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Non-Destructive Evaluation—A Pivotal Technology for Qualification of Composite Aircraft Structures

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ABSTRACT

Tremendous advances in composite materials and a deeper understanding of their behavior have been responsible for the increased use of composites in the development of advanced, new generation civil and military aircraft. Composites play an important role in any aircraft development programme and are strong contenders to their metal counterparts due to their significant contributions towards improving strength, stiffness, fatigue properties & weight reduction. As materials, structural design & processing have evolved, strong emphasis is placed on effective & reliable damage detection, durability and damage tolerance. As a consequence, Non-destructive Evaluation (NDE) has also undergone significant advances towards meeting the growing demands of quality assurance. Advanced Composites Division (ACD) of National Aerospace Laboratories (NAL), has been involved in the development of composite structures for both civil and military aircraft for over a decade and a half. Innovative composite processing methods like co-curing/co-bonding have been successfully employed to realize airworthy structures. The role of NDE in the development of these structures has been critical and not limited to damage detection alone. On several occasions, NDE has provided valuable inputs towards improving design and process parameters. In-spite of the complexity of the structures, stringent quality requirements and tight delivery schedules, NDE has been successful in certifying these composite structures for airworthiness. This paper discusses the implementation of key NDE techniques like ultrasonics, radiography, acoustic emission and thermography for reliable flaw detection, characterization and quality assurance of composite aircraft structures.

Keywords: *Composites, Quality Assurance, Non-destructive Evaluation, Ultrasonics, Infrared Thermography, Acoustic Emission, Radiography.*

1. INTRODUCTION

The application of polymeric composites for aircraft has been an evolutionary process. With the growing confidence on composites, applications have risen from simple tertiary and secondary structures to primary load bearing and control structures. The use of composites results in performance enhancements made possible by weight savings, higher strength and stiffness, durability and damage tolerance. Developments in material forms, advances in design and innovations in processing and fabrication have also been significant drivers for the widespread use of composites for aircraft. These developments demand efficient and reliable quality assurance in manufacturing and inspection in

maintenance. In general, NDE deals with the development of measurement technologies and analysis techniques for quantitative characterization of quality of materials and structures by non-invasive means. NDE employs many Sonic, Thermal, Electromagnetic and Optical methods to ensure quality, structural integrity and safety by probing into the micro-structure of materials to characterize sub-surface flaws. For the aircraft industry, requirement of reliable NDE is not limited during manufacturing and certification alone, but extends through the entire service life of an aircraft. Monitoring for damage, either material, structural or functional is a major maintenance activity encountered during the service life of an aircraft. Hence, the need for reliable inspection during service life of aircraft is equally important. With the fast changing pace of technology, there is a constant need for steady change and extensions in NDE requirements to overcome the challenges. Advanced Composites Division of NAL has had considerable exposure to composites technology through the development of composite aircraft structures & has been successful in realizing airworthy structures for both civil and military aircraft. Innovative concepts of composite fabrication like co-curing/co-bonding have been employed in the development of these aircraft structures. Inspection of such complex structures is a challenging task and stringent quality measures are followed to ensure compliance to standards for airworthiness certification. To accomplish this, State-of-the-Art NDE facilities like Ultrasonics, Acoustic Emission, Infrared Thermography and Radiography are being successfully employed.

2. ULTRASONICS

Sound whose frequencies lie beyond human audible range (>20 KHz) is Ultrasound. The frequency range normally used in NDE is between 100 kHz to 50 MHz. Although Ultrasound behaves in a similar manner to audible sound, it has a much shorter wavelength enabling it to be reflected off from small interfaces such as defects in a material. It is this property that makes ultrasound useful for the NDE of materials. Pulse-echo and Through Transmission are the two most common and widely used techniques of Ultrasonic inspection. The Ultrasonic A-scan method of inspection employs Pulse-echo technique while Ultrasonic C-scan is an automated mode of inspection employing either Through Transmission or Pulse-echo technique or both simultaneously. In the aerospace industry, Ultrasonics has been the most common and reliable NDE method employed for flaw detection and characterization.

