JMEPEG (1999) 8:661-668

Evaluation of the In-Service Performance Behavior of Honeycomb Composite Sandwich Structures

J.E. Shafizadeh, J.C. Seferis, E.F. Chesmar, and R. Geyer

(Submitted 21 May 1999; in revised form 17 August 1999)

When honeycomb composite structures are fabricated for the aerospace industry, they are designed to be closed to their operating environment for the life of the composite structure. However, once in service, this design can break down. Damage can set in motion a chain reaction of events that will ultimately degrade the mechanical integrity of the composite structure. Through thermographic analysis, the tendency of honeycomb composite structures to absorb and retain water was investigated, and an attempt was made to quantify the extent of water ingression in the Boeing 767 aircraft. Through thermographic analysis, the exterior honeycomb composite structures were found to contain less than 50 kg of water per plane. On average, over 90% of the water found on an aircraft was contained in five problematic parts, which included the outboard flap wedge, the nose landing gear doors, the main landing gear doors, the fixed upper wing panels, and the escape slide door. Kevlar lamina induced microcracking, skin porosity problems, and cracked potting compound were the root causes of water ingression and migration in these structures. Ultimately, this research will aid in the fundamental understanding and design of future honeycomb composite sandwich structures.

Keywords honeycomb composites, kevlar lamina, porosity, potting compound, thermographic inspection, water ingression

1. Introduction

Honeycomb composites are designed and manufactured to be light, stiff beam structures. However, their lightweight construction also leads to problems once in service. After manufacturing, honeycomb composite panels are designed to be "closed" to their operating environments, but once in service, the thin aerodynamic face sheets or skins are susceptible to water ingression and foreign object damage.

In a high energy impact, both the face sheet and honeycomb core are damaged. Damage to the face sheet can result in matrix microcracking and fiber breakage (Ref 1). Once the face sheet is fractured, water can easily enter the cells of the honeycomb core through cracks in the face sheet. The presence of standing water in the honeycomb core can destroy the honeycomb core through a freeze-thaw mechanism. When the face sheet is fractured, the honeycomb core is directly exposed to a harsh set of environmental conditions. At a cruising altitude of 9000 m, the temperature inside the honeycomb core is near –40 °C. At this temperature, any standing water that has accumulated within the honeycomb core will freeze. The freezing water expands and stresses the honeycomb cell walls. When the airplane lands, the water melts and the honeycomb wall relaxes. After a number of these freeze-thaw cycles the cell walls will catastrophically fail and destroy the structure of the honeycomb. If a honeycomb cell contains a substantial amount of water, the freezing water can also expand against the face sheet and delaminate, or disbond, the honeycomb core and the face sheet.

Face sheet delamination can also be observed on the ground. The process of repairing damaged composites can often induce damage itself. When composites are repaired, they are often heated to temperatures in excess of 100 °C. Under these conditions, the water contained within the honeycomb cells of the composite part quickly vaporizes. Over 100 °C, the pressure of the vaporized water can exceed the tensile strength of the bond between the face sheet and the core, resulting in delamination of the face sheet (Ref 2).

As a consequence of the many problems that can occur to honeycomb sandwich structures, a number of investigations have recently been performed to try to model impact failure mechanisms and other mechanisms of damage propagation (Ref 1, 3). Along with the mechanical and mathematical models developed to predict damage propagation, a number of novel studies have been conducted in an attempt to minimize honeycomb damage propagation before and after damage initiation (Ref 4-6). Yet despite all of the work conducted in this area, no effort has been made by academia or industry to quantify the scope of the in-service problems with water in honeycomb structures.

This article represents the first part of a two-part investigation to study the scope and mechanisms of water ingression and migration through honeycomb core. In the first part of this study, the extent of honeycomb water ingression problems was explored. An investigation was conducted to determine whether water ingression is a localized problem that occurs occasionally, or whether water ingression in honeycomb sandwich structure represents a systemic composite problem. The second part of this study focuses on a design of experiment (DOE) to understand how water migrates through the core once it is ingressed. For the DOE, an in-flight service evaluation is being conducted on sixteen wing panels, which have

---

J.E. Shafizadeh and **J.C. Seferis,** Polymeric Composites Laboratory, Department of Chemical Engineering, University of Washington, Seattle, WA 98195-1750; **E.F. Chesmar,** United Airlines—SFOEG, San Francisco International Airport, CA 94128-3800; and **R. Geyer,** Boeing Company, Seattle, WA 98124-2207. Contact e-mail: mats.baarman@fundia.fi.

been installed on two United Airlines 767. From these panels, the effects of core type, impact damage, damage location, and tarmac repair procedures on water ingression are being examined. Ultimately the research performed in these two studies will aid in the understanding and design of future honeycomb composite sandwich structures.

2. Experimental Procedure

2.1 Theory of Infrared Thermographic Imaging

The theory behind the detection of ingressed water through thermographic imaging is straightforward. All bodies lose or gain heat to their local environment when placed in nonthermal equilibrium conditions. When bodies lose heat to their local environment they can give off heat in three ways: conduction, convection, and radiation. The radiative heat losses of a body or surface are governed by the Stephan-Boltzman law, which states that the rate at which a surface loses heat through radiation is proportional to the absolute temperature of that surface to the fourth power (Ref 7). By knowing the radiative heat losses of a surface, the temperature of that surface can be known.

