CONF-961219--2

SAND96-2365C
SAND--96-2365C

Nondestructive Inspection of Bonded Composite Doublers for Aircraft

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ABSTRACT

One of the major thrusts established under the FAA's National Aging Aircraft Research Program is to foster new technologies associated with civil aircraft maintenance. Recent DOD and other government developments in the use of bonded composite doublers on metal structures has supported the need for research and validation of such doubler applications on U.S. certificated airplanes. Composite doubler technology is rapidly maturing and shows promise of cost savings on aging aircraft. While there have been numerous studies and military aircraft installations of composite doublers, the technology has not been certified for use on commercial aircraft. Before the use of composite doublers can be accepted by the civil aviation industry, it is imperative that methods be developed which can quickly and reliably assess the integrity of the doubler. In this study, a specific composite application was chosen on an L-1011 aircraft in order to focus the tasks on application and operation issues. Primary among inspection requirements for these doublers is the identification of disbonds, between the composite laminate and aluminum parent material, and delaminations in the composite laminate. Surveillance of cracks or corrosion in the parent aluminum material beneath the doubler is also a concern. No single nondestructive inspection (NDI) method can inspect for every flaw type, therefore it is important to be aware of available NDI techniques and to properly address their capabilities and limitations. This paper reports on a series of NDI tests which have been conducted on laboratory test structures and on a fuselage section cut from a retired L-1011 aircraft. Specific challenges, unique to bonded composite doubler applications, will be highlighted. In order to quickly integrate this technology into existing aircraft maintenance depots, the use of conventional NDI, ultrasonics, X-ray, and eddy current, is stressed. The application of these NDI techniques to composite doublers and the results from test specimens, which were loaded to provide a changing flaw profile, are presented in this paper. The development of appropriate inspection calibration standards will also be discussed.

Keywords: composites, disbonds, delaminations, nondestructive inspection, aircraft repairs

BONDED COMPOSITE DOUBLERS ON AIRCRAFT STRUCTURES

Background - The Airworthiness Assurance NDI Validation Center (AANC) was established by the FAA William J. Hughes Technical Center at Sandia National Laboratories to support nondestructive inspection (NDI) technology development and assessment. The number of commercial airframes exceeding twenty years of service continues to grow. In addition, Service Life Extension Programs are becoming more prevalent and test and evaluation programs are presently being conducted to extend the "economic" service life of commercial airframes to thirty years. The use of bonded composites may offer the airframe manufacturers and airline maintenance facilities a cost effective technique to extend the lives of their aircraft. Limited demonstrations and operational testing have confirmed that under proper conditions, composite doublers can provide a long lasting and effective repair or structural reinforcement [1-4]. Composite repairs (or structural reinforcement doublers) may offer numerous advantages over metallic patches including corrosion resistance, light weight, high strength, elimination of rivets, and time savings in installation. Because of the rapidly increasing use of composites on commercial airplanes, coupled with the potential for economic savings associated with their use in aircraft structures, it appears that the demand for validated composite inspection techniques will increase.

Technology Evaluation Through Specific Application - The AANC is conducting a technology evaluation project with Delta Air Lines, Lockheed Martin, Textron, and the FAA. By focusing on a specific commercial aircraft application - reinforcement of the L-1011 door frame - and encompassing all "cradle-to-grave" tasks such as design, analysis, installation, and inspection, this program is designed to objectively assess the capabilities of composite doublers. Through

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the use of laboratory test structures and a fuselage section cut from a retired L-1011 aircraft, this study is evaluating composite doubler design, fabrication, installation, structural integrity, and non-destructive inspection. The final phase of this project includes the installation of a composite doubler on an L-1011 in Delta's fleet. This will represent the first (non-decal) bonded composite doubler on a U.S. commercial aircraft.

Need for Validated Inspection Techniques - The use of composite doublers in commercial aviation has been suppressed by uncertainties surrounding their application, subsequent inspection and long-term endurance. Before the use of composite doublers can be accepted by the civil aviation industry, it is imperative that methods be developed which can quickly and easily assess the integrity of the doubler. This paper describes the utilization of conventional and enhanced NDI techniques to the unique application of bonded composite doublers.

Primary among inspection requirements for these doublers is the identification of disbonds, between the composite laminate and aluminum parent material, and delaminations between the composite laminate plies. The absence of disbonds and delaminations indicates that the doubler is able to perform its duty [2, 5, 6]. However, due to the newness of the technology and lack of performance data under actual flight conditions, the current approach is to continue inspections of the parent material. Thus, inspections for cracks in the aluminum beneath the composite doubler is also necessary. The development of NDI techniques for composite doubler installations and the results from test specimens which were loaded to provide a changing flaw profile are presented here. Conventional and advanced NDI techniques are being applied by the AANC to aid NDI development and to perform formal validation of new composite inspection technologies. The application of existing inspection techniques for adhesive bond integrity will be reviewed in light of recent advances in adhesive inspection devices.

Typical Composite Doubler Installation and NDI - Figure 1 shows a typical bonded composite doubler repair over a cracked parent aluminum structure. The number of plies and fiber orientation is determined by the nature of the reinforcement required (i.e. stress field and configuration of original structure). Surface preparation is the most critical aspect of the doubler installation. This consists of paint removal, solvent clean, scotch-brite abrasion and chemical treatment to assure proper adhesion. Since the doubler must be installed in the field, vacuum bag pressure and thermal heat blankets, commonly used on in-situ honeycomb repairs, are used to cure the composite laminate and adhesive layer [7].

