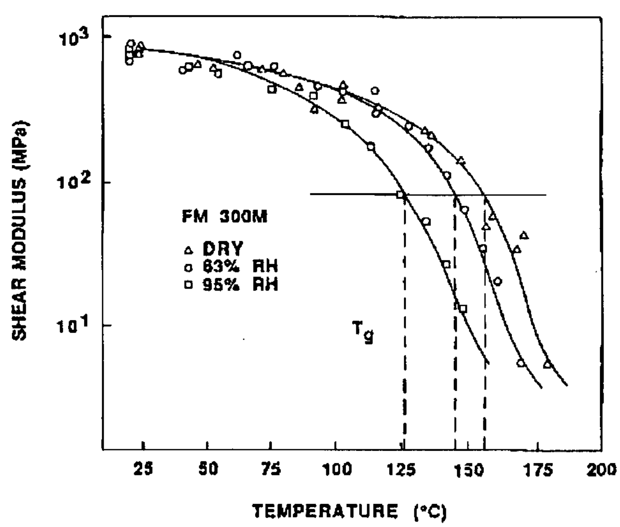


Figure 3. Values of shear modulus versus temperature at various moisture levels from [18].

Conversion coating/oxide layer

Improvement in corrosion resistance that can be achieved by treating aluminum prior to bonding has a significant effect on the durability of the bond produced. In fact, it is often seen that a joint which has been exposed to a hot-wet environment will fail along the interface between the aluminum and epoxy, as opposed to through the adhesive when the joint has remained dry. Hence, the long-term durability to aluminum polymer bonds is determined by the degree of stability of the coating and aluminum oxide in a humid environment [19]. With respect to CF-18 flight controls, the chromate conversion coating is considered to provide adequate protection in marine atmospheres and in high-humidity environments [10].

Recovery of physical properties

The recovery of joint strength upon drying gives indirect evidence that the failure mechanism encountered in flight control surfaces is not linked with moisture ingress. Similar conclusions were reached by researchers studying various adhesives [3,7]. For example, after 1000 hours exposure to 50°C and 100% relative humidity, specimens that were phosphoric acid anodized retained 94% of their initial strength. After 1000 hours drying at 50°C, the anodized samples had recovered completely [7]. Similar test results were obtained by DSTO for sandwich construction representative of CF-18 flight control surfaces [3]. It can be concluded that the strength loss due to plasticisation of the adhesive is recoverable.

Effect of water ingress and damage mechanisms

Water can enter a joint by diffusion through the adhesive, by capillary action along cracks in the adhesive, by wicking along a fabric carrier or by transport along the oxide/polymer interface [7]. Typical aircraft flights can also drive liquid water into the structure due to the pressure differential between ground and high altitude.

Immersion of aluminum joints in water or exposure to high humidity normally leads to a substantial loss in joint strength, but exposure to moderate humidities for long periods does not normally lead to permanent strength loss [9]. Hence, this effect is relatively unimportant compared with environmentally induced loss of adhesion at, or close to, the metal oxide/adhesive interface due to water ingress. Although the difference between the strength for direct ingress and diffusion ingress specimens is not great when wet/moist (Figure 4), the failure mode is fairly different. After long-term exposure, the diffusion ingress samples show cohesive failure in all cases (i.e., through the adhesive) while direct ingress samples failed at the adhesive to core interface [3].

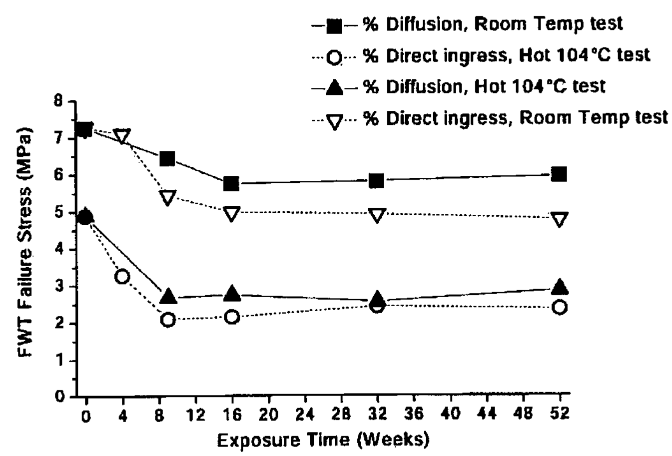


Figure 4. FWT test results for direct moisture ingress and diffusion moisture ingress tested under room temperature and 104°C test conditions from [3].

