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Evaluation of the mechanisms of water migration through honeycomb core

J. E. SHAFIZADEH, J. C. SEFERIS*
Polymeric Composites Laboratory, Department of Chemical Engineering, University of Washington, Seattle, Washington 98195-1750, USA
E-mail: seferis@cheme.washington.edu

E. F. CHESMAR
United Airlines-SFOEG, San Francisco International Airport, San Francisco, CA 94128-3800, USA

B. A. FRYE, R. GEYER
Boeing Commercial Airplane Group, P.O. Box 3707, M/S 5L-06, Seattle, WA 98124–2207, USA

Thirteen commerical wing panels were fabricated and flown on a commercial aircraft to investigate the mechanisms of water migration through various honeycomb cores. A 12.2 J impact damage was not observed to cause damage propagation in aluminum and Korex® honeycomb materials. This was attributed to the ability of the cores to localize the impact damage. In Nomex® and glass fiber cores a different damage propagation mechanism was observed. In these cores, the damage was not confined to the localized area around the impact. Instead, core damage was seen as far as 2.0 cm from the point of impact. This increased core damage allowed the core to retain water. The retained water helped propagate the impact damage through a freeze thaw mechanism. Speed-tape repairs were only found to be statistically significant when water migrated through the core. Filling the honeycomb core with foam was shown to be an effective method for minimizing the damaging effects of water ingression. Slotting and draining the core also offered some relief from water accumulation in the core, but foaming damaged core was established as the most effective technique.

1. Introduction

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 [1]. Yet, once in-service, this design often breaks down. Airline operators frequently find that composite honeycomb structures absorb and retain large amounts of water while in-service. Water absorption in honeycomb composite structures represents a percieved problem for aircraft operators. If left unmanaged, it can cause mechanical deterioration of honeycomb core, delamination of the facesheet from the honeycomb core and increased operating and maintenance costs for the composite structures [2].

Several researchers have investigated water ingression and migration through honeycomb core, but no work has been attempted to statistically understand the mechanisms of water ingression and migration through honeycomb core as a function of in-service cycling [3–5]. This paper represents the second part of a two-part investigation studying 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 were explored. An investigation was conducted to determine whether water ingression is a localized problem that occurs occasionally, or whether it is a systemic composite problem [6]. To quantify the extent of water ingression and migration problems, non-destructive infrared thermographic inspections were performed on 15 United Airlines Boeing 767s. 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 was conducted on sixteen outboard fixed trailing edge panels. From these panels, the effects of core type, impact damage, and tarmac repair procedures were examined. Together, these studies represent the most comprehensive attempt to date to understand the in-service durability of honeycomb structures [7, 8]. Ultimately, the research performed in these two studies will aid in the understanding of the utilization trinity of future honeycomb composite sandwich structures that must consider design, manufacturing and performance connected through capital, operating and life-cycle costs [9].

*Author to whom all correspondence should be addressed.

2. Experimental procedure

2.1. Panel fabrication

As mentioned earlier, a total of sixteen modified Boeing 767-200 upper wing fixed trailing edge panels (part numbers 113T1655, 113T1656, 113T1657 and 113T1658) were fabricated and flown to study the mechanisms of water ingression and migration through honeycomb core. Upper wing fixed trailing edge panels were selected for study due to their ease of fabrication and location on the wing. As shown in Fig. 1, these panels are located on the outboard section of the wing behind the rear spar. Panels in this wing location are directly exposed to the airstream and are seldom damaged on the ground from falling tools or other incidental collisions.

The wing fixed trailing edge panels are manufactured with glass fiber facesheets and honeycomb core. The facesheets of the panels were fabricated from Hexcel F-155 prepreg qualified to Boeing Material Specification (BMS) 8-79. The F-155 prepreg used was a 126°C cure, self-adhesive, epoxy based resin, which was impregnated in a 7781 style glass fabric. The panels were constructed using a vacuum bagging process where five plies of prepreg were used on the tool, or aerodynamic side of the panel and two plies of prepreg and one ply of Tedlar® were used on the bag side. The upper wing panels fabricated in this study were manufactured by Hexcel Structures in accordance with Boeing Composite Process Specification BAC 5317-2. BAC 5317-2 specifies that the panels be cured in an autoclave at 126 ± 5°C and 310 ± 34 kPa for 90 min with maximum temperature ramps of 2.7°C/min.

