INVESTIGATION OF AN ACCELERATED MOISTURE REMOVAL APPROACH OF A COMPOSITE AIRCRAFT CONTROL SURFACE

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Abstract

Moisture ingress in aircraft honeycomb sandwich structures is an ongoing issue that has attracted significant attention from aircraft operators, maintenance depots and the research community. Moisture ingress can lead to skin-to-core bonding degradation, affecting structural integrity.

Current procedures used for removal of accumulated moisture found within the composite honeycomb rudders of Canadian Forces' aircraft impart a significant maintenance burden and excessive aircraft downtime. Moisture removal approaches used for similar structures by other nations are usually complex and invasive. This paper outlines the development of an accelerated, effective and non-invasive approach to removing moisture from the rudder sandwich structure, taking advantage of the original water ingress paths. An experimental study was conducted to evaluate the effects of such drying parameters as temperature, vacuum level, vibration, as well as water removal paths. The moisture removal approach developed was then applied to full-size structures and was proven to be simple and effective.

1. Introduction

Composite skin honeycomb sandwich construction has been widely used for aircraft structures due to its lightweight, tailored stiffness and strength, superb fatigue resistance and low manufacturing cost. Although past experience with composite sandwich aircraft structures have generally been positive, it is widely recognized that these structures are susceptible to moisture ingress- related environmental degradation. Rotor blades from the McDonnell Douglas Apache and Boeing Chinook helicopter are also known to have a problem with water accumulation in their honeycomb core cells [1]. Thermographic inspection of a United Airlines 767 revealed that nose landing gear doors made of a composite honeycomb structure, could contain liquid water in an area as high as 7500 cm^2 (equivalent to 20 kg of extra weight if the cells were fully filled) [2]. Disbonded areas detected inside the elevator sandwich panel structure of an Airbus transport aircraft were attributed to moisture ingress, resulting in an FAA airworthiness directive mandating inspection and reprotection against water ingress for all Airbus A330-200, A340-200 and A340-300 stabilizers and elevators [3].

More significantly, moisture ingress may contribute to structural failure of composite honeycomb sandwich components. In-flight disintegration of a rudder on a Canadian CF-18 Hornet in 1999 and other similar occurrences in the F-18 fleets of other countries led to extensive investigations of in-service degradation of these sandwich structures. The United States Navy, Spanish Air Force and Canadian Air Force have all reported occurrences of F-18 honeycomb structure water retention and skin-to-core bondline failures [4], leading to the belief that such bondline degradation is related to the presence of standing water in the honeycomb cells [5].

Although the mechanism of moisture ingress induced bonding degradation are not well-understood [6], it is required by all F-18 fleets that moisture in the honeycomb core be removed to avoid bonding degradation. Further repairs, typically bonded repair or part replacement may be needed to ensure structural integrity should skin-to-core disbonds be already present. One of the most severe problems that maintenance engineers encounter during hot bonded repair is inadequate moisture removal, which can lead to high void content in the bondline, degradation of adhesive bonds, and even blow-off of the skins due to sudden build-up of vapour pressure in the honeycomb cells [7].

To remove moisture from the honeycomb sandwich structures, heating at an elevated temperature of between 70 °C to 90 °C was attempted. The approach was found ineffective after months of trials. The methods employed by F-18 users in the US and other nations allowed quick water removal but these methods are often invasive. One such process by the US navy involves drilling holes in one side of the skins, puncturing holes in the honeycomb cell walls, removing water through heat drying, and installation of a bonded repair patch over the drilled area [8]. This process has major drawbacks, including the complexity of the procedure and the requirement for highly-trained personnel. Structural weight may also increase if fillers are used to fill the drain holes, which may affect aerodynamic performance of the aircraft. More importantly, the original paths for moisture ingress are not resolved and there is a potential for the introduction of new water ingress paths from the drain holes. This study focuses on development of a simple, efficient and cost-effective method for moisture removal from the CF-18 rudder honeycomb sandwich structure, a key step to restore the structural integrity of the rudders.

2. Moisture Ingress and Migration Paths of CF-18 rudders

The CF-18 rudder consists primarily of a sandwich panel made of an aluminum honeycomb core bonded between two AS4/3501-6 graphite/epoxy skins, producing a lightweight panel with exceptional stiffness, as shown in Fig. 1. The size of the rudder is approximately 1.2 m by 0.4 m. The thickness of the structure reduces from the leading edge to the trailing edge (left to right in Fig. 1). The construction near the leading edge of the rudder is more complex (Fig. 1, A-A). A titanium H channel is bonded to the aluminum honeycomb core with a foam adhesive and partially sandwiched between the skins. Holes are drilled in the H channel, allowing insertion of hinges and grounding studs.