This difference in the degradation mechanisms between diffusion and direct ingress cases is supported when considering the dry recovery of the specimens (Table 1). The diffusion specimens recover much of their original properties which indicates that reductions in Flatwise Tension (FWT) strength are due to moisture in the adhesive causing plasticisation and not due to any permanent degradation of the adhesive bond. On the other hand, the direct ingress specimen did not recover their full FWT strength. This loss of strength indicates that some level of permanent adhesive bond degradation has occurred [3].

Table 1 . Dry recovery of specimens after one year of hot/wet environmental exposure from [3]

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 sort of observation led Kinloch to propose the concept of critical water concentration in an adhesive joint. The premise is that until the amount of water in a joint exceeds a certain level, there is no loss in strength; however, once water concentration in a joint has exceeded a critical value, there are several possible mechanisms by which the joint can be weakened [20]. The proposed mechanisms include:

a. effect on the bulk properties of the adhesive;

b. displacement of adhesive from the substrate; and

c. weakening of the aluminum oxide.

Effect on bulk properties of adhesive

Water may plasticise the adhesive. In general, plasticisation is a reversible effect, but water may nonetheless cause irreversible changes, such as hydrolysis, cracking or crazing [21]. These irreversible changes are more prevalent for adhesives with large levels of water uptake which is not the case for FM-300.

Displacement of adhesive from the substrate

Attack by water on the metal oxide will produce dimensional changes in the oxide layer leading to generation of shear stresses and displacement of adhesive. Using a thermodynamic approach, it has been demonstrated that an aluminum oxide/epoxide interface would be stable when dry but, in the presence of water at the interface, the oxide/epoxide interface would be unstable [7]. This concept could be extended to the conversion coating/epoxide interface.

When considering the stability of a boundary layer of adhesive, there is evidence that the boundary layer of adhesive adjacent to the metal oxide surface may possess a different chemical and physical structure compared to the adhesive away from the interface [9]. In the adhesive, there are strongly alkaline monomer substances that can be mobilized by water, and can negatively influence the stability of the oxides in an adhesive joint. It was found that under the influence of water, an adhesive constantly releases substances which are mostly alkaline in nature [22,23]. This mechanism explains the progressive reduction in joint strength with time and the change in the mode of failure from cohesive to interfacial but does not explain the partial recovery of joint strength on drying.

Weakening of the oxide and conversion coating

Early work on the mechanisms of environmental failure concluded that hydrolysis in a boundary layer of the adhesive near the adhesive/substrate interface was a primary failure mechanism in epoxy/aluminum joints. Subsequent studies have largely rejected this mechanism as a major cause of environmental failure, especially since in many cases the locus of joint failure after environmental attack has been clearly identified as occurring either at the interface or in the oxide layer [9]. Weakening of the chromate conversion coating and/or oxide layer due to water ingress is perceived as a likely cause of bond degradation. The mechanism of strength loss that has received the most support is the weakening of the oxide by hydration [7].

Weakening of the oxide by hydration involves permeation of water through the adhesive, hydration of the oxide and cleavage of the mechanically weak hydrated oxide [11,24,25]. Specifically, water initially passivates the oxide film and protects the metal from attack during an "incubation" period. The intense hydration activity will convert the original oxide to a hydroxide. It is the hydration of aluminum oxide on the adhesive/adherend interface that likely plays an important role in joint failure. Venables [26] found that pseudo-boehmite (Figure 5) may be created by the reaction

$$Al_2O_3 + H_2O \rightarrow AlOOH \qquad (1)$$

Secondly, the aluminum metal comes into contact with water and gas evolution occurs which is governed by the reaction

$$2Al + 4H_2O \rightarrow 2AlOOH + H_2 \qquad (2)$$

Figure 5. Characteristic "cornflake" structure associated with pseudo-boehmite morphology from [9].

The conversion of aluminum oxide to hydroxide is accompanied by a threefold increase in thickness, and the adhesion of the hydroxide to aluminum is sufficiently weak that once the hydroxide forms, it separates from the adherend and leads to bond failure. Experiments [26] confirmed the presence of aluminum hydroxide with a chemical composition between that of boehmite ($Al_2O_3 \cdot H_2O$) and pseudo-boehmite ($Al_2O_3 \cdot 2H_2O$).