The honeycomb core bays used in production trailing edge panels were fabricated from 3.2 mm cell size Nomex® honeycomb core with a nominal density of 50 kg/m^3. In this study, the usual Nomex honeycomb material was substituted with one of four different types of honeycomb core that included aluminum, Korex®, Nomex and glass fiber cores. The non-metallic cores used were qualified to BMS 8-124, while the metallic core was qualified to BMS 4-4. The aluminum, Korex, Nomex and glass fiber cores were all provided by Hexcel and had the following respective Hexcel designations: CRIII-1/8-5052-0.001-4.5, Korex-1/8-3.0, HRH-10-1/8-3.0 and HFT-1/8-3.0. The cell size on all honeycomb cores was 3.2 mm and all cores had a nominal density of 50 kg/m^3, except the aluminum core. The aluminum core had a nominal density of 75 kg/m^3 and was anodized with phosphoric acid to prevent corrosion. Over the aluminum core, an adhesive film, 3M AF-163-2 OST, qualified to BMS 5-129, was used to insure adequate adhesion and bonding between the facesheet and the core. In production panels, the size of the honeycomb core bays ranges from 99 to 39 cm in length and 27 to 33 cm in width. In modifying the honeycomb core bay materials, the overall size of the core bays was fixed by Boeing specification drawings. Therefore, all modified core bays had to conform to the dimensions of the production core bays. In complying with this design constraint, the overall size of the core bays was divided into one, two or three smaller core bays, or subbays. The core sub-bays were manufactured from the different core materials listed above and spliced together with a foaming adhesive from Sovereign Specialty Chemicals (PL 685) qualified to the BMS 5-90 specification. After the bays were spliced together a 20° chamfer was machined out of the core to match the part specification drawings. The spliced core bays had the same dimension as the original production core bays. Each subbay was approximately 650 cm^2 in size. After fabrication, the wing panels were installed on two different United Airlines 767-200s and flown on domestic U.S. routes for fourteen months.

In order to statistically understand and isolate the mechanisms of water migration through honeycomb core, three Design of Experiments (DOE) were constructed. The DOEs were constructed to understand the individual as well as synergistic effects of impact damage, repair procedures, damage location and core composition. The individual DOEs dictated the design and material selection of the honeycomb core bays used in manufacturing the wing panels.

2.2. Design of experiment #1

The first DOE was fabricated to study honeycomb water migration and damage propagation as function of core composition, damage size and limited repair procedures. DOE #1 is outlined in Table I. The face sheets over each core bay were intentionally damaged to allow water into the honeycomb core and create a known path

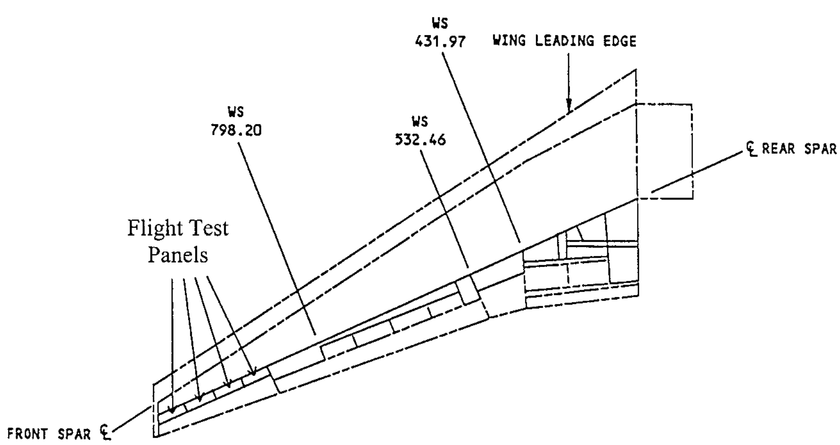

Figure 1 Diagram from the Boeing 767-200 Structural Repair Manual showing the wing location of the upper wing fixed trailing edge panels [7].

TABLE I DOE #1 for evaluating water migration and damage growth through honeycomb core as a function of core material, impact damage and speed-tape repair

Core bay	Core material	Speed-tape	Impacted	Airplane
1	Korex	No	Yes	A
2	Nomex	No	No	A
3	Glass fiber	Yes	No	A
4	Aluminum	Yes	Yes	A
5	Aluminum	No	No	A
6	Korex	Yes	No	A
7	Nomex	Yes	Yes	A
8	Glass fiber	No	Yes	A
9	Korex	No	No	B
10	Korex	Yes	Yes	B
11	Nomex	Yes	No	B
12	Nomex	No	Yes	B
13	Glass fiber	No	No	B
14	Aluminum	No	Yes	B
15	Aluminum	Yes	No	B
16	Glass fiber	Yes	Yes	B

for water ingression. Three holes, 1.6 mm in diameter, were drilled in the center of the aerodynamic facesheet of each sub-bay*. The holes were drilled in the centers of three adjacent core cells forming a triangle with the centers of the holes located 3.2 mm apart.