Advanced Composites Division is a pioneer in using Automated, Multi-axis Ultrasonic Squirter type C-scan and A-scan facilities for the NDE of composite aircraft structures. They have been important NDE tools in quality assurance and airworthiness certification of aircraft components and have played a vital role in ensuring quality not only during manufacturing, but also during service life of aircraft.[1] The efficiency, reliability and repeatability of Ultrasonics in maintaining high levels of quality remain undisputed by other NDE techniques. These facilities have played a critical role in Non-destructive testing & Evaluation, Material characterization and quality assurance in all aircraft programs of national importance.

Fig. 1: LCA CFRP Wing Skin Mounted in the Multi-axis Ultrasonic C-scan Machine

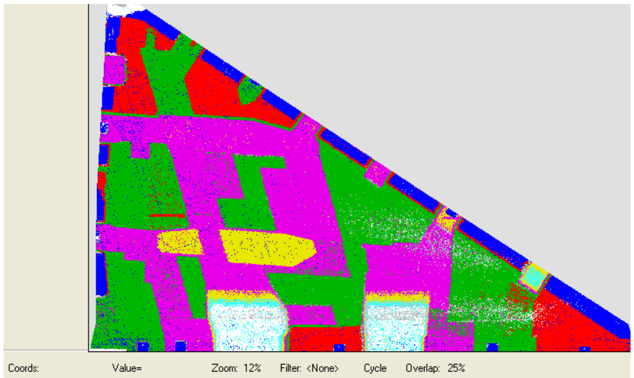

Fig. 2: Ultrasonic C-scan Time-of-Flight Plot of LCA CFRP Wing Skin Showing Thickness Variations

3. ACOUSTIC EMISSION

Acoustic Emission (AE) is the phenomenon of generation of transient elastic waves as a result of rapid release of strain energy caused due to permanent microscopic deformation in a material. AE is a passive NDE technique and uses stress as a stimulus for flaws in a material to generate AE. Of all the NDE techniques, AE is the only one that can be reliably used for monitoring initiation and growth of defects and their location in a structure.

3.1 AE for Damage Monitoring During Fatigue Testing

The Outboard Flap of SARAS aircraft was subjected to fatigue cycling with the objective of studying the effect of debonds on its structural integrity. The naturally occurring debonds at the skin/stiffener interface were a concern as the strength at the adhesive bonded interface was a suspect. Hence, AE was used to provide an early warning of damage initiation; reliable qualitative assessment of structural integrity and an insight into the AE characteristics of debond growth in bonded composite joints. Identifying genuine AE sources from damage mechanisms in a structure subjected to fatigue cycling is quite a challenge due to interference from background noise sources. The AE activity recorded throughout the fatigue cycling showed no signs of any damage such as Delamination growth, Matrix Cracking, Fibre Fracture, etc., but was distinctly different in its signal characteristics when compared to other known composite defect mechanisms. On further analysis of this activity and comparison with data acquired from control specimens with simulated debonds, a good agreement could be reached on the nature of the activity. The observed activity was attributed to debond initiation and growth.[2] Further, AE could clearly differentiate and characterize the activity into "Micro-scale" and "Macro-scale" growth. Micro-scale growths refer to minuscule bond deterioration or debond growth that goes undetected by Ultrasonic scanning. Macro-scale growth refers to large and sometimes, an abrupt growth of a debond that is detected by Ultrasonic scanning. Frequency analysis of Micro-scale growth revealed frequencies restricted to the lower end of the spectrum and was consistent at 150 kHz and 250 kHz. For Macro-scale growth, frequencies were spread throughout the spectrum from 100–1100 kHz. Hence, AE could distinctly characterize the AE activity as debond growth and further classify it into Micro and Macro-scale growth.