Although emphasis is given to the weakening of the oxide layer, results obtained in recent research [6] do not support this damage mechanism. In the case of flight control surfaces, a top coat and a conversion coating are protecting the oxide layer. These layers have interfaces where adhesion fillet bond failure could be occurring. First, assuming that the top coat is an organic resin, it will absorb water to some extent. Its mechanical behaviour will reflect this interaction i.e., it may exhibit a loss of strength; however, the water will ultimately reach the conversion coating and slowly dissolve it [10]. This situation would ultimately weaken the interfaces with the oxide layer and the top coat. This damage mechanism could explain experimental results dealing with the degradation effects of F/A-18 sandwich structures where fillet bond failure between the core and the graphite/epoxy skin is considered to be the cause of catastrophic failures [27]. Thus, the failures are linked to a degradation or loss of (adhesive) connection between the "chrome containing part" of the coating of the honeycomb core and the bonding system [6].

Nondestructive techniques

A variety of nondestructive techniques are available for the inspection of flight controls. All techniques are best suited for certain stages or types of damage (moisture and water ingress, disbonds, core damage, corrosion), but none can detect all types of damage. A combination of test methods is required for complete and reliable inspection. It is therefore important to be aware of the available techniques and their limitations. Results presented herein are qualitative; however, more quantitative results are possible with the use of calibration techniques.

Ultrasonic Testing

Ultrasonic waves can be used to inspect composite skin, to detect water in honeycomb core cell, and to detect disbonds between skin and honeycomb. In through-transmission mode, the transmitting transducer introduces an ultrasonic pulse into the part that is detected by a receiving transducer. The received signal will be affected by the acoustical properties of the test object. Effectively, the attenuation of the sound signal may be caused by any of the following mechanisms [5]:

a. acoustical impedance change where hydration takes place in the structure (i.e., composite, adhesive, core);

b. delamination of the graphite-epoxy skin;

c. disbond between the skin and adhesive; and

d. Disbond between the adhesive and honeycomb core.

Through-transmission ultrasonic testing can be applied on-aircraft using a search unit alignment device (e.g., Figure 6); however, this technique provides discrete measurements for a manually generated inspection grid. The technique is effective in detecting disbonds and water in cells; it requires that both transducers be aligned axially on either side of the specimen and be in contact with the surface. This can be achieved for field inspections but better results can be obtained by removing the component from the aircraft and inspecting it with a C-scan ultrasonic testing system. This technique allows the C-scan mapping of the area inspected where sound attenuation appears as colour changes. Results obtained with the C-scan ultrasonic testing system are shown in Figure 7.

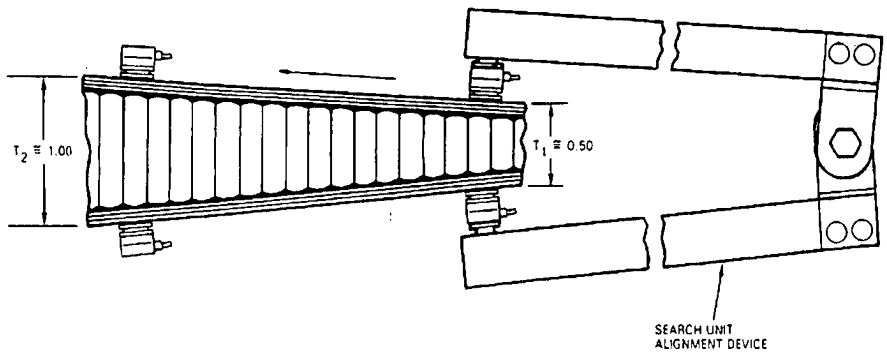


Figure 6. Through-transmission search unit from [28].

Figure 7. C-Scan ultrasonic testing inspection results showing dibonds (highlighted areas) along the leading edge of the rudder.

Radiography (X-Ray)

Radiography provides information on density changes based on a material's x-ray attenuation characteristics. Since water is excess or added material for x-rays to penetrate, water images on radiograph will appear light when compared to images of nearby cells which are void of water (Figure 8). Water images appear similar to areas where extra adhesive has been added for tie in or build up area. Fortunately, proper classification is possible since isolated cells that contain extra adhesive, or fill material, will also contain small gas bubbles that evolved during cure.

X-rays are routinely used in the field for core damage (including corrosion) and the procedure is available for the inspection of CF-18 flight controls [29]. Of all applicable NDT techniques, radiography is considered the most effective for detecting core damage [1]. X-ray also has the potential to detect disbonds under some circumstances and provided that technicians have proper training and experience.

