Smart Bondline Monitoring of an Efficient Industrial Thermoplastic Aircraft Window Frame

D G Bekas[1a], D. Saenz-Castillo [2b], Z Sharif Khodaei [1,c] F. J. Chamorro Alonso[2d] and M.H. Aliabadi[1,e]

[1]Structural Integrity and Health Monitoring group, Department of Aeronautics, Imperial College London, South Kensington Campus, Exhibition Road, SW7 2AZ London, UK

[2] FIDAMC, Foundation for the Research, Development and Application of Composite Materials. Avda.Rita Levi Montalcini 29, Tecnogetafe, 28906 Getafe, Madrid, Spain

[a] d.bekas@imperial.ac.uk , [b]diego.saenz@fidamc.es, [c]z.sharif-khodaei@imperial.ac.uk, [d]francisco.chamorro@fidamc.es, [e]m.h.aliabadi@imperial.ac.uk

Keywords: composite, window frame, Structural Health monitoring, printed tracks, additive manufacturing, thermoplastic.

Abstract

In this work, a smart thermoplastic window frame for a regional aircraft has been designed and manufactured. The aim of the work was to design a smart sensing system for monitoring of a bonded thermoplastic aircraft window frame in operation. The conductive tracks were designed and inkjet-printed onto the window frame and their disruption was used as an indication of a damage event created within the bondline. Based on the electrical resistance measurements, the method was able to detect a damage that was created in the bondline due to an impact event. To verify the proposed methodology, ultrasonic C-scan inspection was also performed.

Introduction

Due to their low structural weight and fabrication cost, along with their improved damage tolerance and design flexibility, adhesive joints are increasingly being employed in several industries such as the aeronautics, aerospace, automotive, etc.[1]. However, the absence of a reliable, simple and non-invasive method for monitoring their structural integrity, without adding extra weight, limits their application. The current acceptable practice is riveting of composite joints, whether metal/composite or composite/composite attachments. Rivet holes will introduce stress concentration zones in the composite and other disadvantages such as discontinuity in the fibres. Therefore, to fully utilize weight savings and high stiffness to strength ratio of composite structure bonded joints are desirable. Thus, it is of high importance to develop a non-destructive methodology that will provide accurate and reliable information regarding the structural integrity of the bondline in real time. One such application is for window frame installation. The traditional design of aircraft window frame is metallic. With novelties in composite fuselage design and manufacturing, it is timely to investigate the design and manufacturing of composite window frame. Due to the complex geometry of the window frame, the traditional methods of hand layup with thermoset prepreg is not appropriate. A novel design will be the application of thermoplastic composite with hot forming press. This will result in fast, repeatable and reliable manufacturing of a window frame which will results in significant weight savings compared to metallic window frame, in particular if it could be bonded. The challenge will be how to monitor the bond-line to ensure the quality and integrity of the bonding during service.

There are several Structural Health Monitoring (SHM) methodologies that are being employed for the detection of adhesive failure in composite joints. These include methods that employ Lamb waves [2–6], Electromechanical impedance measurements [7], optical fibers [8] and electrical-based measurements [9,10]. In all cases the integrity of the bondline is monitored through a sensor or a network of sensors which adds weight to the structure and/or affects its mechanical performance. In addition, the analysis of the obtained results is complex and time consuming while

the use of equipment such as the acquisition system, further contributes to increased weight and costs.
A possible solution to these issues can be provided by additive manufacturing (AM). AM enables the fabrication of thin tracks with complex geometries in a variety of substrates and has been employed for the development of sensors for the SHM of composite structures. However, the performance and reliability of the printed sensors are highly affected by the operational condition of the structure such as temperature and pressure [11].
In this work, the development of a simple, accurate and base-line free method for detecting adhesive failure in complex bonded thermoplastic window frame is reported. For this purpose, conductive tracks were fabricated onto a window frame structure of an aircraft via inkjet printing and used as sensors for monitoring the integrity of the bondline. The design and manufacturing of the novel thermoplastic window frame is also reported. The ability of the proposed methodology to detect adhesive failure was investigated by subjecting the window frame structure to low-velocity impact test. To validate the proposed methodology, the results from the electrical resistance measurement were compared with those of ultrasonic inspection.