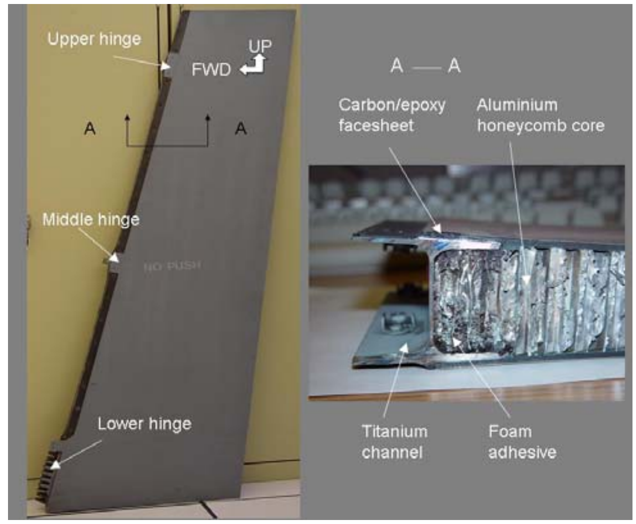

Fig. 1 Configuration of CF-18 rudder

Two major mechanisms of moisture ingress, diffusion and direct ingress, have been found to have a profound effect on bond degradation in composite honeycomb sandwich structure [9,10]. Moisture diffusion occurs in all polymer matrix composites due to moisture transport through organic fibres (if used), polymer matrices or by moisture wicking along fibre-matrix interfaces (even in undamaged materials). Direct ingress, on the other hand, occurs when water in bulk liquid form enters a structure via a direct path such as linked voids, cracks or improperly sealed joints. It has been found that water retention in a composite honeycomb sandwich structure was often associated with direct water ingress. Permanent bondline degradation has been also attributed to direct ingress and the subsequent direct exposure of the bondline to the standing water [9,11].

The recognition of a link between water retention in honeycomb structures and direct ingress led to an investigation aiming at identifying direct water ingress paths in CF-18 rudders. As a result, a moisture ingress cumulative occurrence map for these rudders was developed based on 5-year infrared thermography inspection results of 202 in-service rudders (Fig. 2) [12]. It is clear from this map that moisture ingress does not occur at random locations. Rather, the affected areas are centred near the upper and middle hinges at the leading edge, where hinges, grounding studs and a jig hole right above the upper hinge are also located. This map indicates that these joints and holes on the spar are likely the water entry points. Further investigation demonstrated that water, once in the rudder, can migrate easily along the leading edge via the highly porous foam adhesive that was used to bond the titanium channel and the honeycomb core [12]. If such paths are taken advantage of during drying operation, it was hypothesized that it would be feasible to remove water from the rudder non-invasively and efficiently.

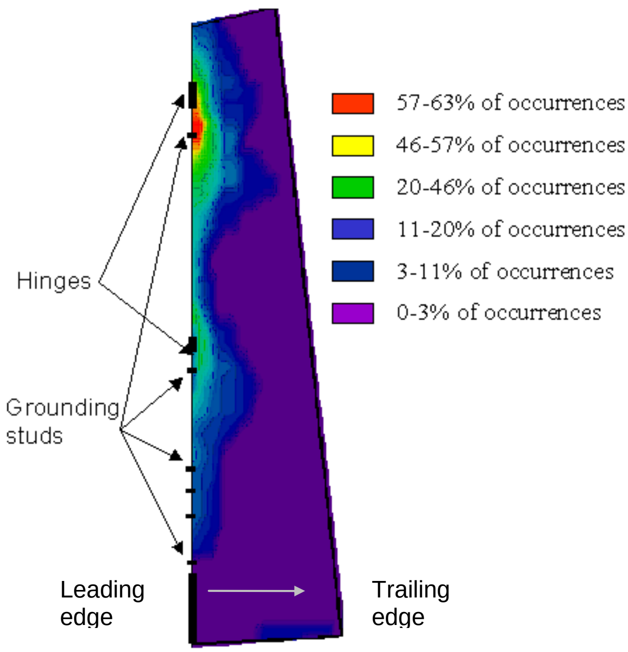

Fig. 2 Water ingress cumulative occurrence map developed based on 202 CF-18 rudders inspected between 1999-2004 using thermography.