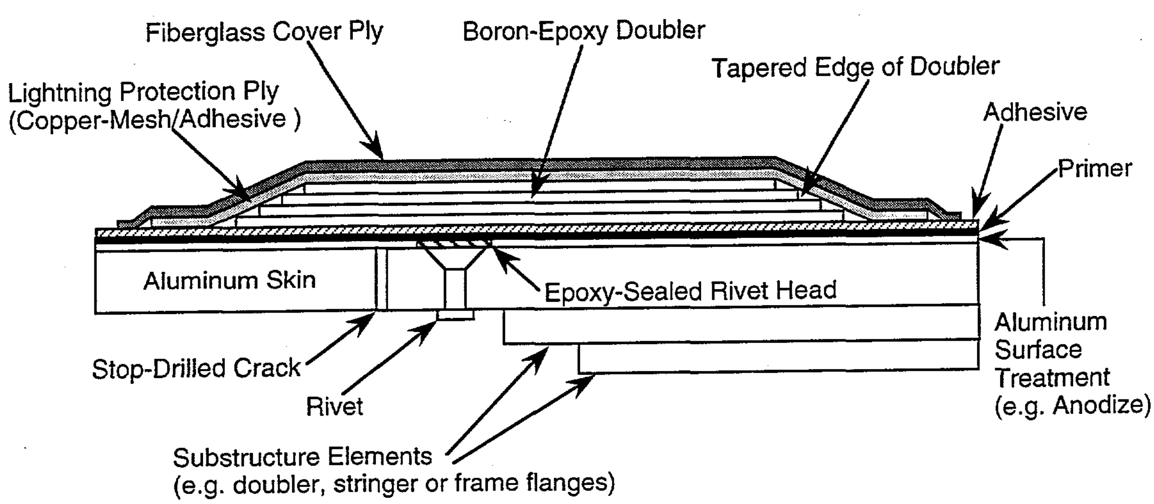


Figure 1: Example of Bonded Composite Doubler Installation on an Aluminum Skin

The taper at the edge of the doubler is used to achieve a uniform stress field in the area of maximum load transition. In some applications, such as the subject L-1011 design, lightning protection is provided by a copper wire mesh which is imbedded in an adhesive film and applied as a top ply over the doubler (see Fig. 1). The lightning protection ply has a larger footprint than the composite laminate in order to provide a conductive link between the copper mesh and the surrounding aluminum skin. Finally, a top ply of fiberglass is installed to supply mechanical and environmental protection for the installation.

Nondestructive inspection is effected by the geometry and material properties of the doubler installation. The thickness of the doubler creates lift-off effects during eddy current inspections and signal attenuation during ultrasonic examinations. The laminate taper, which may be compounded by changing thicknesses within the parent structure, creates a need for careful, and possibly multiple, equipment set-ups and inspections. The lightning protection ply creates an undesirable side effect by disrupting some NDI signals. The discussion which follows will describe how certain NDI techniques are hindered when copper mesh lightning protection is included in the lay-up. In addition, the merits of using 2-dimensional C-Scan imaging to overcome these NDI obstacles will be presented.

ULTRASONICS - INSPECTIONS FOR DISBONDS AND DELAMINATIONS

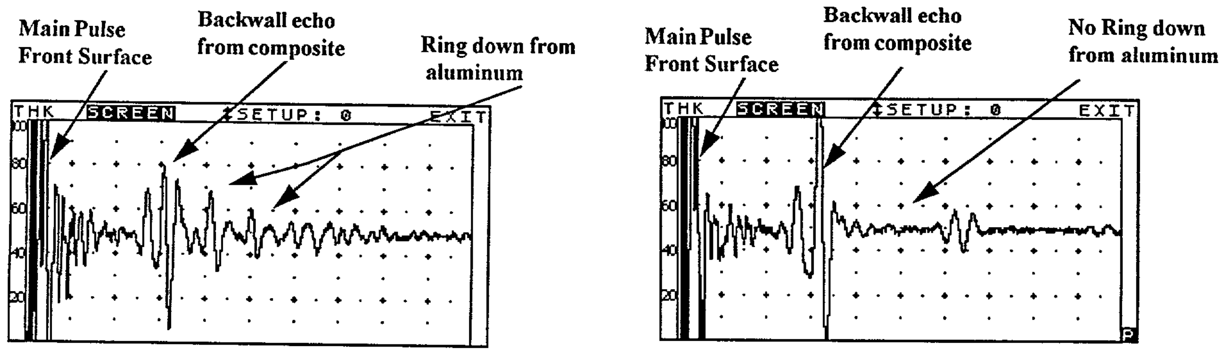
Periodic inspections of the composite doubler for disbonds and delaminations (from fabrication, fatigue, or impact damage) is essential to assuring the successful operation of the doubler over time. Ultrasonic methods have shown the greatest potential for assessing the structural integrity of the doubler laminate. The AANC has used ultrasonics to detect both interply delaminations as well as disbonds at the laminate-to-aluminum interface. Following is a discussion on four ultrasonic inspection techniques - Pulse-Echo (A-Scan and C-Scan), Thru-Transmission, and Resonance testing - which highlights their capabilities and limitations with regards to bonded composite doublers .