Some honeycomb bays were also impacted to study the growth of impact damage as a function of water migration through the core. According to the Structural Repair Manual (SRM) for the Boeing 767-200, the maximum allowable damage diameter before a repair is necessary for a single damage site in a honeycomb core area is 5.1 cm. The fixed trailing edge panels were impacted such as not to exceed the SRM limit for repair. The panels were damaged such that all damage locations were approximately the same size. An impact drop tower was used to damage the panels. The impact energies and damage sizes for each core bay are presented in Table II.

The effectiveness of speed-tape repairs to prevent water ingression through a known ingression path was also explored in DOE #1. When a damage is noticed on an aircraft composite panel and the damage is below the SRM limit for repair, a speed-tape repair may be performed. In a speed-tape repair, the damaged area is cleaned with an appropriate solvent and an aluminum foil tape is applied over the damaged area. For the modified fixed wing trailing edge panels, a square 103 cm^2 piece of speed-tape (3M Y-436) was placed over the holes or damage location before the panels were installed on the aircraft. Two core bays of each construction were manufactured to insure result reproducibility.

TABLE II Impact energies and their resultant honeycomb bay damage sizes as measured by through transmittance ultrasound (TTU)

Core type	Core bay	Impact energy (J)	Damage size diameter (cm)
Aluminum	4, 14	12.2	2.00
Korex	1, 10	12.2	2.09
Nomex	7, 12	8.1	2.14
Glass fiber	8, 16	4.1	3.53

TABLE III DOE #2 for evaluating the effect of water ingression location as a function of core type

Core bay	Core material	Hole location	Airplane
5	Aluminum	Top	A
17	Nomex	Bottom	A
18	Aluminum	Bottom	A
2	Nomex	Top	A
19	Nomex	Top	B
20	Nomex	Bottom	B
21	Aluminum	Top	B
22	Aluminum	Bottom	B

2.3. Design of experiment #2

DOE #2 was constructed to evaluate whether core type and leak path location were significant factors in water ingression and migration, as shown in Table III. Holes were drilled in the facesheets of the honeycomb core bays as described in DOE #1, except on some panels the holes were drilled on bottom, or bag side, of the panel instead of on the aerodynamic, or tool side, of the panel. For structural reasons, an extra ply of F-155 prepreg was added to the bag side of the panel for all core bays which had holes drilled on the bottom side of the panel. Two core bays of each construction were manufactured to insure result reproducibility.

2.4. Design of experiment #3

The last Design of Experiment was created to test possible solutions for minimizing water ingression and migration through honeycomb core in an aircraft service environment. In this DOE, all of the honeycomb core bays were fabricated from HFT-1/8-3.0 glass fiber core with slight of variations between the different core bays, as shown in Table IV.

One possible solution to minimize water accumulation in honeycomb core was to slot and drain the honeycomb core. On one set of core bays slot lines, 0.63 mm wide and 1.78 mm deep, were machined into the lower surface of the cell wall on the bag side of the honeycomb core. The slot lines were cut through the center of each cell in the expanded direction of the core and were spaced 3.2 mm from each other. At the honeycomb core chamfer, or at the location where the bay was spliced to another subbay, another set of slot lines was machined around the core. Chamfer slotting connected all of the parallel slot lines machined in the expanded direction of the core. At the corners where the chamfer slot lines came together, drains holes, 4.8 mm in diameter, were drilled in the core. By slotting and draining the core, any water that entered the core could leave the core

TABLE IV DOE #3 for evaluating different core constructions designed to prevent and minimize the effects water ingression

Core bay	Core material	Impacted	Airplane
8	Standard	Yes	A
23	Foam-filled	No	A
25	Slot and drain	No	A
27	Foam-filled	Yes	B
13	Standard	No	B
28	Slot and drain	Yes	B

by traveling along the slots in the lower surface of the core and drain out the holes in the corner of the bay. Therefore, it should be possible to minimize facesheet delamination and core damage caused by standing water in the core.

Another possible solution to minimize the problems caused by standing water in the core is to limit honeycomb water ingression by filling the honeycomb core with a closed-cell foam. Although foaming the core significant increases the weight of the panel, foam prevents water from entering and damaging the honeycomb cells when the facesheets of the panels are damaged or compromised. To evaluate the effectiveness of foamed honeycomb core, foam filled core bays were constructed and included in DOE #3. In these sub-bays the honeycomb cells were foamed with 83.5 kg/m^3 dense Hexcel cyanate K-foam. After the cells were foamed, the surface of the honeycomb core was sanded. During lay-up, a ply of 3M AF-163-2 OST film adhesive was applied between the core and the prepreg ensure an adequate bonding to the facesheet skins.

Holes were drilled in the facesheets of all sub-bays as described in DOE #1. Specific foam and slotted honeycomb core bays were also impacted as part of DOE #3. The slotted and foam sub-bays were impacted with an impact energy of 4.1 J and had damage diameters of 2.06 and 2.54 cm respectively. Two core bays of each construction were manufactured to insure result reproducibility.