3. Experimental

3.1 Coupon Design and Fabrication

Composite honeycomb sandwich coupons were fabricated including critical features and representative water ingress paths for moisture removal experiments [13]. As shown in Fig. 3, this design took into account features that are important for rudder moisture ingress such as a hole in the front Titanium spar and the porous foam adhesive along the leading edge. The same materials for the skins, core and adhesives, and the same manufacturing process were used (wherever possible) as in the original structure.

A major challenge was to duplicate the paths by which water migrate from cell to cell of the honeycomb core. Such paths may include skin-to-core disbonds, honeycomb core node disbonds, crushed core and other types of core damage [10]. Since adhesive failure disbonds or weakened bonds were the primary source of part failure, it is conceivable that skin-to-core disbonds are also the most important type of degradation mechanism and a major form of water path. In this study, only skin-to-core disbonds were simulated within the honeycomb core area due to the uncertainty about the contributions of other types of defects to water ingress, and the difficulty of duplicating these defects. Although this simplification would impact water removal rates, the comparative study of the various drying parameters would still yield useful information to identify an accelerated method to remove water from the CF-18 rudders.

The water ingress occurrence cumulative map indicates that the water ingress area with 60% occurrence is approximately 25mm deep and 50mm wide, and located near the upper hinge area. Several methods to generate disbonded areas in the sandwich coupons were attempted, including embedding Teflon® film, spraying the bonding surfaces with the mold release agent FreKote®, and removing the skin-to-honeycomb adhesive. Non-destructive inspection (NDI) using thermography and ultrasound indicated that thermographic inspection was able to detect all the areas with embedded defects whereas ultrasonic only detected areas without the adhesive (see Fig. 4). This suggests that although applications of release agents such as Teflon or FreKote causes chemical disbonds, physical barriers to water egress may remain. Therefore, all the panels for the comparative study of drying parameters were fabricated with adhesive removed from a window area of 25mm by 50mm. Several panels with embedded Teflon were also used to study the influence of the disbond generation methods on moisture removal.

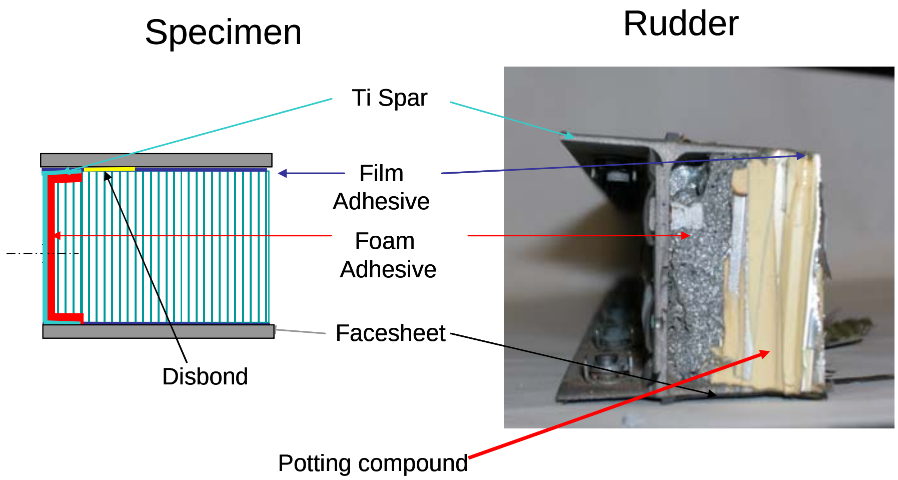

Fig. 3: Cross-section of leading edge of CF-18 rudder (left: design schematic, right: actual specimen**)**

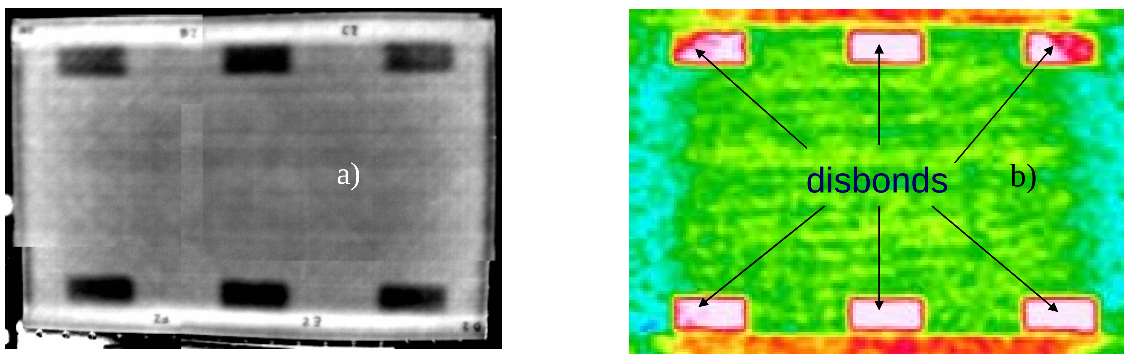

Fig. 4: NDI inspection of the fabricated sandwich panels (460mm X 280mm) with removed adhesive in six simulated disbonded areas of 25mm X 50 mm using a) Thermography b) Ultrasonic Inspection