1. Pulse-Echo Ultrasonics

A-Scan Mode

In conventional Pulse-Echo Ultrasonics (PE UT), pulses of high frequency sound waves are introduced into a structure being inspected. A-Scan signals represent the response of the stress waves, in amplitude and time, as they travel through the material. As the waves interact with defects or flaw interfaces within the solid and portions of the pulse's energy are reflected back to the transducer, the flaws are detected, amplified and displayed on a CRT screen. The interaction of the ultrasonic waves with defects and the resulting time vs. amplitude signal produced on the CRT depends on the wave mode, its frequency and the material properties of the structure. Figure 2 shows two A-Scan signals produced by a contact (gel couplant) inspection of a composite doubler bonded to an aluminum plate. The specimen contained intentional flaws which were engineered at discrete locations. A Quantum ultrasonic device was used to apply the PE inspection. Like most pulse-echo systems, a single transducer on the Quantum device acts alternately as both the sending and receiving transducer. Key portions of the signal in Figure 2 are identified to highlight how the A-Scan can be used to detect disbonds and delaminations. The primary items of note are: 1) the unique signature of the amplitude vs. time waveform which allows the user to ascertain the transmission of the ultrasonic pulse through various layers of the test article which indicates a good bond, and 2) the absence of signature waveforms indicating a disbond.

C-Scan Mode: Use of UT Scanning Technology - In the case of disbond and delamination inspections, it is sometimes difficult to clearly identify flaws using the A-Scan signals alone. Small porosity pockets commonly found in composites, coupled with signal fluctuations caused by material nonuniformities can create signal interpretation difficulties. Improvements in disbond detection can be achieved by taking the A-Scan signals and transforming them into a single C-Scan image of the part being inspected. C-Scan technology uses information from single point A-Scan waveforms to produce an area mapping of the inspection surface. These 2-D images are produced by digitizing point-by-point signal variations of an interrogating sensor while it is scanned over a surface. C-Scan area views provide the inspector with easier-to-use and more reliable data with which to recognize flaw patterns. A variety of PC-based manual and automated scanning devices can provide position information with digitized ultrasonic signals [8]. Specific emphasis can be placed on the UT signal - and highlighted in the color-mapped C-Scan - based on user specified amplitude gates, time-of-flight values and signal waveforms.



No Disbond Present

Disbond Present

Figure 2: A-Scan Waveform from Bonded and Disbonded Portions of a Test Specimen

Mechanics of C-Scan System - The basic C-Scan system used by the AANC to inspect bonded composite doublers is shown schematically in Figure 3. The scanning unit containing the transducer is moved over the surface of the test piece using a search pattern of closely spaced parallel lines. A mechanical linkage connects the scanning unit to X-axis and Y-axis position indicators which feed position data to the computer. The echo signal is recorded, versus its X-Y position on the test piece, and a color coded image is produced from the relative chracteristics of the sum total of signals received.

The entire ultrasonic C-Scan device is attached to the test article using suctions cups connected to a vacuum pump. The unit is tethered to a remotely located computer for control and data acquisition. A gimbal is used to hold the transducer arm perpendicular to the surface and pneumatic pressure is used to maintain a constant force against the part being scanned. The transducer arm of the scanning unit consists of a UT emitter/receiver transducer in a contained water column. The confined column of water is used to provide uniform coupling for the ultrasonic waves moving into and out of the test article. Both manual and automated (motorized) scanners were utilized in this study.

Gating - User specified depth gates allows only those echo signals that are received within a limited range of delay times following the initial pulse or interface echo to be admitted to the receiver-amplifier circuit. One of the key aspects of a successful composite doubler inspection is the positioning of a series of gates corresponding to specific thicknesses of the Boron-Epoxy doubler. The gates are set so that front reflections from the doubler and back reflections from the aluminum substrate are excluded from the display. Thus, echoes from within the testpiece and at the aluminum-to-composite bond interface are emphasized.

Figure 4 shows a C-Scan image (based on amplitude) of a bonded composite doubler installation. The engineered flaws are clearly visible when viewed side-by-side with adjacent, unflawed material. Time-of-flight information can also be displayed in image format to determine the depth of the damage. Field-ready inspection systems for ultrasonic data acquisition, signal processing, and image display have emerged in recent years and have the potential to become widely used for aircraft applications [9, 10]. Reference [11] provides additional information on how the C-Scan technique can aid in the interpretation of composite inspections.