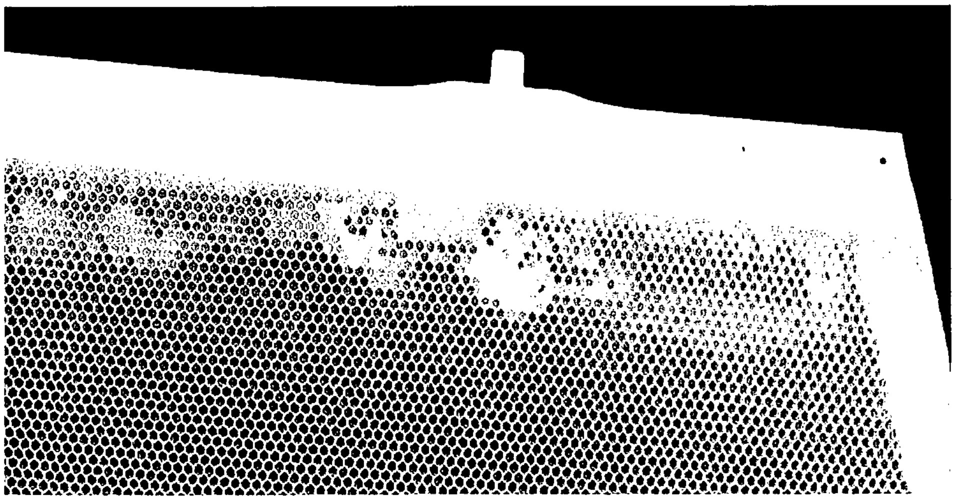


Figure 8. X-Ray inspection results showing water along the leading edge of the rudder.

Neutron radiography (N-Ray)

N-rays provide indications of water in individual cells (Figure 9) as well as extremely low levels of moisture (i.e., cell hydration). This capability is attributed to the neutron's characteristic attenuation by elements of low atomic numbers, such as hydrogen. Other indications found by neutron radiography include moisture in repaired areas where sealant had been injected, blown core where water may have frozen and expanded, voids in the sealant of repair patches, inconsistencies and porosity in the original sealant, repaired damage in the honeycomb, and foreign object debris. N-ray also has the potential to detect disbonds, core damage and corrosion provided that technicians have proper training and experience.

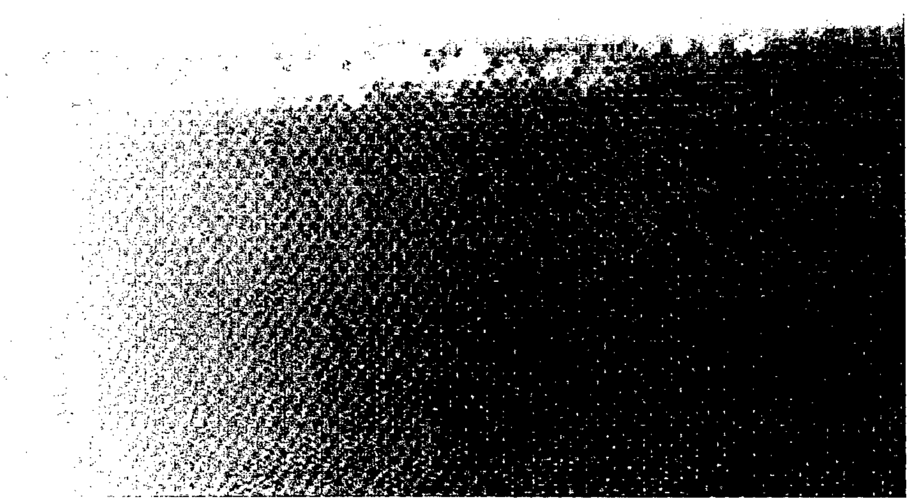


Figure 9. Neutron radiography inspection results.

Thermography

Infrared thermography conveys information about the temperature and emissivity of the surface of the target. The infrared thermography system uses electronic cameras and devices to see heat patterns and, in special cases, to measure temperatures. This type of passive system gives the ability to examine the radiant heat emitted by components and evaluate their condition. Hence, it is possible to survey a component and detect deterioration within that component as long as there is a thermal difference to be detected. Otherwise, objects with the same thermal radiant pattern or temperature will be invisible to each other. It is considered to be qualitative in nature because it is impossible to distinguish between disbond, moisture or water in the honeycomb core. Recent tests were carried out by the Canadian Forces Nondestructive Testing Centre and provided positive detection of defects within flight control surfaces. For these tests, CF-18's that were in subzero environment were brought inside a heated hangar and subsequently inspected using an infrared camera. The type of results obtained during these tests is shown at Figure 10. Indications obtained via this technique were later confirmed to be water in honeycomb cells using radiography. This technique is currently considered the best tool to rapidly screen flight controls with defects. It should also be noted that the applicability of this technique for the inspection of control surfaces during warmer weather still requires development.