In the test panels, the silicone rubber adhesive sealant RTV162 was applied to seal the three edges of the coupons, and a hole of 4.8mm was drilled on the centre of the front spar to simulate the jig hole or holes for the ground studs and hinges [13]. Syringes were then used to inject water in the honeycomb cells in the disbonded area, and then into the foam adhesive. To inject water into the honeycomb cells, an X-ray image was taken of each coupon to indicate the centre of each honeycomb cell and 101 holes of 0.8mm in diameter were drilled in the centre of each honeycomb cell in the window area. 0.1 g of water (or 20% cell volume) was injected into each drilled hole, which was then sealed using epoxy paste adhesive Hysol EA 9396. Water was then injected into the foam adhesive though the drilled hole on the spar. The total water amount injected into each coupon was approximately 20 g, with 10 g in the cells and 10 g in the foam adhesive. Due to the complex nature of water paths and lack of information, great care was taken to ensure the same starting condition for each of these coupons.

3.2 Moisture Removal approaches

Water removal has been studied for centuries as a means of preservation of food, wood and crop dehydration, fabrication of paper, textiles, pharmaceutical and construction products, dehumidification in the air conditioning industry and sewage treatment. Various techniques have been developed to achieve efficient moisture removal, including the application of heat, vacuum [14], ultrasound [15][16], centrifugal forces [17][18] and electrical pulses [19].

In this study, various moisture removal approaches were studied with consideration of the drying parameters that are potentially effective, low-cost and easy-to-apply. Such parameters include heating, vacuum, vibration and generation of additional moisture channels. Each of these factors was investigated as follows:

Heating: Heating is the most commonly used method for moisture removal. Heating can be conducted by various means such as convection, conduction, radiation and microwave [20]. According to a previous study, prolonged exposure to a humid environment above 85 °C may cause permanent adhesive degradation [21]. In this study, the drying temperature was set to be around 70 °C.

Vacuum: Vapour can travel through any existing moisture paths easily. Based on water phase diagrams, water can evaporate at a temperature well below 100 °C at less than atmospheric pressure. Maximum vacuum was used in the experimental study, with an achievable level of about a pressure of 11 kPa at the lab or in the field. This pressure is well below 20 kPa, the required minimum for water evaporation at 70 °C.

Vibration: Energy from vibration allows water to be separated from surfaces and move easily with minimal energy input. This technology is especially attractive as a means of drying heat-sensitive materials, because it has been found to be very effective for room temperature drying with no more than 1 °C temperature increase [22]. In this study, an ultrasonic vibration source on the order of 10 MHz was generated by Tektronix PG508 50MHz pulse generator. The vibration signal was enhanced to 20 dB by an EIN RF power amplifier (model 411 LA, 10 watts linear, Rochester, NY) and was transmitted to the bottom surface of the coupon via a cylindrical transducer with a surface of 60mm in diameter.

Water Ingress/Egress Channel: Years of service led to material aging and possibly damage in the rudders. Some types of damage such as node disbonds and core crushing cannot easily be simulated in the coupons, but they could be important water ingress paths. To demonstrate the influence of other possible core damage, a hole of 0.25mm in diameter was created in the centre of the first rows of honeycomb cells near the spar.

The above drying factors as well as their combinations were studied using fabricated sandwich coupons. The drying time, defined to be the time to reach 90% water removal, was compared with a baseline case where only intermediate heating at 70 °C was applied. Methods that are more effective than the baseline case were selected and applied to real rudders.

3.3 Test Scenarios of Moisture Removal

Eight Test Scenarios (TSs) were investigated as listed in Table 1. The sandwich coupons were subjected to the given condition and the weight of the coupons were monitored periodically depending on the drying rate. In all tests, coupons were placed flat, with the disbonded interface on the bottom side. The drying effectiveness was evaluated by the weight loss of the composite sandwich coupons, using Eqn (1).

$$\%\,Moisture\ \ removed = \frac{Weight\,reduction}{Total\ water\ amount} \times 100\% \qquad (1)$$

where the total water amount was calculated based on the measured coupon weight before and after water injection. The typical coupon weight after water injection was around 400 g and the resolution of weight measurement was 0.01 g. Each test scenario was repeated two to four times. Since consistent results were obtained, only one set of results for each test scenario is shown in this paper.