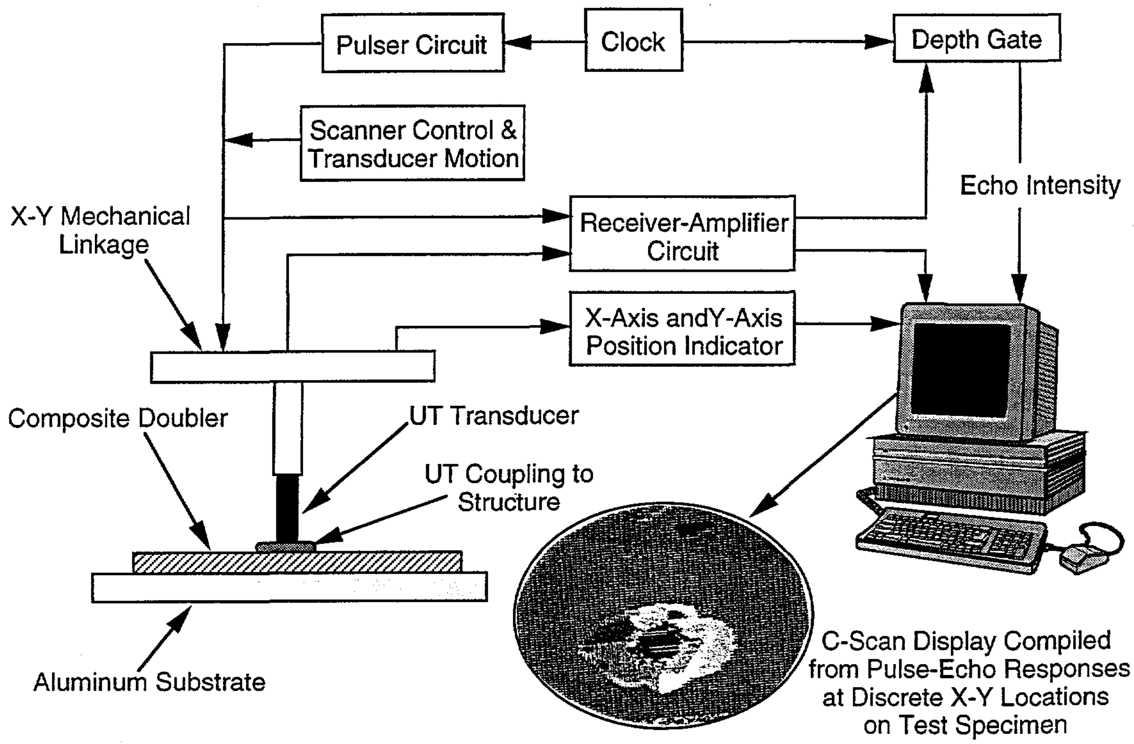


Figure 3: Schematic of C-Scan Setup for Pulse-Echo Ultrasonic Inspection

In addition to improving the inspector's ability to interpret the inspection results, automated systems afford many advantages over conventional point-by-point, hand-held inspection methods:

1. The area mapping capability significantly reduces the time required to perform on-site examinations.

2. Inspections are more repeatable and effective than with point-by-point hand-held methods. They provide programmable test procedures, thus assuring that proper setup, calibration, and scanning requirements are met.

3. Extensive training or skill above present practices is not required because data collection is similar to conventional methods. Some basic computer skills may be required.

4. Human factors are improved. An inspector observes proof of an effective inspection from the quantitative content of the C-Scan image. Viewing the trends and spatial relationships of patterns as they are created on the viewing screen keeps the inspector's interest high and reduces inspector fatigue.

System Set-up and Use of Calibration Blocks - Special precautions must be taken in order to produce a good inspection in areas where the doubler thickness changes (taper regions). Thickness variations require the user to track the front surface of the doubler and set the depth gates as appropriate. By employing a series of gates in one scan, it is possible to collect data over a wide range of depths. However, in the case of extremely thick doublers - the L-1011 doubler is 72 plies thick - it may be necessary to use several different scans each containing their own unique set of gates. For example, on the L-1011 doubler, separate scans may be obtained for 30 ply, 50 ply, and 72 ply thicknesses. This process improves the resolution in the area of interest and avoids the acquisition of potentially misleading signals.

A representative calibration block containing artificial flaws of known size and depth should be used to ensure a repeatable inspection. Amplifier gains and signal gates should be established during scans of the calibration block. Depending on the physical size of the composite doubler and the degree of thickness variation, the inspector can then determine the number of scans necessary to completely cover the doubler. Material properties and the doubler thickness will determine the frequency of the transducer needed to resolve the composite front and back surfaces and whether the doubler is scanned with a contact or water column configuration.