The radiative heat losses of a body or surface are also directly proportional to the wavelength or frequency of the radiated light emitted from the surface (Ref 7). By knowing the peak wavelength of the light emitted from a surface, the temperature of that surface can be determined. At " low" temperatures (–100 to 1000 °C), surfaces emit light in the infrared region of the spectrum.

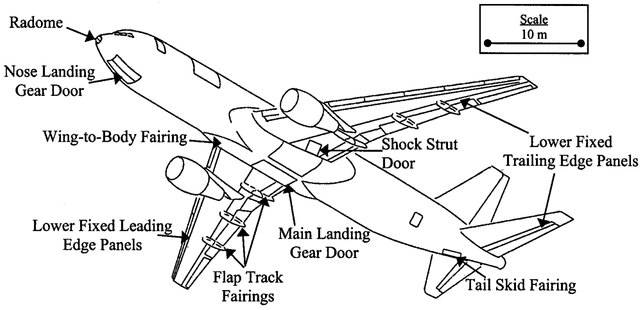

Fig. 1 Bottom view of Boeing 767 showing location of honeycomb composite structures

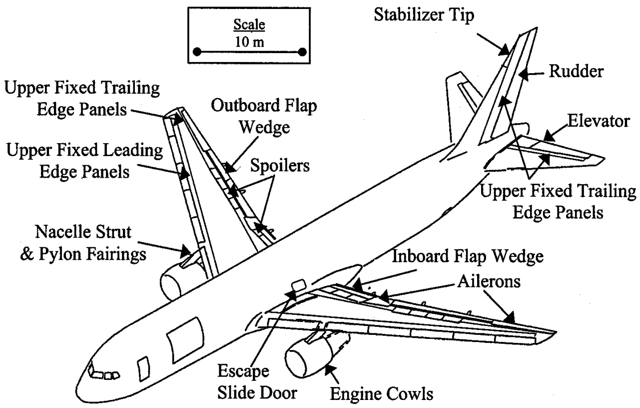

Fig. 2 Top view of Boeing 767 showing location of honeycomb composite structures

Using an infrared camera, the wavelength and the peak intensity of the emitted light can be recorded, and the temperature of the surface can be precisely known. Water can be detected in honeycomb composite structures through infrared thermal imaging because the localized area in contact with ingressed water will lose or gain heat at a different rate than an area that contains air or is under vacuum. Through infrared thermal imaging an entire aircraft structure can be inspected and the extent of ingressed water can be assessed.

2.2 Inspection Procedure

In this study, Boeing 767-200 and 767-300 aircraft were selected for evaluating the in-service performance behavior of honeycomb composite sandwich structures. The Boeing 767 was selected for inspection based upon two main factors: (a) the large number of composite honeycomb panels on the aircraft (the average weight of the exterior honeycomb composite panels on a Boeing 767 is 2700 kg) and (b) the wide range of aircraft ages that could be evaluated (the aircraft inspected in this study ranged from 5 to 16 years in age).

Figures 1 and 2 show the exterior honeycomb composite structures of a 767. Most of the thermographic inspections were performed on the lower surfaces of the aircraft. The composites on the lower surfaces of the aircraft represent approximately 66 wt% of the exterior honeycomb composites on the airframe of the 767. A limited number of inspections were performed on the upper wing surfaces, and little ingressed water was observed. However, it should be noted that ingressed water was most easily detected on the lower surfaces of the aircraft.

Fifteen United Airlines Boeing 767s (both 767-200s and 767-300s) were thermographically inspected at airports located in Los Angeles, New York, Indianapolis, and San Francisco by United Airlines and Boeing's Non-Destructive Testing Laboratory personnel. These airplanes represent 35% of United Airlines entire 767 fleet. The 767s inspected were chosen on a random basis. The thermographic inspections were carried out within half an hour after landing because it was during this time when ingressed water was most easily detected. The thermographic inspections were conducted with an Inframetrics model SC1000 infrared camera (Inframetrics, Inc., North Billerica, MA) with a temperature sensitivity less than 0.1 °C.

3. Results and Discussion

3.1 Infrared Inspections

From the images taken by the thermographic camera, the amount of water contained within honeycomb composite structures can easily be analyzed. The first step in determining the amount of water present in an aircraft structure was to quantify the surface area of ingressed water. From the surface area, the volume and subsequent weight of water can be determined.

When water ingresses into a honeycomb panel, it follows a leak path from the service environment to the interior of the honeycomb panel. When the water reaches the honeycomb core, it spreads out in an apparently random pattern. By knowing the size of the ingressed water pattern, an estimate of the surface area of the ingressed water can be made. If it is assumed that the average core thickness of an exterior composite structure is 2.5 cm and all of the cells that contain water are completely filled, then from the volume and weight of water within, a composite part can be determined. Because all of the cells within the honeycomb structure are not completely filled with water, this calculation places an upper bound on the amount of water contained within the panel.

Table 1 shows a typical thermographic inspection of a United Airlines 767. In the table it can be seen that less than a dozen honeycomb components contained water, and the airplane was found to contain 28.4 kg of water.