Table 1: Test scenarios for moisture removal experiments on simulated CF-18 rudder composite sandwich coupons

No	Methods	Equipment Required
TS1	Low heating only	Heating at 40°C in a convection oven
TS2	Intermediate heating only (Baseline)	Heating at 70°C in a convection oven
TS3	Vacuum only	Room temperature and maximum vacuum in a vacuum oven
TS4	Combined vibration and vacuum	Drying in a vacuum oven using ultrasonic vibration
TS5	Combined heating and vacuum	Drying in a temperature controlled vacuum oven, or in a vacuum bag in a temperature controlled oven (two types of coupon design)
TS6	Combined heating, vacuum and additional drying channels	Heating at 70 °C and maximum vacuum, with additional water channel in a vacuum oven

* Unless specified, vacuum refers to maximum vacuum (typically 11 kPa).

3.4. Test Results and Discussions

3.4.1 Effect of Heat and Vacuum

It is not surprising that the drying rate increases with temperature. An increase of the drying temperature from 40 ºC (low) to 70 ºC (intermediate) enhanced the water removal amount from 24% to 53% after 10 continuous days of drying (see Fig. 5). Elapsed time in all the graphs is the accumulative time during which the coupons were kept at the set conditions. At the end of 10 days of drying, the water removal rate at the low temperature dropped to nearly zero. Although drying at the intermediate temperature in the baseline scenario continued to remove water after 10 days, it was too slow to be practical for repair operations.

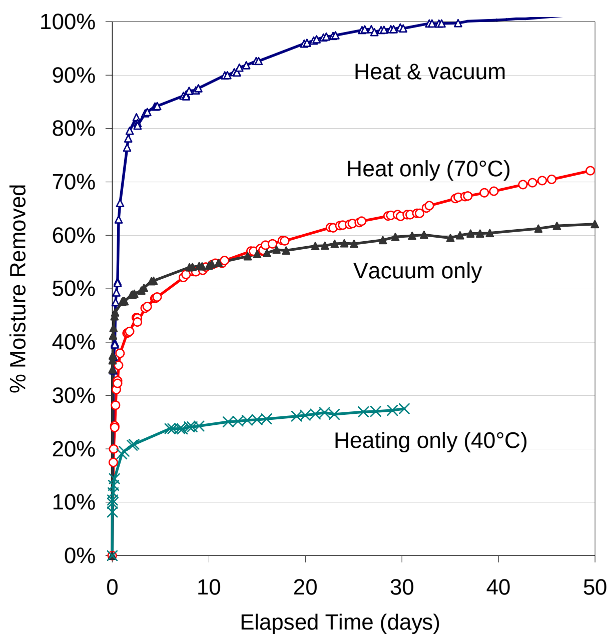

Fig. 5 Effect of temperature and vacuum

Among the investigated test scenarios in Fig. 5, only combined heating and vacuum drying was found to be effective at removing all the water from the rudder. Using this combined approach, the moisture removal rate was initially high with 80% water removal in less than two days, followed by a drastically reduced drying rate. An additional 9 days was needed to remove the remaining 20% of the water. The rate of the drying depends on the water evaporation rate in the honeycomb cells and the permeability of the disbonded areas. It is conceivable that the drying rate reduction after 50% water removal was related to the low permeability of the thin layer of adhesive between the disbonded area and the foam adhesive at the leading edge, as shown in Fig. 3. This thin layer of adhesive formed due to resin flow during processing and slowed down the water removal rate during the process. In these trials, the honeycomb sandwich coupons were placed with the disbonded side facing up. While water evaporates at a constant rate under set conditions, the limited gap between the core and the facehsheet, and the longer travel distance from the entry point limited the water migration rate. Furthermore, the vapour concentration in the cells reduces with time, leading to a reduced vapour migration rate. The tests suggested that if skin-to-core disbonds are the primary water ingress paths, it is important to avoid direct pressure on the skin to close these gaps. Therefore, should vacuum bagging be used for such water removal, care has to be taken to avoid direct contact of the bagging materials.

A similar overall drying efficiency was observed for vacuum-only and heat-only approaches. However, the effectiveness varies with the stage of the drying, with a faster initial water removal rate for the vacuum-assisted approach but a slower rate after 50% of the moisture was removed. This indicated that pressure gradient as a result of vacuum application is more effective in removing water from the adhesive foam, which is directly exposed to the environment. However, in the long term, heating became the primary driver for water removal.