2.5. Panel inspection

Before and after the in-flight service cycling, through transmittance ultrasound (TTU) inspections were performed on the panels to measure the size of the damaged area in each honeycomb core bay. During the TTU inspections, the panels were scanned with waterjet coupled transducers, 1.91 cm in diameter. The panels were scanned at a rate of 25.4 cm/sec at a frequency of 1 MHz while being indexed in increments of 4.06 cm. During the TTU inspections, the damage area was analyzed at two different ultrasound amplitudes: 18 dB and 12 dB.

While cycling for fourteen months on the two 767 aircraft, the panels had an average service time of 4,400 flight hours with two takeoffs and landings per day with an average flight time of five hours per takeoff. After the in-service cycling and TTU inspections, a 420 cm^2 square was cut from the center of each core bay. The individual core bays were then weighed and dried in a vacuum oven at 75°C under a constant pressure of 4.8 kPa for 5 days. After drying, the core bays were weighed and the difference between the initial and final weights was reported. For all of the DOEs, three data analyses were performed: water absorption, gross damage growth and percent damage growth.

3. Results and discussion

3.1. Design of experiment #1–holes, impact damage and speed-tape

3.1.1. Water absorption

There are two basic statistical models for analyzing and interpreting Design of Experiments (DOE): factorial models and hierarchical models [10]. Factorial models assume that all of the measured response variables (e.g., damage growth, water absorption) can be analyzed independent of their source of variance. Hierarchical models assume that the response variables are interrelated with their respective sources of variance. In understanding the response of different honeycomb cores to water absorption and impact damage, a hierarchical model must be applied. The mechanisms of water migration and damage growth in honeycomb composite structures were unique to each type and density of core. Subsequently, the sources of variance had to be analyzed as a function of core type. In Table V, the statistically significant variables that affect the water absorption characteristics of the different honeycomb cores are presented. From the analysis of variance, 73.1% of the variation in the data could be attributed to the sources outlined in Table V.

As shown in Table V, the locations of the individual core bays on the aircraft were not found to play a statistically significant role in water absorption. This is an important result because it indicated that all core bays experienced comparable flight conditions during the fourteen-month service evaluation, independent of the individual aircraft's flight schedule or the location of the bays on the aircraft.

The absorption of water by the aluminum and Korex core bays was also found to be unaffected by a 12.2 J impact. The lack of an affect may be attributable to a few possible causes. It is first possible that the panels were not in service long enough to allow sufficient time for damage propagation. Aluminum and Korex are relatively strong web materials when compared to Nomex and glass fiber. These materials may have required a longer service time to reveal the degradative effects of continuous environmental cycling.

It is also possible that while in service, water did not accumulate or remain in the core bays long enough to significantly damage the core. In Figs 2 and 3, photomicrographs of the impact damage to the aluminum and Korex core bays are shown. For these composite structures, damage to the honeycomb cores and facesheets extended only one or two cells beyond the point of impact. Outside this small damage area, the core and facesheet were unaffected by the impact, (as confirmed by optical microscopy). The localization of the impact damage prevented the creation of a voluminous reservoir for the accumulation of water inside the core. By minimizing the amount of water in the cells the detrimental mechanical effects

TABLE V Statistical analysis of variance for the water absorption characteristics of different honeycomb cores using a hierarchical DOE model

	Core type			
Source of variance	Aluminum	Korex	Nomex	Glass fiber
Location/airplane				
Impact speed-tape			XX	XX
Impact & speed-tape			X	XX

XX–Significant at 1% confidence level.
X–Significant at 5% confidence level.

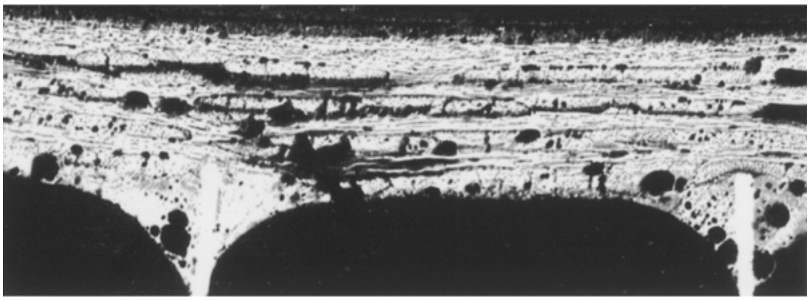

Figure 2 Photomicrograph of an aluminum core bay impacted with 12.2 J at 25× magnification.