Experimental setup

Manufacturing of the window frame

The manufacturing of the thermoplastic window frame performed via consolidation using inductive hot pressing. The selected stacking sequence resulted in a symmetric laminate was $[+45/-45/+45/-45/0/0]_S$ obtained after FEM simulation applying a typical aircraft fuselage load scenario . The thermoplastic laminates were cut-up and hand laid-up using CF/PEEK fabric 5H-S with industrial code TPWF PEEK-HTA40 manufactured by Toho-Tenax and supplied by Porcher Industries. The thermoplastic pre-preg had an fibre areal weight of 475 g/m^2 with a ply nominal thickness of 0.310 mm (consolidated).
The thermoplastic plies were manually cut, and the composite patterns are obtained. Afterwards, the laminate was lined up applying welding points in each new ply. To avoid possible manufacturing defects, such as resin dry areas, the positioning of the welding points was shifted between plies.
The tooling that was used for the manufacturing of the frame consisted of a male and female part is shown in Figure 1.

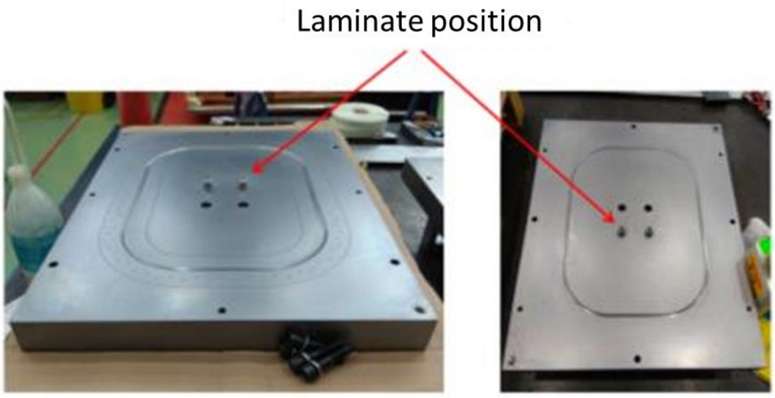

Figure 1 Female (left) and male (right) tooling for window frame consolidation

To allow an easy component demolding, two plies of polyimide (Kapton) and a release agent (FREKOTE) were placed along with in both the male and female tooling parts. The consolidation cycle, as suggested by the supplier, involved heating of the structure at a temperature between 380-420^{0}C with a rate of 5-15^{0}C/min. To ensure a uniform temperature distribution, the internal temperature of the final composite part was monitored using a thermocouple. The consolidation time was 20mins while the applied pressure was 8-15bars.
At the end of the consolidation process, the part was demolded and trimmed to the desired dimensions and inspected for any defects created during manufacturing.

The frame was inspected for defects created during manufacturing according to aerospace standards. Ultrasonic C-scan inspection of the frame performed using a Automated TRITON 8000 TT+ equipment supplied by Tecnitest. The applied technique was double-through transmission using a reflector plate, with a single probe working in a scanning frequency of 5 MHz. Figure 2 depicts the amplitude C-scan (grey scale) of the window frame after trimming where no indications above 6 dB, therefore no defects in the frame can be observed. It can be concluded that the manufacturing of the thermoplastic window frame has been successful with high quality and repeatable final part.