To quantify the water removal rate, the time to achieve a target of 90% water removal was used for comparison. Since most of the tests terminated before such drying level was achieved, this evaluation time was calculated by extrapolating the experimental curve based on the assumption that a constant drying rate was maintained after termination of the experiment. Using this approach, 90 days and 11 days were calculated for intermediate heating only and combined vacuum-assisted heating scenarios for the coupons, respectively, suggesting that the vacuum-assisted heating method could be potentially a factor of eight faster than the heating-only method.

3.4.2 Effect of Vibration

Ultrasonic vibration-assisted water removal was also attempted, in conjunction with vacuum. The vibration transducer was attached to the bottom side of the coupon, which transfer the vibration energy to the water via the skin. It was found that for the energy and spectrum of the vibration used for this study, vibration- assisted vacuum drying did not increase the water drying rate. One possible explanation is that the total power of the transducer used for this study did not meet the required power for effective dewatering as studied previously. In contrast, the rate was reduced because sealing of the vacuum oven was affected by the vibration transducer cables, increasing the pressure from 11 kPa to 20 kPa. Further investigation is needed to understand the effect of vibration on water removal within sandwich structures.

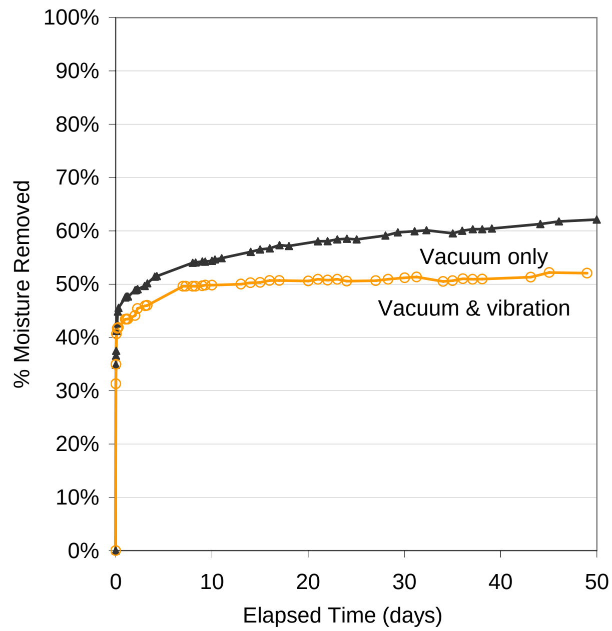

Fig. 6 Effect of vibration

3.4.3 Effect of Water Ingress/Egress Channel

In this study, other types of water paths such as node disbonds were not taken into account in the coupon design. To account for the effect of other types of water migration paths that may exist in the CF-18 rudders, a small hole of a diameter of 5mm was drilled into the first and second row of the honeycomb walls and the coupons were subjected to the combined heating and vacuum condition, as shown in Test Scenario 6 in Table 1. The test results (Fig. 7) shows that the inclusion of a water channel through the honeycomb core led to a significant reduction in drying time from 11 days to 0.5 days. Again, the water removal rate was extremely fast at the beginning; it took only about 6 hours to remove up to 85% water from the coupons. The rate was then reduced to a similar value as the coupons without additional water channel, showing that, despite of the direct path from the disbonded to the foam adhesive area, the moisture removal rate for water that is further away from the entry point was dominated by the permeability of water migration from cell to cell. The introduced channel was investigated to demonstrate the effect of the channels that may have existed in the rudders. In particular, no additional channels would be introduced to the real practice of CF-18 rudder moisture removal.