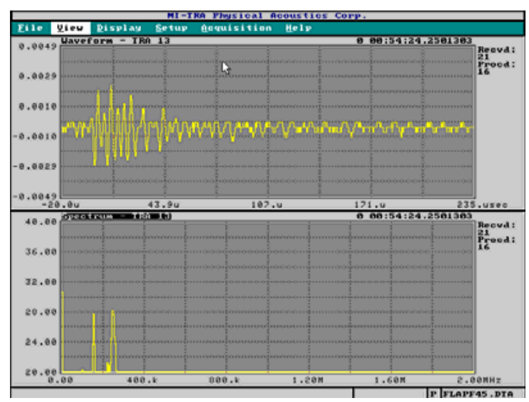

Fig. 3*:* Acoustic Emissions for Micro-Scale Growth of Debond

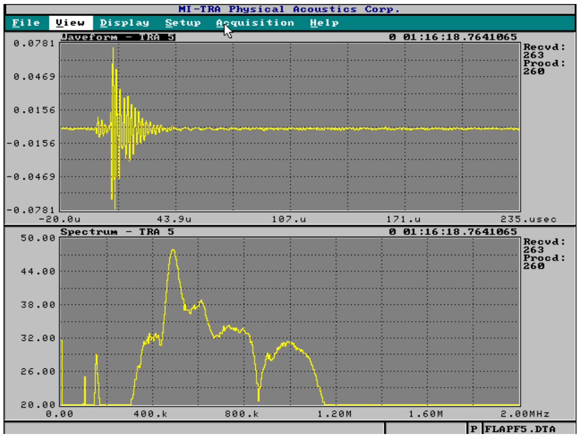

Fig. 4*:* Acoustic Emissions for Macro-Scale Growth of Debond

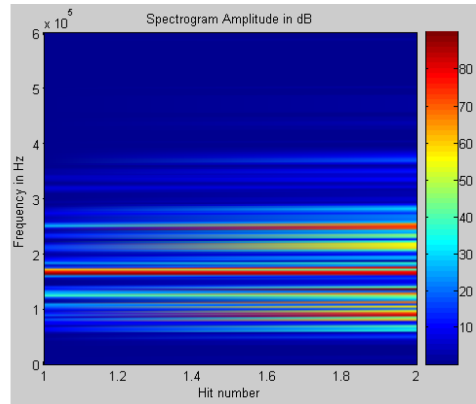

Fig. 5*:* Acoustic Emission Signature Generated for Bearing Failure in CFRP

3.2 AE for the Detection of Bearing Failure in Composites

For SARAS aircraft, development of a Composite Wing through the "Vacuum Enhanced Resin Infusion Technology—VERITy" fabrication method was initiated. As a first step in the programme, development of a prototype Wing Box was initiated. The Wing Box has two crucial joints, the Skin Splice & Spar Splice Joint. These joints are crucial as they are mechanically fastened features in the Wing. To ascertain the strength of the Wing structure at the splice locations and to validate the design of the splice joints, Static testing of these joints was essential which a mandatory requirement for airworthiness certification is also. It was quite a concern to designers to obtain a realistic assessment of structural integrity of these joints during the structural qualification tests. In such a situation AE was the immediate choice for detection and early warning of any premature damage initiation and growth in the new material system (HS Carbon UD fabric G0827/RTM 120 Epoxy Resin system) adopted to fabricate the Wing. The recorded AE activity during the course of static testing was successfully characterized in terms of typical AE parameters as bearing failure at fastener holes.[3] Further to this, AE was also successful in characterizing Bearing failure into its principal failure modes (Matrix Cracking, Fibre-Matrix Debonding & Fibre Fracture) in the frequency domain.

4. THERMOGRAPHY

For the Non-destructive Evaluation of aircraft components, thermography is operated in an active mode. Active Thermography is a surface thermal radiation measurement technique used to detect the variation of temperature patterns after thermal excitation. The technique is capable of revealing defects by searching for anomalous temperature patterns in the time-dependent surface temperature response following the thermal excitation. Active Thermography has many approaches like Pulse Thermography, Pulse Phase Thermography, Lock-in Thermography, Step-heating Thermography and Vibro Thermography. Compared to conventional NDE techniques, Active Thermography offers a number of attractive advantages. It is non-contact and inspection can be performed with only single side access to the part. It allows testing of a relatively large area in a single shot and can accommodate curved surfaces. As it is portable and suited for field applications, it has been effective for in-service inspection of aircraft at repair depots.