A summary of the other 767s inspected reveal similar trends, as shown in Table 2. The table demonstrates that all the 767 exterior honeycomb composite panels inspected contained less than 50 kg of water after many years of service. The younger airplanes also appear on average to contain less water than the older airplanes. However there are some older airplanes that defy this generalization. This data also indicates that not all honeycomb composites on the aircraft contain water. In fact, Table 2 indicates that most of the water in the honeycomb composite structures was limited to a handful of problematic parts. Five parts, which include the outboard flap wedge, the nose landing gear door, the main landing gear door, the upper fixed wing panels, and the escape slide door constitute the bulk of the composite parts that absorb water. These parts were responsible for more than 90 wt% of the water contained within the honeycomb core. The water contained within these parts was a consequence of both in-service conditions and the construction of the panels.

Table 1 Typical thermographic inspection of United Airlines 767

Damage location	Number of panels with water	Water surface area, cm^2	Weight of water, kg
Outboard flap wedges	2	630	1.6
Nose landing gear doors	4	7,520	19.1
Main landing gear doors	2	470	1.2
Upper fixed wing panels	4	2,100	5.3
Escape slide doors	0	0	0.0
Aileron	1	310	0.8
Engine inlet panel	1	160	0.4
Miscellaneous panels with small damage	6	80	0.2
Total damage found	**20**	11,**270**	**28.6**

For each of the damaged parts listed in Table 2, the cause of the water ingression was traced back to a root cause. In determining the root cause of water ingression in the honeycomb structures, the various ingression patterns in the panels were analyzed. From the degree of pattern repetition in a particular location, the initial point of ingression and the shape of the ingressed water pattern within the panel, a determination was made of the most likely mechanism of water ingression.

3.2 *Damaged Parts*

Outboard Flap Wedges. The flap wedge is located on the outboard trailing edge of the wing, as shown in Fig. 1 and 2. The flap wedge is bolted on the main flap assembly and is designed to extend with the flap to give the aircraft lift during takeoff and landing. When the flap wedge was constructed, a Nomex (E.I. DuPont de Nemours & Co., Wilmington, DE) honeycomb was used in the core, and the facesheet was fabricated from low-flow epoxy prepreg. (Prepreg is a thin sheet of fibers that has been uniformly impregnated with a polymer matrix.) The prepreg used in the flap wedge was a fairly common prepreg and had many advantages and disadvantages to its use. The prepreg was a self-adhesive prepreg and did not require an adhesive film to adhere to the honeycomb core, but it also had known porosity problems. Past research has shown that laminates fabricated from this type of prepreg can contain 3 to 5% voids (Ref 8). These voids are typically found both in the face sheet and skin to core fillet, as demonstrated in Fig. 3.

During manufacturing of the outboard flap wedge, a thin surfacing film was used to fill in most of the voids on the surface of

Table 2 Summary of thermographic inspections of United Airlines 767s

		Weight of water, kg							Water contained in five parts, %
Aircraft number	Aircraft age	Flap wedge	Nose landing gear door	Main landing gear door	Upper fixed wing panel	Escape slide door	Sum of problem parts	Aircraft total	
1	16	0.1	0.0	4.6	0.0	18.9	23.6	24.6	96
2	16	3.7	15.0	3.7	3.7	0.0	26.1	26.7	98
3	15	1.0	4.1	3.5	1.6	0.7	10.9	11.0	99
4	16	4.5	10.0	1.8	10.0	13.1	39.4	40.4	98
5	15	0.1	0.0	2.0	0.0	1.6	3.7	4.3	86
6	15	0.5	0.0	0.0	0.0	19.7	20.2	20.4	99
7	15	2.0	0.8	4.5	3.3	0.7	11.3	15.8	72
8	15	0.8	0.0	2.1	0.7	0.0	3.6	4.9	73
9	15	0.3	2.9	2.4	11.8	0.3	17.7	19.1	93
10	15	1.6	19.1	1.2	5.3	0.0	27.2	28.4	96
11	16	4.5	18.8	0.2	1.8	2.4	27.7	32.7	85
12	15	0.5	4.0	0.9	0.0	0.0	5.4	5.7	95
13	6	1.3	0.0	1.2	0.0	0.0	2.5	3.0	83
14	6	0.1	0.8	0.6	0.2	0.0	1.7	1.6	100
15	5	0.3	0.8	0.0	0.0	1.3	2.4	2.5	96
Average		**1.3**	**4.8**	**1.8**	**2.4**	**3.7**	**14.0**	**15.1**	**91**

the face sheet. However not all of the voids were filled. Through the "unsurfaced" voids, water was able to migrate into the face sheet. Once in the face sheet, the water caused microcracks to develop in the skin through a freeze-thaw mechanism. The microcracks that developed formed between the voids in the laminate and created a leak path from one void to another. As a result of the high porosity and the incomplete surfacing of the wedge, leak paths were created from the surface to the honeycomb core. Once in the honeycomb core, the voids in the honeycomb core fillets allowed water to travel from one cell to another. Through microcracks in the face sheets water was able to migrate freely through the outboard flap wedge, as shown in Fig. 4 (Ref 9).