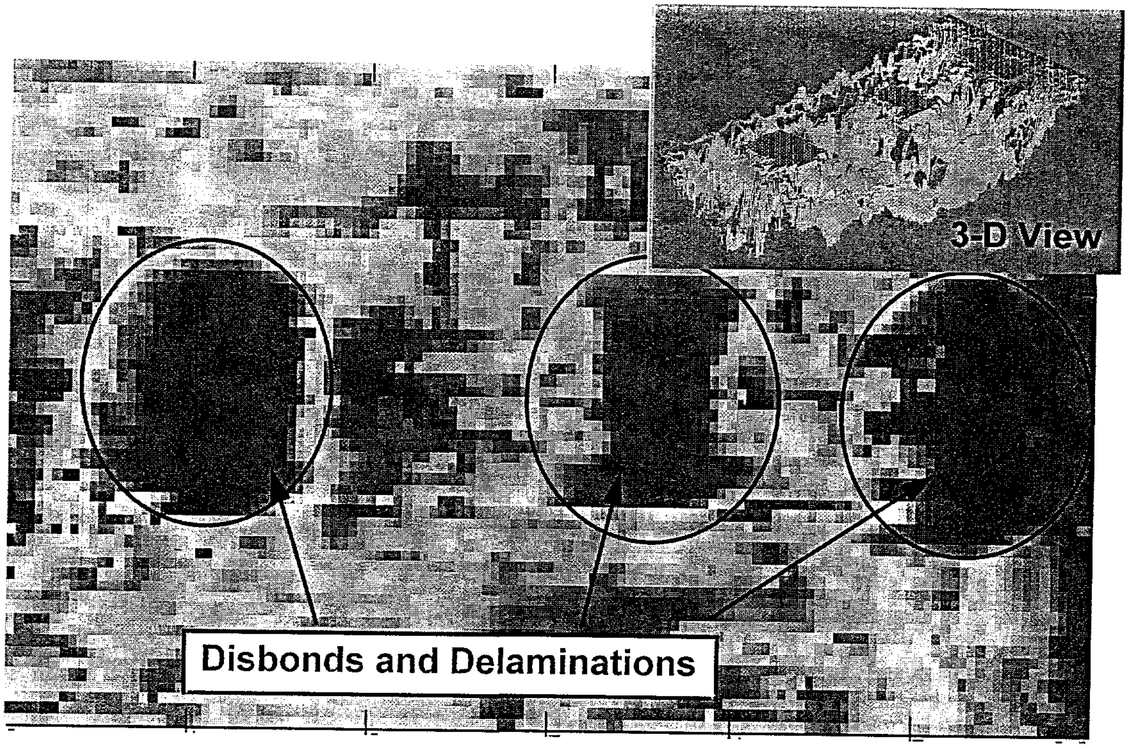


Figure 4: Pulse-Echo Ultrasonic C-Scan of Bonded Composite Doubler Generated by a Manual Ultrasonic Scanning Device

2. Thru-Transmission Ultrasonics (TTU)

Damage Tolerance Testing

A series of fatigue coupons were designed to evaluate the damage tolerance performance of bonded composite doublers. The general issues addressed were: 1) doubler design - strength, durability 2) doubler installation and 3) NDI techniques used to qualify and accept installation. Each specimen consisted of an aluminum "parent" plate, representing the original aircraft skin, with a bonded composite doubler. The doubler was bonded over a flaw in the parent aluminum. The flaws included fatigue cracks (unabated and stop-drilled), aluminum cut-out regions, and disbond combinations. The most severe flaw scenario was an unabated fatigue crack which had a co-located disbond (i.e. no adhesion between doubler and parent aluminum plate) as well as two, large, 25.4 mm diameter disbonds in the critical load transfer region of the doubler perimeter. Figure 5 shows one of the test specimens with engineered flaws. Tension-tension fatigue and residual strength tests were conducted on the laboratory specimens. The test results are presented in Ref. [5]. Thru-Transmission Ultrasonics and Resonance inspection techniques were interjected throughout the fatigue test series in order to evaluate the reliability and limitations of these techniques.

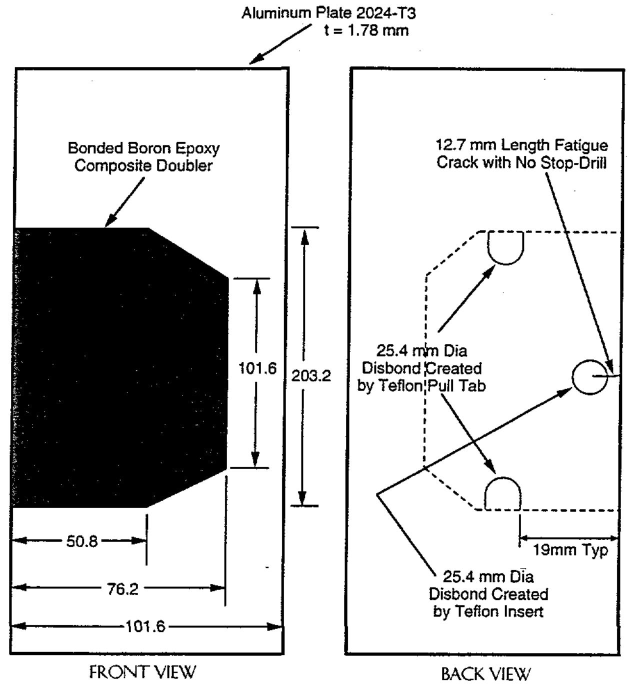


Figure 5: Composite Fatigue Test Specimen with Engineered Flaws

<u>TTU Composite Doubler Inspection</u>

Prior to conducting the fatigue tests, a thru-transmission ultrasonic immersion inspection was performed on each of the coupon specimens. This ultrasonic baseline used two 5 Mhz immersion transducers to produce a C-Scan image. The test set-up is similar to the one depicted in Figure 3 except that two transducers are used in a sender-receiver pair and water is used (immersion or water jet stream) to couple the ultrasound pulse to the part. The TTU C-Scan records the amplitude of the signal transmitted through the test article as a function of its position. A detailed map of the composite doubler and flaws are shown as a plan view. Both flaw size and position within the plan view are recorded, however, flaw depth is not recorded. Electronic gates, similar to those described above, are used during data collection, however, the primary information in TTU is the signal amplitude. Reference [12] provides related information on how ultrasonic TTU data can be presented and interpreted. Figure 6 shows the disbonds detected in the Figure 5 test specimen. Note the clear indications of the three 25.4 mm diameter disbonds.