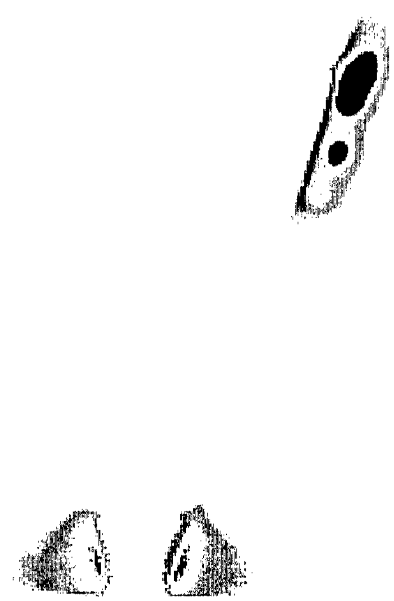
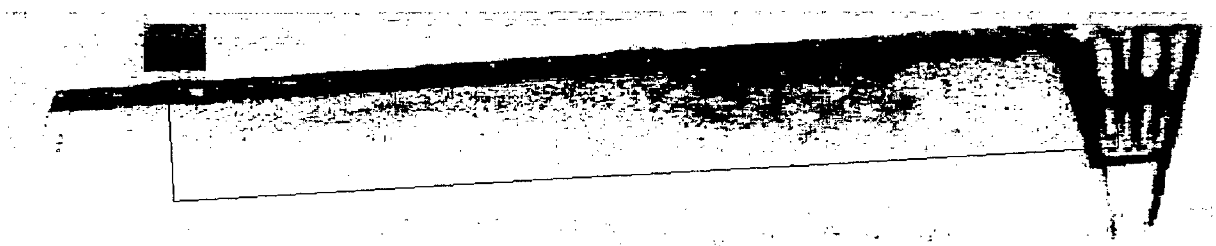
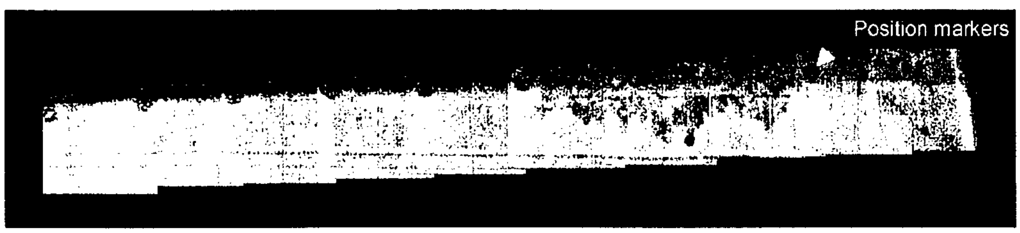


Figure 10. Thermography inspection results - inspection of rudders via thermography shows water indication below the top hinge of the right hand rudder.

Active thermography systems are also commercially available and provide the ability to detect water and bond degradation independently of ambient temperature. This type of system takes advantage of the dynamic cooling of the test object surface after it is instantaneously heated with a uniform light pulse from a flashlamp array. The infrared camera allows the monitoring of the varying surface temperature and the collected data is used to generate an image of the subsurface structure of the sample. The principle is that the heat from the surface diffuses into the bulk of the sample at a rate determined by the thermal diffusivity of the sample material. If a defect is encountered, the flow of heat into the bulk is obstructed, and the rate of cooling at the surface immediately above the defect is retarded [30]. Characteristically, detection via active thermography systems is not temperature dependent, providing the ability to inspect components in warm and cold weather. The results obtained with the active thermography system were highly repeatable and allowed detection of degraded bonds (Figure 11) and detection of water in cells (Figure 12).



(a)



(b)

Figure 11. Inspection results showing regions with degraded bond (a) via ultrasonic C-scan, and (b) via active thermography.