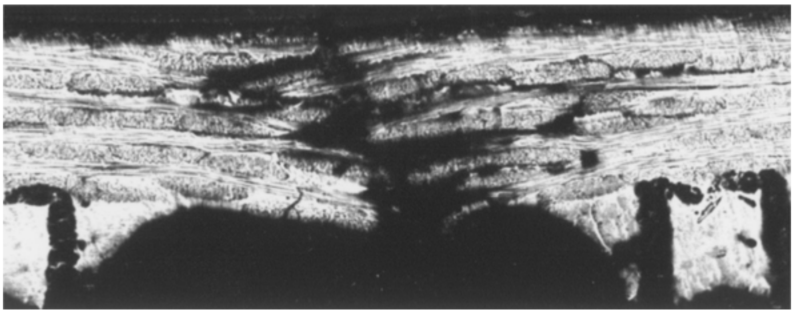

Figure 3 Photomicrograph of a Korex core bay impacted with 12.2 J at 25× magnification.

from the water continually freezing and thawing were diminished.

The localization of the impact damage may also have aided in removing water from the core. During flight, high-speed air flowing over the damaged honeycomb core bays created a negative pressure gradient inside the honeycomb core [11]. This pressure gradient lowered the vapor pressure of the water or ice in the core and increased the rate of evaporation or sublimation. This effect was also enhanced at altitude. At a cruising altitude of 7,000 to 9,000 m, the vapor pressure of water is near 26 Pa and the specific humidity (grams of water/grams of dry air) is approximately 0.04% [12]. These dry conditions further facilitate the removal of water from the core. Because all of the water in the aluminum and Korex panels was confined to a small area near the point of ingression, most of the water could be removed through these two mechanisms.

For the Nomex and glass fiber cores, impact damage was found to have a statistically significant effect on water ingression and migration through the sandwich structure. This is attributed to the mechanism of damage propagation through the core. When the Nomex honeycomb composite structures were impacted, both the core and facesheet sustained a great deal of damage, as shown in Fig. 4. In this figure, only the area immediately surrounding the impact location is shown, however, small microcracks could be observed in the Nomex honeycomb core as far away as 1.5 cm from the impact location. This damage allowed water to migrate significant distances away from the ingression point and into the core. At altitude, the pressure gradient for water removal is largest around the point of ingression. As the distance from the impact location increased, the pressure drop from cell-to-cell decreased and the effective driving force for water removal decreased. The net result was a greater amount of water retained by the honeycomb core. Water retained in the core is known to cause freeze-thaw damage in the core, which further damages and fractures the core, and ultimately increases the water retention volume of the core.

Figure 4 Photomicrograph of a Nomex core bay impacted with 8.1 J at 25× magnification.

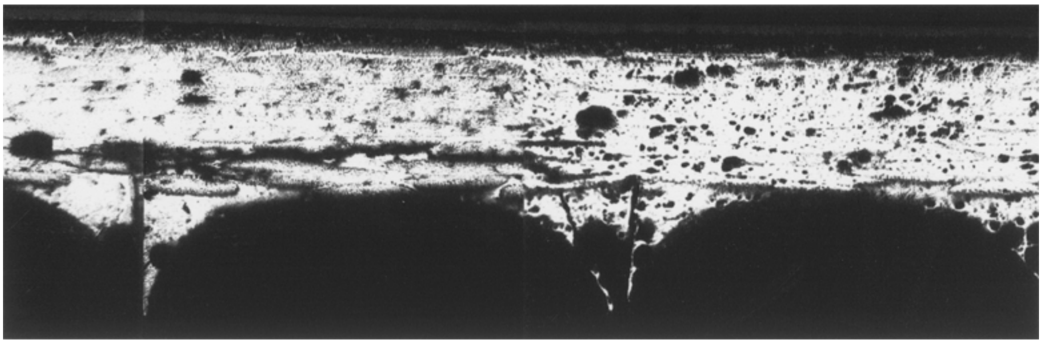

Figure 5 Photomicrograph of a glass fiber core bay impacted with 4.1 J at 25× magnification.

For the honeycomb composites manufactured with glass fiber core, similar behavior was observed. After being impacted, the facesheets of the composite structures microcracked and small sections delaminated, as shown in Fig. 5. But unlike the Nomex core, the facesheet damage was limited to the immediate area around the impact. Although, the facesheet did not show extensive damage, the core and the skin-to-core fillets were observed to have widespread failures. From the TTU inspections, the initial diameter of the core damage was observed to be 3.5 cm, but through microscopy, small core microcracks were observed to extend as far as 2.0 cm from the center of the impact. From the photomicrographs and TTU inspections, it can be concluded that the glass fiber core absorbed the brunt of the impact damage. Like the Nomex core, the glass fiber core sustained a greater amount of damage than the aluminum or Korex cores in spite of the fact that smaller impact energies were used on the glass fiber cores. The larger amount of core damage allowed a greater amount of water to become trapped within the core. The extensive damage away from the small impact center also reduced the ability of the core to dry during flight, as described earlier.