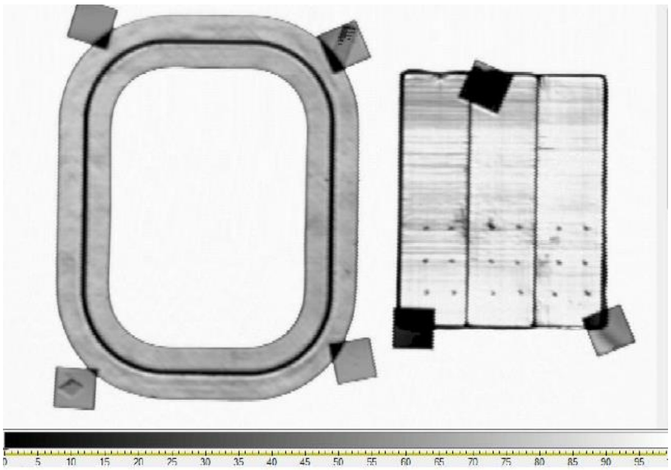

Figure 2 Amplitude C-scan images of thermoplastic Window Frame (after trimming)

Manufacturing of the composite panel

The thermoplastic window frame is to be fitted into a thermoset panel representative of a composite fuselage. For the thermoset composite panel, 16 plies of unidirectional Hexply 914-TS-5-134 prepreg were employed. The stacking sequence was $[0/45/\ -45/90]_{2s}$ and the composite final dimensions were $600x500mm^2$. At the end of the manufacturing process the central part of thermoset panel was removed using a water jet cutter in order to place the thermoplastic frame.

Design and manufacturing of the smart sensors

The tracks have been designed to monitor the bondline at both edges of the bonded surface. It is likely that the damage starts from either side of the bonded surface. The geometry of the sensors have also been designed to divide the monitored region into 4 different quadrants each with a different terminal. This results in not only detecting damage, but also localizing which quadrant the damage is present. Prior to the printing process the surface of the thermoplastic window frame was thoroughly cleaned using isopropanol. To electrically isolate the silver tracks from the conductive carbon fibers, thin lines of a dielectric polymeric ink (DM-INI-7003) were inkjet-printed onto the surface of the window frame. The printing of the polymeric ink was performed using a piezoelectric inkjet printer. The piezo voltage was selected at 20 V and the jetting frequency was set at 5kHz. The substrate temperature was selected at 30 °C and the drop spacing was 35μm. The width of the printed tracks was set at 1 mm. The polymeric ink was cured using a UV-LED system for 10 mins. At the end of the curing process, a silver nanoparticle suspension was employed for the development of the conductive silver-based tracks onto the cured polymeric lines using the same inkjet printer. The concentration of the nanoparticles within the ink was approximately 30-35 wt. %, and their diameter was under 50nm. The viscosity varied from 10 to 18mPa·s and the surface tension was between 35 and 40 $mN \cdot m^{-1}$. The width of the printed tracks was 0.5mm. To ensure an enhanced electrical conductivity, 3 layers of silver-based ink were printed on top of each other. Sintering of the ink took place in a laboratory oven for 1 hour and the selected temperature was 150^0C. The resulting window frame with the inkjet-printed tracks is depicted in Figure 3. In order detect any debonding occurred at the edges of the bondline (either from the inside or the outside) two conductive tracks were printed.