At Advanced Composites Division, Pulse Thermography is being successfully employed for the inspection of monolithic and sandwich aircraft composite components and structures. Pulse Thermography heats the sample surface with a uniform short pulse of light, and an Infrared camera interfaced to a computer monitors the surface temperature response to the thermal impulse as a function of time. It is possible to carryout both qualitative and quantitative analysis as the technique is well supported by advanced Infrared cameras, improvements in signal processing and computer technology. The technique has been successful in detecting various defect conditions in composites such as Foreign Material Inclusions, Delaminations, Debonds, Voids, Impact Damage, etc. It is also a valuable tool for damage assessment and validation of aircraft repair.

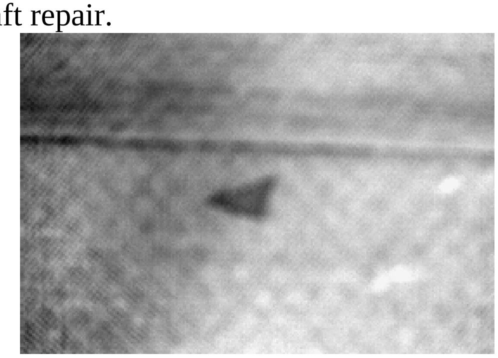

Fig. 6: Thermo Graphic Image of a Foreign Material Inclusion in a CFRP Main Rotor Spar of Helicopter

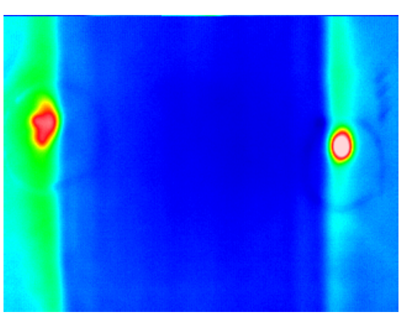

Fig. 7: Thermo Graphic Image of Air Bubble in a CFRP Aircraft Panel

5. RADIOGRAPHY

Real-time X-ray Fluoroscopy facility at Advanced Composites Division has been extensively used for the inspection of aircraft honeycomb sandwich components. Unlike in conventional Radiography, this system employs an Image intensifier that converts incident X-ray radiation into digital images in real-time. This eliminates the need of films to process and develop X-ray images resulting in reduced inspection time and real-time viewing of X-ray images. The system has been capable of detecting various defect conditions in honeycomb sandwich components such as Lack of Core Filler Material, Core Crushing, Absence of Core, Opening of Cell Nodes, Foreign Material Inclusions, etc.

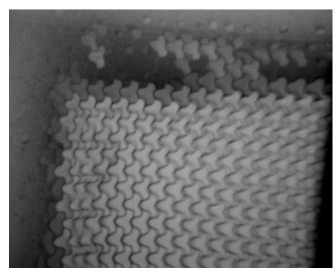

Fig. 8: X-ray Image Showing the Absence of Core Filler at the Edges of the Core in a CFRP Honeycomb Panel

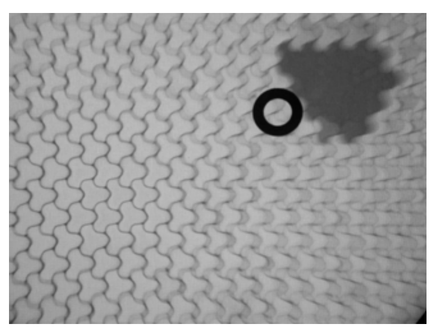

Fig. 9: X-ray Image Showing the Absence of Core in a CFRP Honeycomb Panel

6. CONCLUSIONS

The NDE techniques mentioned above are the most suited and relevant for the inspection and characterization of composites. These NDE techniques are complimentary to each other, are essential for detecting various defect conditions in composites and play a very crucial role in the quality assurance of composite airframes. A successful NDE programme requires an integrated knowledge of the NDE techniques, material properties, failure mechanisms, load environments, etc. A mere knowledge of NDE methods is simply insufficient for effective NDE. It is imperative that properly trained and skilled personnel are responsible for decision making, considering the impact NDE has on aircraft quality assurance.

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