Nose Landing Gear Doors. The nose landing gear doors are located on the bottom of the aircraft, and, as the name implies, they enclose the nose landing gear during flight. The nose landing gear doors are attached to the 767 airframe through fasteners potted in the door. In fabricating the nose landing gear doors, holes ranging from 0.5 to 6.2 cm in diameter are drilled out of the honeycomb core. Fittings are placed in the holes to attach the necessary actuators and fasteners. After drilling, the holes were then filled with a potting compound. (Potting compound is a filled thermosetting material used to provide a substantive attachment point for the fasteners in the honeycomb core.) During fitup, the fasteners were wet installed in the fitting locations and torqued with a force greater than 130 N. Wet installation involves coating the fastener with a sealant material to prevent water ingression. Over time, cracks form in the sealant and potting compound as a result of thermal and mechanical cycling. The cracked potting compound resulted in a leak path being formed from the service environment of the landing gear door directly into the honeycomb core. The leak path for water ingression began outside the door. It then followed the fitting itself into the potting compound, then directly into the honeycomb core. Once in the honeycomb core, the water spread from the localized area around the fitting to the rest of the core, as shown in Fig. 5.

Through cracks in the potting compound, originally designed to prevent water ingression, water was able to infiltrate and spread throughout the honeycomb core. In Fig. 5 the effects

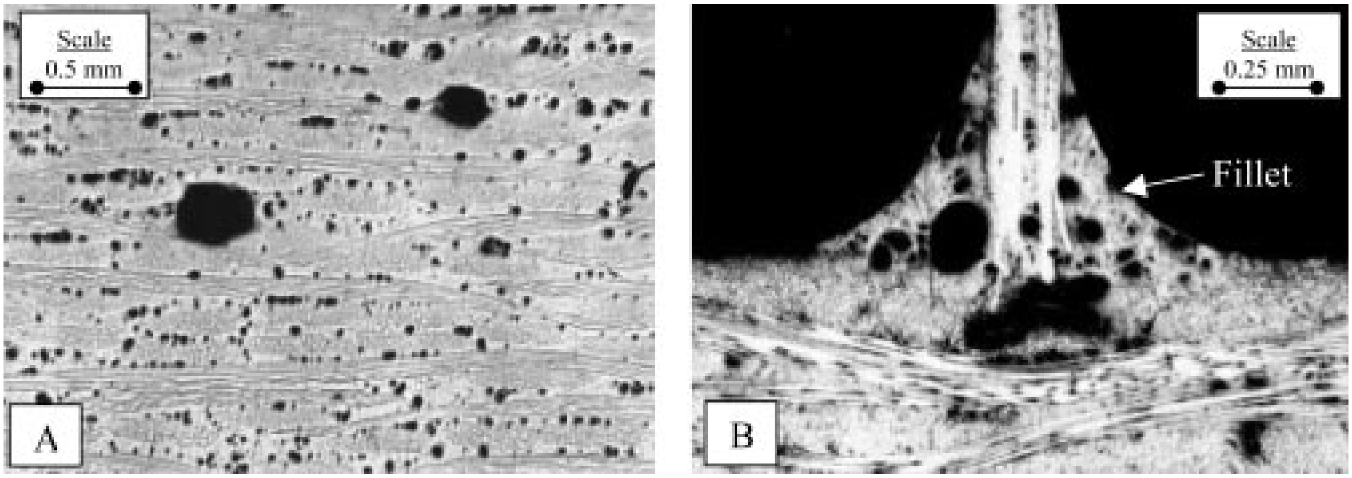

Fig. 3 Example of typical porosity problems with (a) laminates and (b) honeycomb core fillets