Speed-tape alone was also not found to play a significant role in the absorption of water and had no effect when water did not accumulate in the core over time. Over an impact, speed-tape was not found to be a significant factor for the absorption of water in the aluminum or Korex cores; although, it was found to be significant in Nomex and glass fiber cores. Speed tape was not a significant factor when used over the aluminum and Korex core bays because, in-service, water was not found to migrate through the cores. Over impacted Nomex and glass fiber core bays, speed tape decreased the tendency of the parts to absorb water. However, without impact, the water was limited to the drilled cells and was removed in-service. Speed-tape only stopped water migration when water was found to migrate away from the point of ingression.

3.1.2. TTU inspections

3.1.2.1. Gross damage growth. Along with the statistical analysis of water absorption, an analogous study was performed on impact damage. Through TTU inspections, the physical growth of the damage caused by drilling holes and impacting the wing panels was determined. In assessing the damage of the panels, two levels of damage were distinguished, an 18 dB threshold level and a 12 dB threshold level. The 18 dB damage level represented gross failure or delamination of the core or facesheet, while the 12 dB limit represented the 18 dB damage plus limited microcracking or absorbed water within the core. Fig. 6 illustrates the differences between the two damage levels. In the far right square core bay of Fig. 6, a glass fiber sub-bay is shown. In this figure, a central black damage area can be noticed. This area was defined as an 18 dB damage level. Outside this dark area, a lighter colored oblong region can also be observed. This region was defined as a 12 dB damage area.

A statistical analysis was performed on the gross damage growth for both the 18 and 12 dB damage areas. The significant sources of variance at 18 dB were identical to the significant sources of variance identified in the water absorption analysis. The only difference between the two analyses was that the significant variables at the 5% level in Table V were significant at the 1% level in the gross damage DOE analysis. When the data was analyzed in terms of gross damage propagation at the 18 dB and 12 dB levels, 86.5% and 74.1% of the

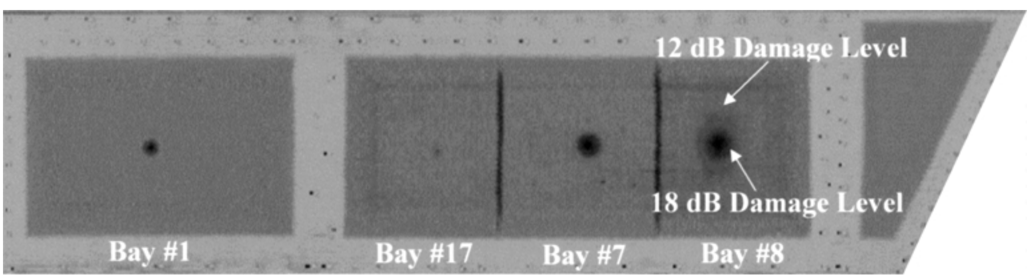

Figure 6 Typical TTU scan of an upper wing fixed panel showing 18 and 12 dB TTU damage levels after 14 months of service.

TABLE VI Statistical analysis of gross damage growth for DOE #1 using through transmittance ultrasound inspections with a threshold of 12 dB

Source of variance	Core type			
	Aluminum	Korex	Nomex	Glass fiber
Location/airplane				
Impact				XX
Speed-tape				
Impact & speed-tape				XX

XX–Significant at 1% confidence level.
X–Significant at 5% confidence level.

respective variance in the data could be explained by the model.

A statistical analysis at the gross damage change at the 12 dB level revealed a slightly different set of results. In Table VI, a summary of the analyses is presented. As shown in this table, the sources of variance at the 12 dB level were only significant in the glass fiber core. This is attributed to the damage mechanism in glass fiber core. Unlike the other cores studied, when the glass fiber core was impacted, the core sustained most of the damage and little damage in the facesheet was observed, as earlier illustrated in Fig. 5 and Table II. The greater core damage allowed significant amounts of water to travel into the core and remain in the core during flight. The 12 dB damage represents the core damage front which contains water or microcracking damage, but has not caused complete failure of the core. With the other core materials, this damage front was not detected on a gross damage scale basis. Again, the presence of speed-tape over the impact was shown to reduce the growth of damage and ingression of water.

3.1.2.2. Percent damage growth. Lastly, a statistical analysis was performed on the percent damage growth of DOE #1. The percentage damage growth was defined according to Equation 1

$$DG = \left(\frac{D_{\mathrm{F}}}{D_{\mathrm{O}}} - 1\right) \times 100 \qquad (1)$$

Where DG represents the percent damage growth, D_{F} represents the final damage size, and D_{O} represents the initial damage size. In Equation 1, the minus one is a constant that does not affect the analysis of variance because the analysis is invariant to additive constants. Dividing the final damage size by the initial damage size gives additional pieces of information not included in an analysis of gross damage change. The quotient between the final and initial sizes measures the relative growth of the damage and considers the 'initial baseline damage' of panels. In analyzing the data from a percentage point of view, 89.4% and 74.4% of the respective variance in the 18 and 12 dB analyses could be explained.