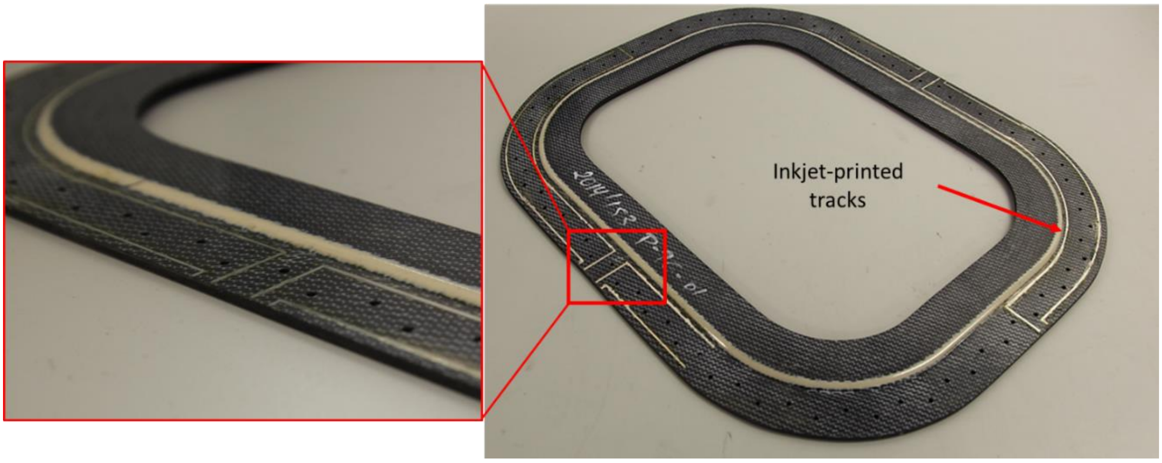

Figure 3 Inkjet printed tracks onto the window frame

<u>Bonding of the window frame</u>

For the bonding of the window frame onto the thermoset composite panel, a layer of a 914 epoxy was used as adhesive. The bonding process took place at a heating table for 1.5h at 170^{0}C and the applied pressure was 1 bar. At the end of the bonding process, four durable surface-mounted connectors with an operating temperature range of −40 °C to +85 °C were also used. The final window frame structure is depicted in Figure 4.

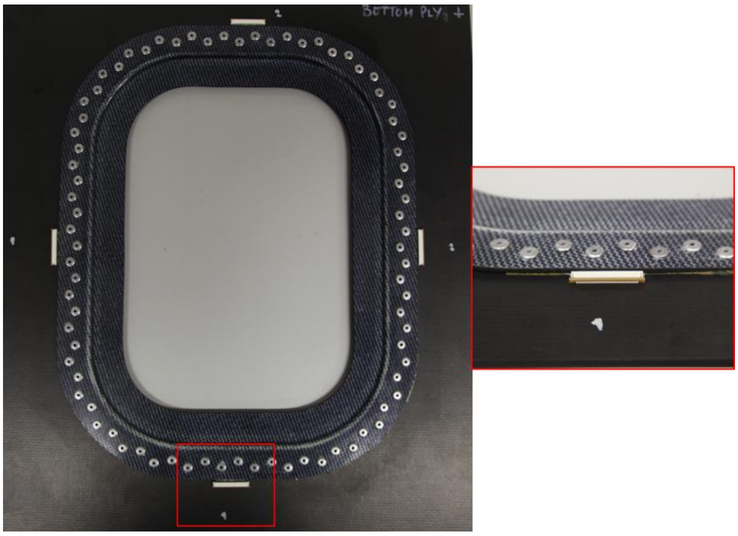

Figure 4 Window frame structure with printed conductive tracks at the bondline

The electrical resistance of the printed tracks was measured using the 2-probe method and found to be 4Ω, indicating that the bonding process did not disrupted the printed tracks. The disruption of the conductive tracks will be an indication of a damage created at the bondline at the location of the track. It should be noted that the development of the printed tracks has a negligible effect on the mechanical performance of the structure as it was shown in a previous study [9].

<u>Low velocity impact testing - electrical resistance measurements-ultrasonic inspection</u>

An Instron CEAST 9350 drop tower was used to impact the window frame structure and create a debonding between the frame and the panel. The impact location that was selected was the upper corner of the window frame. For the impact testing a hemispherical impactor with a radius of 20mm and a mass of 2.41 kg was used. The impact testing took place at ambient conditions with temperature and relative humidity of 23 ^{0}C and 50-60%, respectively. The selected impact energy was set at 20J, simulating the event of tool drop that can occur during transportation or assembly.