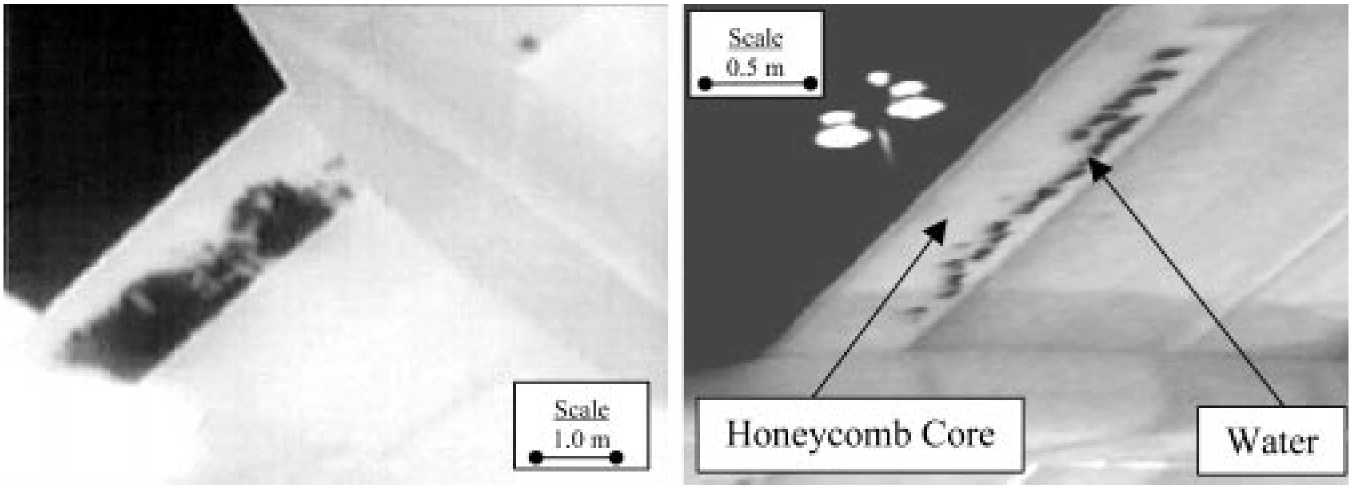

Fig. 4 Infrared images of two 767 outboard flap wedges showing the location of water in honeycomb sandwich structures. (Dark areas represent liquid water.)

of the cracked potting compound can readily be noticed. As shown in Fig. 5(a), water can be seen in a band pattern approximately 0.3 m from the aft end of the panel. It is in this location where a series of holes was drilled and potted in the honeycomb to attach the fitting for the door actuator. On the aft door, depicted in Fig. 5(b), a greater number of spots can be seen. The pattern of these spots can also be traced back to eight large potted regions where the hinge fittings and actuators were fastened to the honeycomb core.

Main Landing Gear Doors. The main landing gear doors have some of the same water ingression problems as the nose landing gear doors, except that in the main landing gear doors, the honeycomb core itself enhances water ingression and migration. The landing gear doors were fabricated from honeycomb core, which was nearly 11.0 cm thick in some locations. In fabricating honeycomb panels this thick, two pieces of core were bonded together. These pieces of core were bound together using a prepreg septum. The prepreg used in the septum was the same prepreg that was responsible for water ingression in the outboard flap wedge. As mentioned earlier, this particular prepreg had known porosity problems, and it was these problems that allowed water to migrate through the honeycomb core.

When the main landing gear doors are fabricated, holes for the leading and trailing edge erosion plates, actuator, and fastener fittings were drilled in the honeycomb core and filled with potting compound. Over time the potting compound cracked and water migrated into the honeycomb core. Once in the honeycomb core, the water spread from the localized area around the fitting to the rest of the core through the septum.

Figure 6 presents thermographic images of the main landing gear doors. In the figure large blotches of water appear to pool in the landing gear doors. The large blotches are a result of core septumization and the large holes drilled in the core for different types of fasteners. Figure 6 also shows the edges of the panels. The leading and trailing edges of the main landing gear door contain a metal erosion plate that was sealed and fastened to the edges of the honeycomb core. The erosion plate was attached to the panel to prevent degradation of the leading and

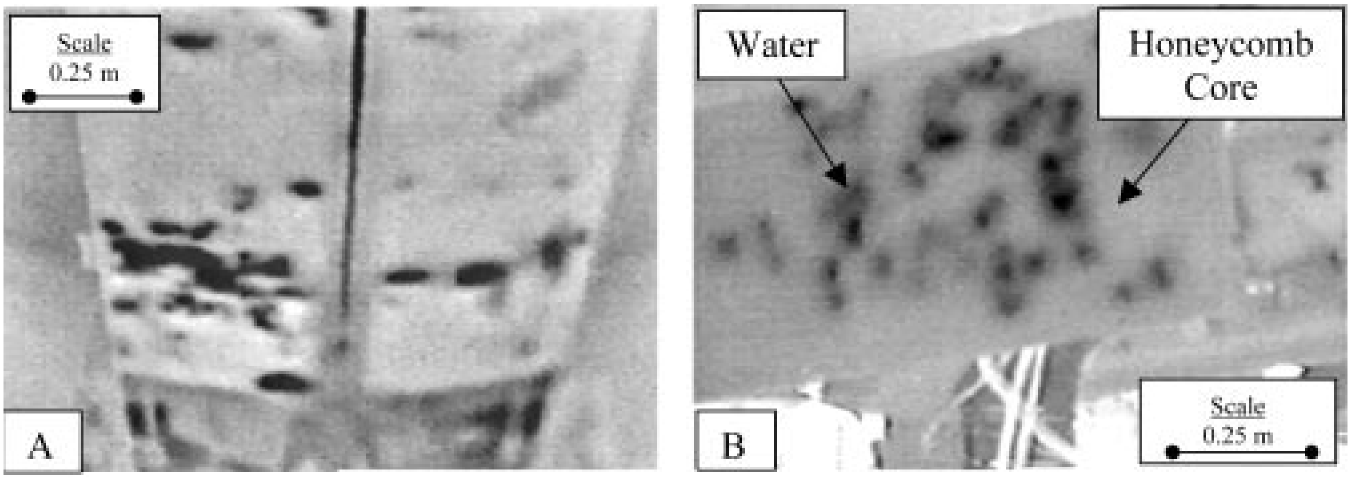

Fig. 5 Infrared images of the 767 (a) forward and (b) aft nose landing gear doors showing the location of water in honeycomb sandwich structures. (Dark areas represent liquid water.)