The 18 dB percent damage growth analysis again closely tracked the 18 dB gross damage change and water absorption analyses. At the 12 dB damage level, impact damage and impact damage coupled with speed-tape were again shown to be significant for the glass fiber core. Some differences did emerge when the 12 dB gross damage changes analysis was compared to the 12 dB percent damage growth analysis shown in Table VI.

In terms of percent damage growth, impact damage was statistically significant at the 12 dB threshold level for the aluminum, Korex and Nomex cores. However, speedtape over that impact was not found to be a significant source of variance. This implies that while speedtape may be good for stopping gross impact damage growth, impact damage may still propagate and grow in-service. Although the overall growth may not be significant, the damage growth does become statistically significant when compared to the initial damage size. The 12 dB analysis also indicated that while the percent damage growth from cycling did increase from 14 months of in-service cycling, this damage was not delamination or core failure, but rather the result of some small amount of microcracking or water in the core. This damage may grow over time to facesheet delamination or core failure, but this growth was not observed in this study.

For all of the core sub-bays in this Design of Experiment, no water absorption or damage growth was noticed when only holes were drilled in the panels. This strengthens the argument for the idea that distance from point of ingression controls damage propagation through the core. When holes were simply drilled in the panel, water was confined to the area directly under the holes in the facesheet. Also, the damage was not observed to propagate on either a percent scale or on a gross damage scale. When the damage size was increased, through impacting, to extend one or two cells away from the point of water ingression, damage growth on a percent basis was observed to occur.

3.2. Design of experiment #2–effects of hole location

In examining the DOE for hole location, no water absorption, gross damage growth (at either the 18 or 12 dB level) or percent damage growth (at either the 18 or 12 dB level) was observed in any core bay. For DOE #2, hole location was not shown to be a significant factor for water absorption or damage propagation for either the aluminum or Nomex cores. However, it is not apparent whether hole location is truly a non-factor or whether the panels required a longer service time to differentiate damage propagation between the top and bottom.

3.3. Design of experiment #3–minimizing the effects of water ingression

3.3.1. Water absorption

In DOE #3, a factorial model was used to statistically analyze the data because only glass fiber honeycomb was used to fabricate the core bays. As a result, all of the core bays had similar mechanisms of damage propagation and water absorption.

For all of the honeycomb core bays, the aircraft itself was found to have a statistically significant effect on water absorption, as shown in Table VII. For the slotted honeycomb core, large differences in water content were detected between the different core bays. The flight time, number of take-offs and landings per

TABLE VII Statistical analysis of variance for the water absorption characteristics of standard, slotted and foam-filled honeycomb cores using a factorial DOE model

Source of variance	Glass fiber core
Location	
Airplane	X
Impact	X
Foam filled	
Slot and drain	

XX—Significant at 1% confidence level.
X—Significant at 5% confidence level.

day and general airport locations were about the same for both aircraft, and for the first DOE these factors did not affect the damage propagation or amount of water absorbed by the core. This is attributed to the localization of the water around the hole or impact location on these core bays. For the slotted core bays, water, de-icing fluid and the other fluids were not locally confined within the core bays. Rather, the fluids were allowed to travel throughout the core bay via the slotted cells. Because of the significantly higher volume of water passing though the panel, it is possible that different amounts of fluid were retained by the core panels depending upon flight route, local area weather, and aircraft pretreatment before flight.

For the standard glass fiber and foam filled honeycomb bays, water accumulation or damage propagation was again not observed to occur in the core bays without an impact. However as discussed above, water was observed to pass through the core bays that had slotted honeycomb core with drain holes, as shown in Fig. 7. In this figure, the dark regions of the slotted core bays represent residual water absorbed by the core. Water was able to infiltrate the core over the 14 month service life, but through microscopy, the absorbed water was not observed to damage the core bay or cause core microcracking. In some of the slotted core bays, the ingressed water did not drain evenly, and sometimes water favored one drain hole over another based upon the panel's location on the wing and the inclination on the wing, as shown in Fig. 7A. But for the most part, water was able to pass through the honeycomb core. In some regions, the honeycomb slots in teh core became plugged or filled. This prevented water form entering or leaving part of the core, as demonstrated in Fig. 7B. In Fig. 7B, a diagonal line of slots down the center of the core was filled and only half of the cells in the core were able to transport water away from the point of ingression.

Due to the large deviation in water absorption by the different core bays (especially the slot and drain core bays), the factorial water absorption model only captured 39.9% of the variance in the data. A hierarchical model was attempted to fit the data, and the adjusted correlation coefficients were slightly lower.