Since this technique requires the sending-receiving transducer pair to be located in front and back of the structure being inspected, accessibility and deployment issues severely restrict the field application of TTU techniques. The motion of the transducer pair must be linked and water coupling to the structure, through complete immersion of the part or through focused water jets, is necessary. This further complicates field deployment and effects the size of the structure that can be inspected. However, TTU is a very accurate NDI technique and was used primarily to establish a basis of comparison for other, more fieldable techniques.

4. Resonance Test Inspection Method

After conducting the baseline inspections, a high frequency ultrasonic resonant bond inspection was conducted. The instrument used in this study was a Staveley Sonic Bondmaster. The type of inspection used to characterize the boron/epoxy doubler was the resonance test method. In this method, a narrow banded 12.7 mm diameter transducer is driven at its resonant frequency of 330 kHz. The transducer is placed on a composite doubler standard with the use of couplant. This produces a standing ultrasonic wave in the material. Reference [13] describes how a transducer verifies the amplitude signal (sound pressure) at a point of reception. The Boron-Epoxy has a damping affect on the transducer. The primary results are increased bandwidth, shift in resonant frequency, and change in signal amplitude. The transducer is nulled on an unflawed composite area. The transducer is then moved to a flawed location. Changes in the acoustic impedance of the transducer as it moves over the flawed area is detected. The flaw changes the standing wave pattern in the material. These changes are subsequently detected as differences in the acoustic impedance at the surface of the material caused from the loss of material damping. Changes in the acoustic impedance create changes in the electrical impedance which are monitored by the instrument and displayed in the form of an amplitude/phase plot. In the general sense, the phase information is related to the depth of the disbond in the doubler or a thickness variation caused by the slope in the taper. Signal amplitude is predominately effected by the relative size of severity of the disbonds in the composite doubler. Sensitivity, the angle of the dot movement (rotation), and operating frequency can be adjusted on the instrument to maximize the differences between a flawed and unflawed inspection site.

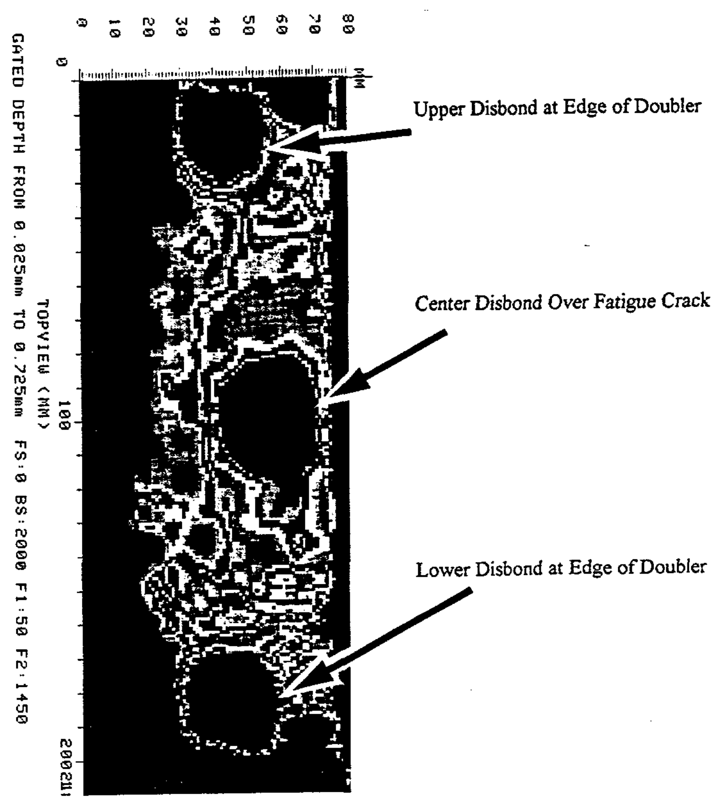


Figure 6: Thru-Transmission Ultrasonic Results (View from Aluminum Plate Side)

Figure 7 shows some sample Bondmaster results and how the screen plots are used to detect the presence of a flaw. Following is a brief summary of the high frequency bondtester inspection results on a composite doubler specimen which was subjected to 144,000 fatigue cycles.

1) The initial inspection on this sample verified the presence of engineered disbonds. Low signal flaw indications were found in the initial inspection (0 fatigue cycles) of the boron/epoxy doubler. Since these signals did not exceed the alarm threshold they were classified as flaw indications rather than actual defects. Each indication was documented for later data comparisons. After 72,000 fatigue cycles, the low signal was still present but it could not be classified as a disbond or delamination. It was possible to accurately establish the presence and shape of the engineered disbond flaws over the duration of the fatigue tests using the ultrasonic inspection technique.

2) When the specimens were fatigued, the engineered cracks propagated across the width of the specimen. The excessive displacement in the aluminum as the crack opened generated a cohesive failure in the adhesive layer. However, the cohesive failure was confined to a 6.35 mm width strip which was centered over the length of the crack. Growth in the cohesive

failure area matched the propagation of the aluminum crack. Using the ultrasonic inspection technique, it was possible to monitor the changing boundaries of this disbond "strip" as the crack grew in length.