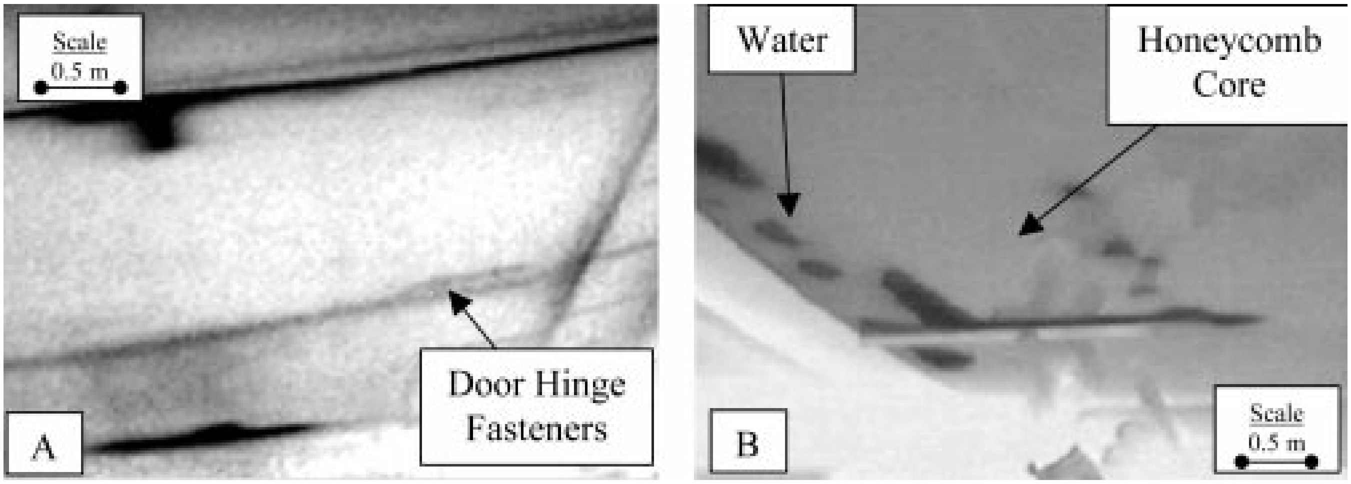

Fig. 6 Infrared images of (a) the body and (b) leading edge of the 767 main landing gear doors showing the location of water in honeycomb sandwich structures. (Dark areas represent liquid water.)

trailing edges of the panel when the panel was placed in the airstream during takeoffs and landings. The erosion plate was attached to the panel with more than 30 fasteners that led from the service environment of the panel directly into the honeycomb core. The cracking of the potting compound allowed water to migrate into the core and was responsible for the water pattern shown in Fig. 6. In the figure water ingression into honeycomb core around the fasteners of the main landing gear door hinge fitting can also be seen.

Fixed Upper Wing Panels. Another part found to contain water was the upper fixed wing panels. Although few upper surfaces were checked for water ingression, some of the fixed upper wing panels were thermographically inspected because they were visible from the ground. The undersides of several fixed wing panels could be inspected by scanning the wheel well of the main landing gear door.

When the fixed wing panels were originally designed, the designers incorporated woven Kevlar prepreg plies into the panel's construction to make the panels more hail and impact resistant. After several years of service, a large number of panels developed problems. Microcracks were found on the paint finish of the panels. The microcracks extended through the facesheet, and the cells of the honeycomb core were found filled with water. Several studies were conducted to determine the source of the microcracking. The Kevlar lamina in the panels were determined to be the source of the microcracks through intensive studies. Kevlar fibers are highly anisotropic and have extremely different coefficients of thermal expansion in the radial and axial directions. When exposed to severe repeated environmental cycling (as seen on commercial aircraft), the radial and axial expansion of the fibers cause large localized stress fields to develop in the lamina (Ref 10, 11). At very low temperatures the stress fields created in the lamina approach, and exceed, the yield strength of the matrix. Matrix yielding and microcracking relieves some of the internal stresses caused by the Kevlar fiber. With continued cycling, the microcracks expand and create leak paths from the surface of the panel to the honeycomb core. Once water enters the