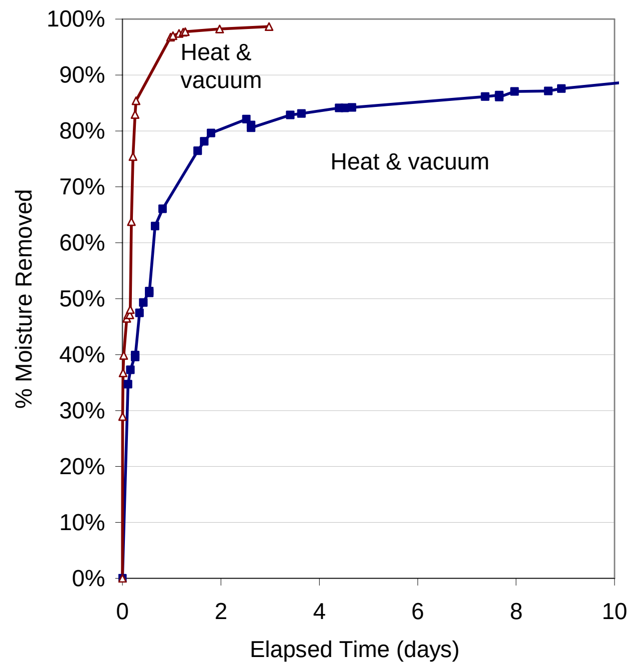

Fig. 7 Effect of water ingress/egress channel

3.4.4 Effect of Coupon Design

Fig. 8 shows the different moisture removal rates of coupons with different disbond design. All the coupons were subjected to vacuum drying at an elevated temperature of 70 ºC. As suggested by ultrasonic test results, the coupon with the application of Teflon or FreKote to create skin-to-core disbonds showed no indication of physical disbonds while adhesive removal did show evidence of these disbonds. A maximum of 50% of the water was removed from the coupons that had no indication of physical disbonds, with all of these occurring in the first 3 hours.

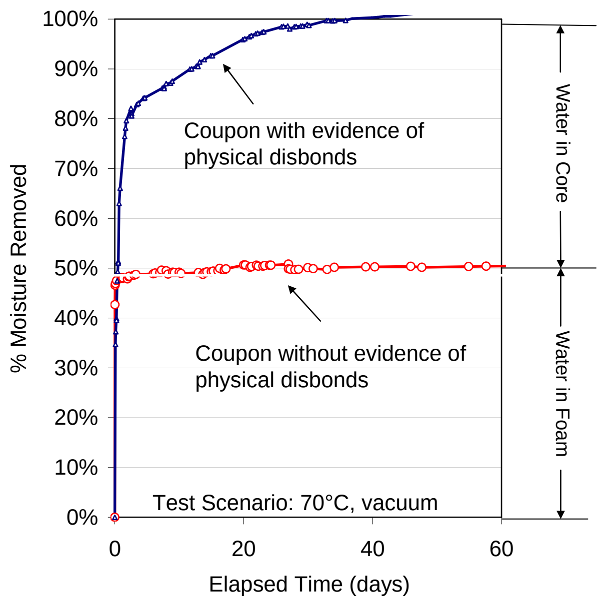

Fig. 8 Effect of design of skin-to-core disbonds

Little further drying was observed in the next 60 days equivalent of continuous drying time, as shown in Fig. 8. Further NDI on the coupons indicated complete water retention in the honeycomb cells, suggesting that only water in the foam adhesive had been removed. On the other hand, when physical disbonds are present, it was possible to completely remove water both in the foam adhesive and in the core. It took around 12 days to reach 90% moisture removal and about 30 days to completely remove the water. The observed moisture removal results confirmed the speculation that while chemical disbonds may be created by all the mentioned methods, they do not guarantee the generation of water ingress/egress paths.

3.5 Summary of the moisture removal effectiveness

The effectiveness of the studied test scenarios as listed in Table 2, the drying time to achieve 90% drying was compared for all the test methods. It has been found that combined vacuum and heating method increased greatly the moisture removal rate compared to the baseline case with heating only. This method is easy to conduct and could potentially enhance the efficiency of CF-18 rudder drying. This approach has been selected for field test of rudder moisture removal.

3.6 Field Tests of Rudder Moisture Removal

Prior to this study, moisture removal was attempted on a rudder with significant water ingress detected by infrared thermography (see Fig. 9). In this trial, sealant on the front spar was removed and the rudder was subjected to an elevated temperature in the range 70 to 90 ºC. After nearly two months of the experiment, little success was achieved as indicated in Fig. 10.

The same rudder was then used for drying trials using the approach developed in this work. In this experiment, the sealant jig hole above the upper grounding stud was removed, while hinges and grounding studs remained in place for the first attempt. The upper and middle hinge areas, including the exposed jig hole, were sealed in a vacuum bag and then placed in a temperature-controlled oven. The drying temperature was set to 70 ºC while maximum vacuum was applied. After a one-day trial, inspection using thermography was conducted on the rudder, showing significant water removal as shown in Fig. 11. Area with water ingress has shrunk by 60%, indicating the effectiveness of the combined heating and vacuum drying method.

Table 2: Comparison of estimated time to remove 90% of moisture for the studied test scenarios

	Temperature			Vibration
	Room temperature (22 ºC)	Low (40 ºC)	Intermediate (70 ºC)	Vibration
No vacuum	N/A	(TS1) more than 500 days*	(*Baseline TS2*) 90 days*	N/A
Maximum vacuum	(TS3) 300 days*	N/A	(TS5) 11 days	(TS4) 500 days*
vacuum and channel	N/A	N/A	(TS6) 0.5 day	N/A

* The drying time was calculated by extrapolating the experimental curve to reach 90% water removal.