To evaluate the integrity of the bondline, electrical resistance measurements were conducted after the impact event using a 72 Pro IDM71 Digital Multimeter by RS. The proposed methodology for the bondline health monitoring has been reported in [9] and is based on a simple but effective assumption: upon damage within the bondline, the conductive printed tracks will be disrupted resulting in a "lost" connection between the terminals of the multimeter.

To evaluate the extent of damage within the bondline and validate our hypothesis, ultrasound inspection was employed. C-Scan inspection was performed at the damage location area using a portable ultrasound camera system, DolphiCam supplied by DolphiTech. For the C-scan the inspection depth was at 5.50mm (structure's thickness) and the excitation frequency was 3.8MHz. To improve the analysis of the obtained images, a total number of eight was selected as a signal average. The studied quantity was time of flight, which, was displayed in a 2D graph at the DolphiCam software.

Results and Discussion

Electrical resistance measurements-ultrasonic inspection

Figure 5 depicts the window frame structure before and after the impact event along with the results from the electrical resistance measurements and the C-scan inspection. The impact location is indicated with a white square while a schematic representation of the conductive printed tracks was added in order to better understand which conductive circuit was affected by the impact event. Based on the results obtained from the electrical resistance measurements, after impact, the conductive track which was located on the inside top-right corner of the window frame was interrupted and the connections between the two terminals of the multimeter were lost (indicated with red colour). This was a clear indication of a defect created at the bondline, since the detection of damage using this method it is not affected by any degradation within the frame or the panel. In addition, the connection between the remaining three circuits remained intact and their resistance remained unchanged. The results from the electrical resistance measurements were verified via C-scan inspection. As can be seen in Figure 5, the C-scan image obtained from the impacted specimen, indicated a damage which was created at the edge of the bondline. The damage area was calculated at 144mm^2 and resulted in the interruption of the conductive printed track that was located in this area.