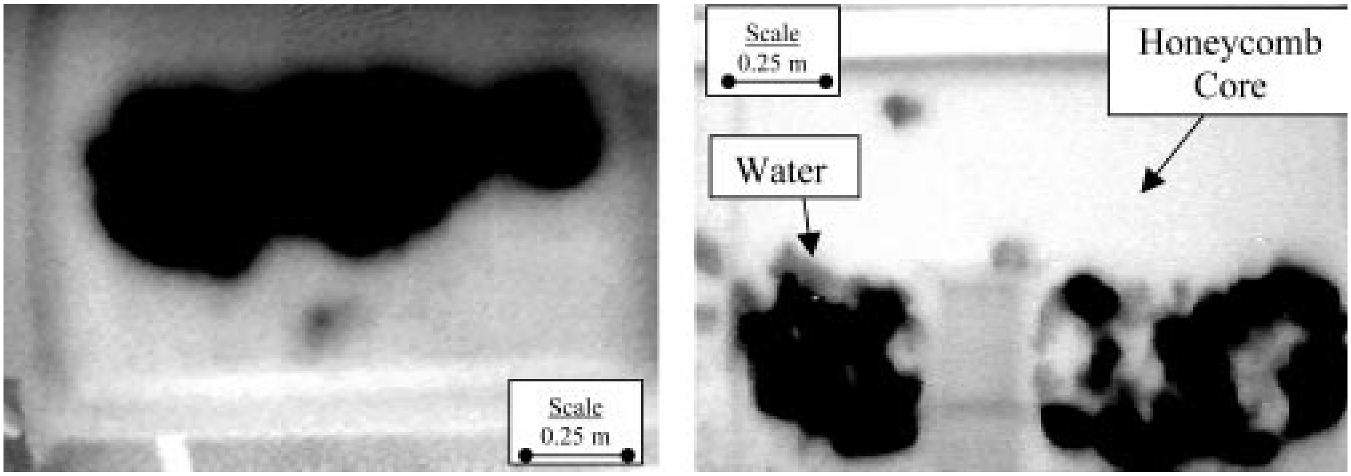

Fig. 7 Infrared images of two 767 upper fixed wing panels showing the location of water in honeycomb sandwich structures. (Bottom view.) (Dark areas represent liquid water.)

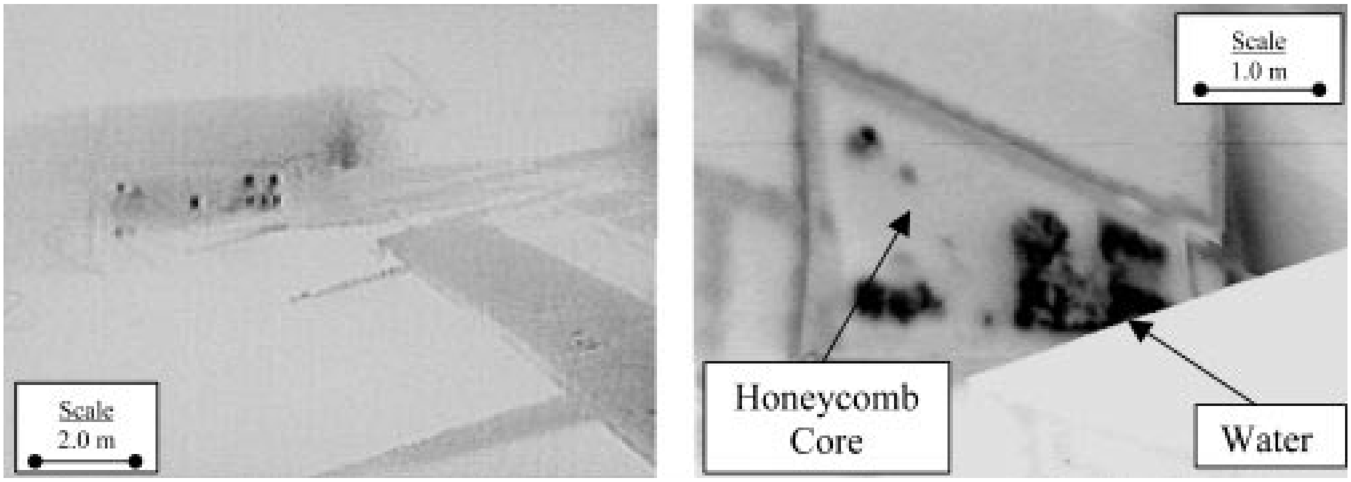

Fig. 8 Infrared images of two 767 escape slide doors showing the location of water in honeycomb sandwich structures. (Dark areas represent liquid water.)

facesheet, fiber swelling and deflation aggravate the problem by increasing the cyclic stress profile of the lamina (Ref 12).

The problems with Kevlar and commercial aircraft have been known for over ten years. After problems with the upper fixed wing panels appeared, service bulletins were issued by the Boeing Company alerting airlines of the tendency of these parts to absorb water (Ref 13). However, the panels were not immediately removed from service. The panels were only removed and repaired, or replaced, when delaminations, which required corrective action by the airline, developed. If the parts were believed to contain water, but no damage was observed, the parts were not repaired. Water was known to cause damage in composite parts, but water itself was not considered damage and was therefore not required to be repaired (Ref 14), although the water contained in the honeycomb structure will eventually delaminate the skin and damage the honeycomb core.

On the 767, all of the upper fixed wing panels do not have the same facesheet gauge thickness. The outboard panels have thinner skins than the inboard panels. When water ingression problems in these panels appeared, the thinner-skinned panels were found to delaminate first. These panels delaminated first because the leak path in these panels was shorter than in other panels with thicker skins. The shorter leak path in the outboard panels allowed water to accumulate and delaminate the facesheet sooner. The panels thermographically inspected and shown in Fig. 7 represent panels that have thicker facesheets and have not yet delaminated.

Escape Slide Doors. Through thermographic analysis, water was also observed to accumulate in the escape slide doors. The mechanisms of water ingression in the escape slide door are a combination of the problems seen with the other composite parts described earlier. In the body of the escape slide door potting problems are again believed to be responsible for water ingression. In Fig. 8, the pattern of water migration throughout the door is shown.

On the door, holes approximately 5.0 cm in diameter were drilled in the honeycomb core to attach the pack board. The pack board was used to affix the emergency escape slide system. The pack board was affixed to the door with a group of six large fasteners in the aft section of the panel and another four fasteners in the forward section of the panel. Cracks in the potting compound allowed water to ingress and spread throughout the door.