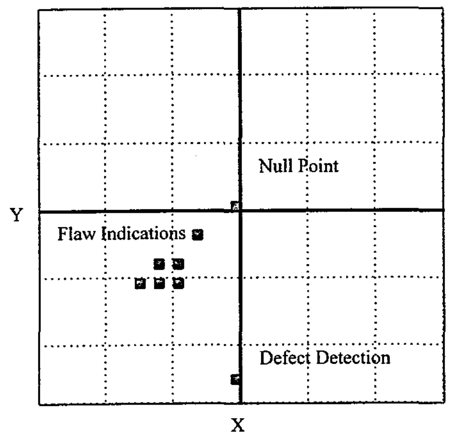


Figure 7: Representative Bondtester Output for Disbond and Delamination Inspections on 13 Ply Fatigue Coupons

The use of well characterized calibration standards is essential to properly set-up the resonant UT device [14]. However, even with the use of calibration standards it was found that material nonuniformities, inherent in composites and more prevalent in thicker laminates, can create difficulties in the application of the UT Resonance testing. The results from this study showed that it was difficult to obtain consistent signals from doublers in excess of approximately 20.3 mm (0.080") thick. In regions above this thickness, significant changes in the signal amplitude and phase occurred even during inspections of unflawed portions of the doubler. The signals varied from "unflawed" to "flawed" indications, thus, it was not possible to clearly interpret the readings.

EDDY CURRENT AND X-RAY - INSPECTIONS FOR CRACKS IN PARENT MATERIAL

1. Eddy Current Technique

Eddy Current (EC) inspection uses the principles of electromagnetic induction to identify or differentiate structural conditions in conductive metals [12]. It was applied to numerous bonded composite doubler installations in order to assess the ability of EC to detect cracks in aluminum skin beneath a composite laminate. The presence of a crack is indicated by changes in the flow of eddy currents in the skin. EC signals are physically monitored using impedance-plane plots which show the reactive and resistive components of a coil as functions of frequency, conductivity, or permeability.

Because eddy currents are created using an electromagnetic induction technique, the inspection method does not require direct electrical contact with the part being inspected. The composite doubler, between the EC transducer and the aluminum being inspected, does, however, create a lift-off effect which changes the EC signal. This lift-off effect can mask important aspects of flaw detection and must be counteracted by careful equipment set-up, use of suitable calibration standards, and experience in EC signal interpretation. Eddy currents are not uniformly distributed throughout the skin; rather, they are densest at the surface immediately beneath the coil (transducer) and become progressively less dense with increasing distance below the surface. Thus, the inspection sensitivity through composite doublers is decreased by the lift-off effects (equal to thickness of doubler) and associated need to inspect below the surface of the EC transducer. The depth of EC penetration can be increased by decreasing the inspection frequency. These lower frequency inspections, however, are accompanied by a loss in sensitivity. Therefore, EC inspection through composite doublers becomes a balance between signal resolution and the frequency required to inspect beneath a particular laminate.

Figure 8 shows a representative EC signal of a cracked structure located beneath a Boron-Epoxy laminate. Two variations are shown to demonstrate the ability of EC to detect both first (surface) and second (substructure) layer cracks in aircraft structure. Initial testing conducted by the AANC on specimens without the copper mesh lightning protection established the following limits of crack detectability through composite doublers: 1) a 0.060" long first layer (surface) crack can be detected in the aluminum through a 0.310" thick doubler, 2) a 0.15" length surface crack can be detected through a 0.5" thick laminate, and 3) a 0.15" long subsurface crack (0.040" th. surface plate) can be detected through a 0.310" thick doubler.

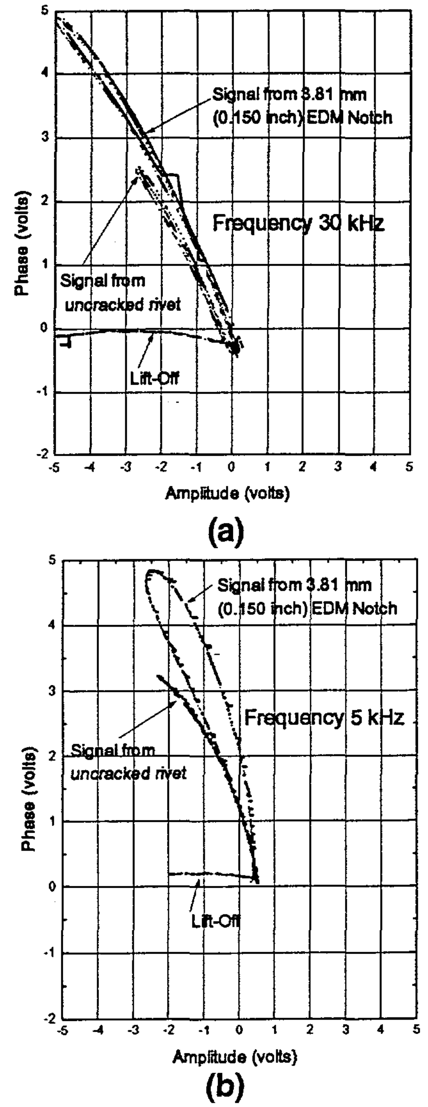


Figure 8: EC signal for a) 1st layer crack through 0.085" thick doubler and b) 2nd layer crack through 0.085" thick doubler and 0.040" thick skin

In the case of the L-1011 application, the addition of the copper mesh lightning protection created difficulties in carrying out the standard EC inspections for cracks using a pencil or sliding probe. Since the copper mesh is a conducting material, it disrupts the flow of eddy currents at the surface of the laminate (see location of lightning protection in Fig. 1). This, in turn, causes the balance point on the impedance plane display to vary with probe orientation. The use of ultra-low frequencies (500 Hz) to inspect the part helped the EC inspection to look "past" the copper mesh and into the area of interest, however, the signal resolution was significantly diminished and key location pointers such as fasteners were no longer evident. This study determined that the combined detrimental effect of probe lift-off (doubler thickness) and copper mesh lightning protection is not a problem until the doubler reaches approximately 15 plies thick (0.10"). Beyond this point, the signal-to-noise ratio is below acceptable levels. The unstable signal movement alone is greater than the expected signal variation due to the presence of a crack.