3.3.2. 18 dB damage growth

By modeling the damage propagation with the 18 dB gross damage growth, 59.5% of the variance in the data could be accounted for. When the damage growth was analyzed from this point of view, foam filling the core was shown to be significant in minimizing damage propagation at the 5% confidence level. Filling the honeycomb core bays with foam performed two important functions. It first decreased the initial damage size of a 4.1 J impact from to 3.53 cm to 2.06 cm minimizing the amount of microcracking and delamination at the point of ingression. The foam also filled the empty cells of the honeycomb and prevented water from filling those cells. Through both of these mechanisms, the foam minimized the propagation of damage normally observed in the standard glass fiber core.

Slotting and draining the core was not shown not to be a significant factor in gross damage propagation at the 18 dB level, as shown in Table VIII. This behavior may be explained by the residence time of water in the core. When water or other fluids enter the slotted core, the time required for the liquid pass through all of the slots and drain out of the core was relatively long. It is possible to imagine a rainy day or deicing scenario where the core bays becomes partially filled with water prior to take-off. If the plane takes-off and the panels have not fully drained, then the water contained in the core will freeze, expand and damage some of the core. From this scenario, it is possible to imagine that slotting the core will worsen the problems of water ingression in the core, but from the DOE analysis, slotting and draining the core neither helped nor hindered the propagation of damage at the 18 dB level. Similar results to those shown in Table VIII were seen in the 18 dB percent damage growth analysis.

3.3.3. 12 dB gross damage growth

In Table VIII, the factorial analysis of the damage propagation level at 12 dB is presented. At the 12 dB level,

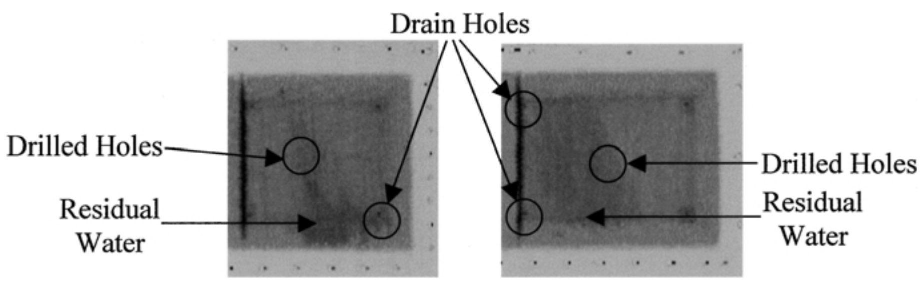

Figure 7 TTU scan of two slotted core bays showing residual water absorbed by the core from water passing through the drilled holes in the surface to the drain holes in bottom of the panel.

TABLE VIII Statistical analysis of gross damage growth for DOE #3 using through transmittance ultrasound inspections with a threshold of 12 dB and 18 dB

Source of variance	12 dB	18 dB
Location		
Airplane	XX	X
Impact	XX	XX
Foam filled	X	X
Slot and drain	X	

XX–Significant at 1% confidence level.
X–Significant at 5% confidence level.

the presence of slots and drains in the honeycomb core become a significant factor in minimizing water ingression. Slotting the honeycomb core helped prevent the long-term retention of water and fluid in the core bays that aided in preventing widespread core damage and microcracking. However the slotting of the core did little to mitigate the gross microcracking and delamination of the facesheet detected at the 18 dB level. With the 12 dB factorial model 76.3% of the variance in the data could be explained.

4. Conclusions

In this work, the mechanisms of water ingression and migration through honeycomb core were explored using an in-sevice Design of Experiment. The effects of impact damage and speed-tape repair on water absorption and damage propagation through the core were investigated for four different honeycomb cores. When glass fiber and Nomex based sandwich panels were impacted, extensive damage was seen throughout the facesheet and core. This damage allowed water to accumulate in the core and migrate through a freeze-thaw mechanism. For the aluminum and Korex cores, the impact damage was localized around the point of impact. The localization of this impact allowed the core to dry during flight. From the altitude conditions and air flowing over the impact location, a negative pressure gradient was created inside the core. This pressure gradient provided a driving force for the removal of water around the point of impact. This effect was not seen in the Nomex or glass fiber cores due to the extent of damage. In addition, speed-tape repairs were found to be an effective repair only when water was found to migrate through the core. However, some small damage was observed to propagate through the panels despite the presence of speed-tape. Filling the honeycomb core with foam was shown to be an effect method for minimizing the damaging effects of water ingression. Slotting and draining the core also offered some relief from water accumulation in the core, but foamed core was shown to be more effective. Overall, it can be shown from these investigations that damage and water alone are not sufficient for the propagation of water through honeycomb core. Other factors such as core type and damage size need to be considered in evaluating the durability of honeycomb composite sandwich structures.

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