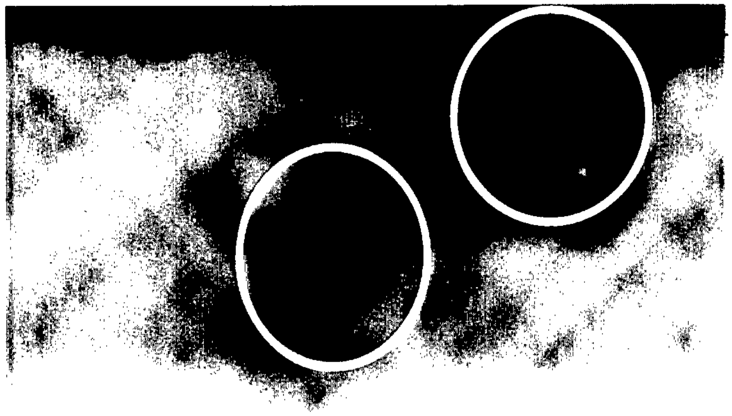


Figure 12. Active thermography inspection results
- highlighted areas are cells containing water.

Helium Mass Spectrometer Leak Detection

Preventing water to ingress the sandwich structure should ensure durability of the flight control. The traditional means to detect leaks in flight controls is a hot-water leak test. This test is generally conducted on all bonded honeycomb assemblies immediately after fabrication or repair. It is performed by immersing the part in a shallow tank of heated water. The heat causes the entrapped air to expand, and if there are any leakage paths, bubbles will be generated at the leakage site. Recently, aerospace companies e.g., Boeing, Airbus, Bombardier, have made use of a new leak testing method referred to as helium mass spectrometer leak detection. The technique proposed by Bombardier Aerospace [31] is as follows:

a. the flight controlled surface is "bagged";

b. the bag is evacuated to remove most of the air present;

c. the helium is introduced within the bag;

d. the seal is verified to ensure there is no leakage;

e. the part is left in the helium atmosphere for a minimum of one hour; and

f. with an helium mass spectrometer leak detector, testing is done to detect escape points.

The new leak detection method provides an enhanced capability to determine the presence of a leak. First, there is no water ingress in the flight control surface. Second, measurements can be taken over a long period if desired (more than a day). Overall, the results obtained with this technique are very promising. As an example, in the preliminary testing done, leaks were found at the grounding points in close proximity to the disbonded regions highlighted at Figure 7.

Conclusions

The introduction of water in such a sandwich structure can affect the adhesive, the top coat, the conversion coating, the oxide layer and the aluminum honeycomb core. To date, the water ingress is directly linked to the reduction in bonding strength between the adhesive FM-300 and the aluminum honeycomb core. The failure mechanisms in this particular case are extremely complex and may be a combination of several different failure modes. The problem seems to be a degradation or loss of (adhesive) connection between the "chrome containing part" of the coating of the honeycomb core and the bonding system. Various nondestructive testing techniques have proven to be effective in detecting the presence of moisture, the presence of water, the degradation of bond strength, the corrosion in honeycomb cells, and in verifying the control surface seal integrity to prevent water ingress. None of the NDT techniques can detect all of the stages or types of damage; however, this capability can be achieved via a combination of NDT techniques.

Recommendations

The NDT techniques gave qualitative results but more quantitative results are possible in all cases with the use of calibration techniques. Also, a better knowledge of the damage mechanisms should guide the actions taken to ensure continued airworthiness. Hence, it is recommended to:

a. correlate nondestructive testing indications with destructive inspection of defects to validate NDT results;

b. determine the procedures to be followed when water is detected in flight controls, i.e., drying, leak testing, resealing;

c. develop a procedure to establish acceptance/rejection criteria based on NDT inspection results and Composite Repair Engineering Development Program activities;

d. determine the nondestructive inspection interval based on acceptance/rejection criteria and disbond growth data; and

e. determine design improvements for durability and resistance to environmental effects if new spare flight controls are manufactured e.g., the use of inorganic polymers to provide more stable top coats less likely to cleave when subjected to ultraviolet light, heat, oxidation and water.

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List of symbols/abbreviations/acronyms/initialisms

°C	Degree Celcius (unit for temperature)
Cr(III)	Trivalent chromium
Cr(iv)	Hexavalent chromium
DND	Department of National Defence
FWT	Flatwise Tension
MPa	Mega Pascal (unit for pressure)
NDT	Nondestructive testing
QETE	Quality Engineering Test Establishment
RH	Relative humidity
T_g	Glass transition temperature