2. X-Ray Inspections

Radiography is a very effective inspection method to interrogate the interior of the parent material covered by the composite doubler. This technique provides the advantage of a permanent film record. However, it is more expensive then other inspection techniques and requires safety considerations due to the potential radiation hazard. This method utilizes a source of X-rays to detect cracks in the structure covered by the composite doubler. Variations in density over the composite are recorded as various degrees of exposure on the film and produce differential densities or X-ray absorption of penetrating radiation. To increase the contrast on the film, the X-ray inspection was performed at low kilovoltage (80 kV).

For the L-1011 application, the X-ray inspection, currently used by Delta to detect cracks around the door, will be used after the doubler is installed. The AANC performed tests to demonstrate the application of X-rays to detect cracks through composite doublers. Several fatigue crack specimens and an L-1011 fuselage section were inspected through the 72 ply composite doubler. The damage detection threshold for cracks under the doubler is 25.4 mm (1.0"). Test results showed the ability to detect cracks less than 25.4 mm in length. Fatigue cracks on the order of 9.5 mm (0.38") in length were found under 10.16 mm (0.40") thick (72 ply) Boron-Epoxy doublers. Comparisons with X-rays taken without composite doublers demonstrated that while the doubler may darken the X-ray image slightly it does not significantly impede the X-ray inspection. Power and exposure times were adjusted in order to maintain the specified film density (per L-1011 NDT Manual) of between 2 and 3. The initial set-up (80 kV, 12 mA 152.4 cm source-to-film-distance and 30 second exposure time) on medium speed film produced a film density of 0.98 The requirement specified in the NDT manual is a film density between 2 and 3 for the critical areas. Increasing the exposure time to 90 seconds produced a film density of 2.64. Image quality indicators, inserted into the field of view, verified the resolution and sensitivity of the radiographic technique.

CONCLUSIONS

Before the use of composite doublers can be accepted by the civil aviation industry, it is imperative that methods be developed which can quickly and reliably assess the integrity of the doubler. Primary among inspection requirements for these doublers is the identification of disbonds, between the composite laminate and aluminum parent material, and delaminations in the composite laminate. Surveillance of cracks in the parent aluminum material beneath the doubler is also a concern. This paper reports on a series of tests which were conducted to evaluate both conventional and advanced NDI techniques for bonded composite doublers.

Several ultrasonic methods were successfully applied to the problem of disbond and delamination detection. Thru-Transmission ultrasonics is a highly sensitive technique, however, deployment issues severely restrict its field application. The ultrasonic Resonance test method works well in mapping out flaw shapes and delineating the flaw edges. Inspection results depend upon effective acoustic impedance match between the aluminum and the composite doubler. In thinner laminates, resonance testing is able to repetitively detect disbond flaws as small as 6.35 mm (0.25") in diameter. Material nonuniformities inherent in composite laminates produce inconsistent signals when resonance ultrasonics is applied to laminates greater than 20.3 mm (0.080") thick. In this region, it is not possible to interpret the equipment's readings.

Pulse-Echo ultrasonics can be easily implemented on an aircraft using hand held inspection devices. Anomalies in A-Scan signals can be used to detect laminate flaws although signal fluctuations, caused by material nonuniformities, can create interpretation difficulties. The best compromise between field deployment and ease of signal interpretation is achieved through the use of Pulse-Echo C-Scan ultrasonics. Extensive testing has shown that the two-dimensional, color coded images produced by manual and automated scanners are able to reliably show flaws on the order of 6.35 mm (0.25") in diameter. Time savings, human factors issues, and repeatability are some of the main advantages associated with C-Scan ultrasonics. Key to implementing this NDI technique is the use of representative calibration standards which allow for accurate equipment settings (amplifier gains and signal gates) over the full range of laminate thickness.

Crack detection in the parent aluminum material can be accomplished using conventional eddy current and X-ray techniques. The success of the eddy current technique is primarily determined by two installation factors: 1) lift-off effects due to the thickness of the composite doubler, and 2) signal disruption from other conductive medium such as copper mesh lightning protection. X-ray inspections are as effective as before the doubler was installed. Boron-Epoxy material may darken the X-ray image slightly, however, power and exposure times can be adjusted to achieve the required film density and resolution.

In spite of significant successes in military applications, bonded composite doublers have not been certified for use on the U.S. commercial aircraft fleet. Most of the concerns surrounding composite doubler technology pertain to long-term survivability and the validation of appropriate inspection procedures. After final validation of the NDI techniques presented here is completed, disbond, delamination, and crack inspections will be used to closely survey the first composite doubler installation on a commercial aircraft.

ACKNOWLEDGMENTS

This project is sponsored by the William J. Hughes Technical Center under Sandia National Laboratories contract number DTFA-03-91-A-0018

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