Around the escape slide door a dark “ halo” region can also be seen outlining the panel. This halo is attributed to Kevlar filler plies in the solid laminate edge band. Kevlar was used in the edge band to bring it up to the nominal required thickness of the part. The Kevlar edge band extends from the edge of the honeycomb core bay all the way to the edge of the panel. At the edge of the panel, the Kevlar was exposed to the air from which it was able to wick moisture into the edge band of the panel. It is the wicking of water into the panel that is responsible for the halo around the door.

4. Conclusions

In understanding the lifecycle of honeycomb composite structures it is important to review their performance once in service. In this article, the tendency of honeycomb composite structures to absorb and retain water was investigated. Through a thermographic inspection of 35% of United Airlines 767 fleet, an attempt was made to quantify the extent of water ingression and migration problems in the aircraft industry.

Through the thermographic inspections performed, the honeycomb composite structures on the 767 were found to contain less than 50 kg of water. In reviewing the data, not all of the honeycomb structures of the aircraft were found to contain water, and little water ingression was attributed to foreign object damage. Most of the water found on the aircraft was contained in a handful of problematic parts. Five parts, which include the outboard flap wedge, the nose landing gear doors, the main landing gear doors, the fixed upper wing panels, and the escape slide door, were responsible for more than 90 wt% of the water in the honeycomb panels. Problems with skin porosity were attributed to water ingression in the outboard flap wedge. The water found in the nose and main landing gear doors was due to cracks in the potting compound around the fasteners and hinge fittings. The Kevlar lamina in the upper wing panels caused microcracking in the facesheet of the panel, thereby compromising the honeycomb core. Lastly, water in the escape slide door was traced back to potting compound problems and Kevlar. Ultimately, the work presented in this article will aid in the understanding and design of future honeycomb composite sandwich structures.

Acknowledgments

The authors would like to express their appreciation to the Hexcel Company, the Boeing Company, and United Airlines for their support and participation in the Graduate Team Certificate Program at the University of Washington. The individual contributions of the following participants are also greatly appreciated: M. Caldwell, B.A. Frye, C. Martin, R. Popa, M.P. Thompson, W.H. Vogt, and P.A. Wachter.

References

1. S. Abrate, Localized Impact on Sandwich Structures with Laminated Facings, *Appl. Mech. Rev.*, Vol 50 (No. 2), 1997, p 69-82
2. R.A. Garrett, R.E. Bohlmann, and R.E. Derby, Analysis and Test of Graphite/Epoxy Sandwich Panels Subjected to Internal Pressure Resulting for Absorbed Moisture, *Advanced Composite Materials—Environmental Effects: A Symposium*, 1978, p 234-253
3. D. Cise and R.S. Lakes, Moisture Ingression in Honeycomb Core Sandwich Panels: Directional Aspects, *J. Mater. Eng. Perform.*, Vol 6 (No. 6), 1997, p 732-736
4. R. Wong and R. Abbott, Durability and Damage Tolerance of Bonded Sandwich Panels, *35th International SAMPE Conference*, Vol 35, 1990, p 366-380
5. C.L. Wu, C.A. Weeks, and C.T. Sun, Improving Honeycomb-Core Sandwich Structures for Impact Resistance, *J. Adv. Mater.*, Vol 26 (No. 4), 1995, p 41-47
6. D.B. Weems and R.E. Fay, A Moisture Barrier for Composite Sandwich Structure, *American Helicopter Society National Meeting*, 1995
7. D.G. Giancoli, *Physics for Scientists and Engineers*, Englewood Cliffs, Prentice Hall, 1988

8. J.E. Shafizadeh, B.S. Hayes, and J.C. Seferis, Fundamentals of Breather Technology in Prepreg Consolidation, *J. Adv. Mater.*, Vol 29 (No. 4), 1997, p 42-49
9. 767 Service Bulletin (767-57-0061), “Wing Trailing Edge—Outboard Trailing Edge Flap Wedge Inspection, Repair, and Modification,” Boeing Commercial Airplane Group, Seattle, WA, 1998
10. H.Y. Loken, D.A. Nollen, M.W. Wardle, and G.E. Zahr, *Water Ingression Resistant Thin Faced Honeycomb Cored Composite Systems with Facesheets Reinforced with KEVLAR Aramid Fiber and KEVLAR with Carbon Fibers,* Wilmington, DuPont Corporation, 1988
11. R.H. Moore and D.A. Dillard, Time Dependent Damage in Laminated Composites, *American Chemical Society—Polymer Preprints,* Vol 29 (No. 2), 1988, p 141-142
12. R.E. Mauri, F.W. Crossman, and W.H. Warren, Assessment of Moisture Altered Dimensional Stability of Structural Composites, *23rd SAMPE Symposium,* Vol 23, 1978, p 1202-1217
13. Service Letter, “737-SL-51-18-A: Kevlar and Kevlar/Graphite Composite Water Ingestion,” Boeing Commercial Airplane Group, Seattle, WA, 1985
14. *Boeing 757-300 Structural Repair Manual*, Boeing Commercial Airplane Group, Seattle, WA, 1994