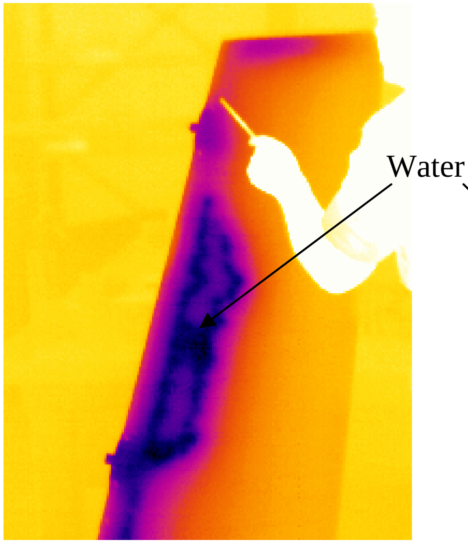

Fig. 9 Thermography image showing moisture ingress area in a CF18 rudder panel

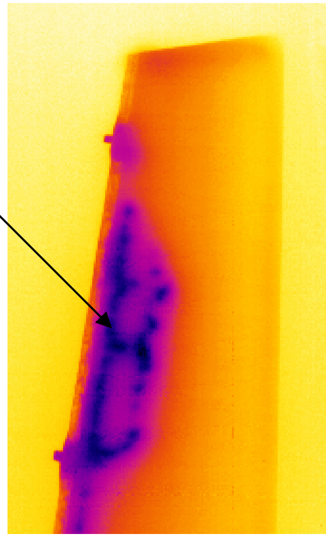

Fig. 10 Moisture ingress area after two months of moisture removal at around 80 ºC

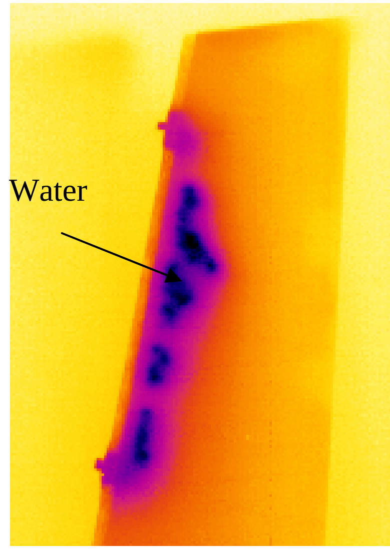

Fig. 11 Moisture ingress area after 8 hours of vacuum-assisted drying at 70 ºC

4. Conclusions

Moisture ingress in composite honeycomb sandwich structures has been attributed to weakened skin-to-core bonds and disbonds. Moisture removal from CF-18 rudders is a critical step in repair of these composite honeycomb sandwich structures to ensure structural integrity. Based on a previously developed moisture ingress cumulative occurrence map, water ingress was attributed to direct water paths via holes on the front spar. The finding of these paths led to the investigation of an effective and non-invasive moisture removal method, which could provide long-term effectiveness to prevent future water ingress. The key to the procedure was to remove water from their original paths of these rudders and to seal the paths after repair.

Experimental studies were first conducted on coupons with representative water ingress features. Drying factors taken into account included heat, vacuum, vibration and additional moisture paths. Experimental result demonstrated that the baseline method of rudder drying at an elevated temperature of around 80 ºC was not effective. It would take more than 90 days to remove 90% of the water from the honeycomb sandwich coupons. By comparison, combined heating and vacuum application were able to remove 90% of water in 11 days, improving the efficiency by a factor of 8. This time may be further reduced to 0.5 days if there are other types of direct water paths other than skin-to-core disbonds.

Thermographic inspection after moisture removal experiments on a real rudder showed that, while no indication of moisture removal was observed after drying in an oven at around 80 ºC for 2 months, the combined heating and vacuum heating method was able to reduce the moisture ingress area by 60% in a single day. This experiment was conducted when only one of the several possible water entry points, the jig hole on the spar above the upper hinge, was exposed by removing the sealant in the hole. The experiment demonstrated that the combined heating and vacuuming method was effective. The observed moisture removal efficiency may be further enhanced by exposing more water entry points. In this procedure, hole drilling in the skin, which is currently used as a part of the maintenance procedure by other F-18 users, is not necessary. The key to this fast and non-invasive moisture removal procedure developed in this study is to take advantage of the original water paths.

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