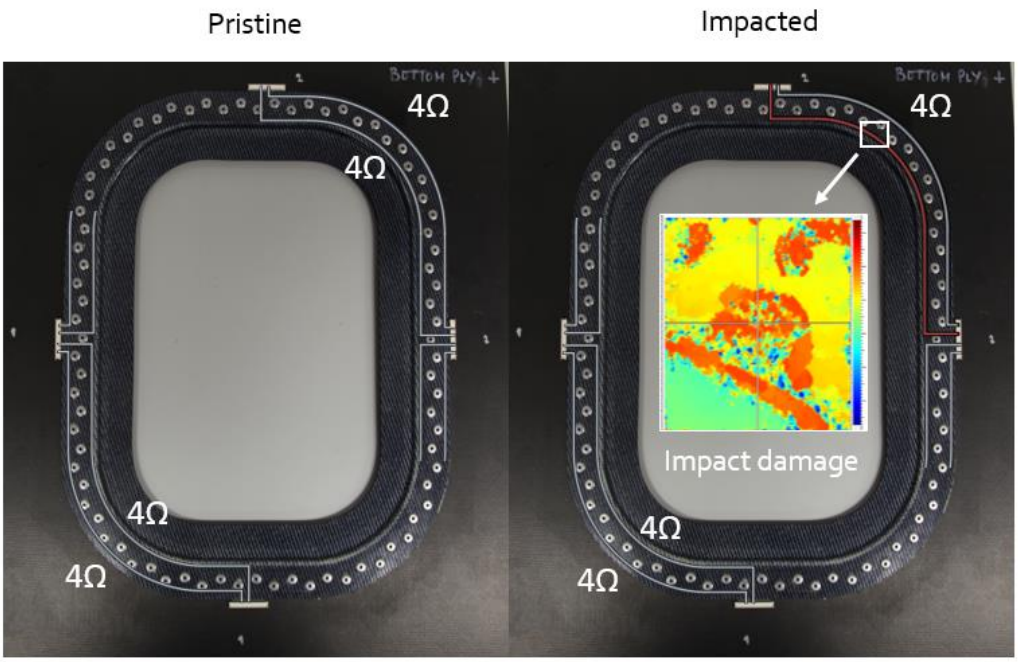

Figure 5 Window frame structure before and after the impact event

Conclusions

A reliable and effective methodology for the bondline health monitoring of a innovative thermoplastic window frame structure is presented. The manufacturing of the window frame is detailed which shows high quality of final part with good potential of industrialization. The proposed methodology for monitoring of bonded frame inside a fuselage skin involves the inkjet printing of ultra-thin conductive tracks that act as sensors. Upon damage the disruptions in the conductive circuits were used as indication of a damage event that is located in the bondline. The proposed methodology is a base-line free method while the design of the printed tracks can be modified according to the dimensions of the bondline and/or the permissible size of the defect.

Acknowledgment: The research leading to these results has gratefully received funding from the European JTI-CleanSky2 program under the Grant Agreement n◦ 314768 (SHERLOC). This project is coordinated by Imperial College London and lead by Leonardo S.p.A, as Topic Manager.

Reference

[1] Banea MD, Da Silva LFM. Adhesively bonded joints in composite materials: An overview. Proc Inst Mech Eng Part L J Mater Des Appl 2009;223:1–18. doi:10.1243/14644207JMDA219.

[2] Lambinet F, Sharif Khodaei Z. Smart Patch Repair with Low Profile PVDF Sensors. Key Eng Mater 2017;754:359–62. doi:10.4028/www.scientific.net/kem.754.359.

[3] Fu H, Sharif Khodaei Z, Aliabadi MHF. An Event-Triggered Energy-Efficient Wireless Structural Health Monitoring System for Impact Detection in Composite Airframes. IEEE Internet Things J 2019;6:1183–92. doi:10.1109/JIOT.2018.2867722.

[4] Sharif-Khodaei Z, Aliabadi MH. Assessment of delay-and-sum algorithms for damage detection in aluminium and composite plates. Smart Mater Struct 2014;23. doi:10.1088/0964-1726/23/7/075007.

[5] Bekas D, Sharif-Khodaei Z, Aliabadi MH. An Innovative Diagnostic Film for Structural Health Monitoring of Metallic and Composite Structures. Sensors 2018;18:2084. doi:10.3390/s18072084.

[6] Fu H, Bekas D, Khodaei ZS, Aliabadi MH. Structural Health Monitoring for condition based maintenance of composite structures. Int. Symp. Struct. Heal. Monit. Nondestruct. Test., 2018.

[7] Sharif-Khodaei Z, Ghajari M, Aliabadi MH. Impact Damage Detection in Composite Plates using a Self-diagnostic Electro-Mechanical Impedance-based Structural Health Monitoring System. J Multiscale Model 2016;06:1550013. doi:10.1142/s1756973715500134.

[8] Lambinet F, Sharif Khodaei Z. Damage Detection in Composite Skin Stiffener with Hybrid PZT-FO SHM System. Key Eng Mater 2017;754:367–70. doi:10.4028/www.scientific.net/kem.754.367.

[9] Bekas DG, Sharif Khodaei Z, Aliabadi MH. Structural Health Monitoring of Scarfed Repaired Composite Panels Using Inject-Printed Patterns. Key Eng Mater 2018;774. doi:10.4028/www.scientific.net/KEM.774.235.

[10] Bekas DG, Sharif-Khodaei Z, Baltzis D, Aliabadi MHF, Paipetis AS. Quality assessment and damage detection in nanomodified adhesively-bonded composite joints using inkjet-printed interdigital sensors. Compos Struct 2019;211:557–63. doi:10.1016/j.compstruct.2019.01.008.

[11] Augustin T, Karsten J, Kötter B, Fiedler B. Health monitoring of scarfed CFRP joints under cyclic loading via electrical resistance measurements using carbon nanotube modified adhesive films. Compos Part A Appl Sci Manuf 2018;105:150–5. doi:10.1016/j.compositesa.2017.11.015.