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Development and Validation of Nondestructive Inspection Techniques for Composite Doubler Repairs on Commercial Aircraft

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Development and Validation of Nondestructive Inspection Techniques for Composite Doubler Repairs on Commercial Aircraft*

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Abstract

Composite doublers, or repair patches, provide an innovative repair technique which can enhance the way aircraft are maintained. Instead of riveting multiple steel or aluminum plates to facilitate an aircraft repair, it is possible to bond a single Boron-Epoxy composite doubler to the damaged structure. In order for the use of composite doublers to achieve widespread use in 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. A series of NDI tests were conducted on laboratory test structures and on full-scale aircraft fuselage sections. Specific challenges, unique to bonded composite doubler applications, were highlighted. An array of conventional and advanced NDI techniques were evaluated. Flaw detection sensitivity studies were conducted on applicable eddy current, ultrasonic, X-ray and thermography based devices. 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 report. It was found that a team of these techniques can identify flaws in composite doubler installations well before they reach critical size.

* This work was performed for the Federal Aviation Administration (FAA) Technical Center under US Department of Transportation Contract DTFA 03-95-X-90002. This document is currently under review by the FAA for parallel publication by the Department of Transportation.

Acknowledgments

Numerous people have contributed to the success of validating bonded composite doublers for commercial aircraft applications. In addition to the FAA Airworthiness Assurance Center (Sandia Labs), team members for the L-1011 door corner repair included Lockheed-Martin Aeronautical Systems (doubler design and analysis - Bob Bell, Surendra Shah, and Kevin Jones), Delta Air Lines (Engineering Repair Authorization document, doubler installation and NDI support - John Marshall, Malcolm Westberry, Chuck Minafo, and Raymond Worley), Textron Systems Div. (specimen fabrication and installation - Tom Shahood and Jeff Brown), the FAA Atlanta Aircraft Certification Office (review and approval - Charles Perry and Paul Sconyers), and the FAA William J. Hughes Technical Center (project oversight - Pete Versage, Chris Smith, and Dave Galella; FAA Chief Scientist NDI - Al Broz). Specific contributions to the NDI information presented here came from John Gieske (Sandia Labs - use of focused ultrasonic transducers), Bob Thomas, Skip Favro, and Xiaoyan Han (Wayne State University - use of Thermal Wave Imaging system), David Hsu and Dan Barnard (Iowa State University - use of Dripless Bubbler ultrasonic system), and David Moore (Sandia Labs - application of radiography through composite doublers). Support for the use of the SAIC Ultra Image scanner system was provided by Bob Grills, Glenn Andrew, and Bart Drennan. Floyd Spencer of Sandia also helped in the NDI probability of detection studies. These contributions are gratefully acknowledged. This work was funded by the FAA William J. Hughes Technical Center under a U.S. Department of Transportation contract.

FOREWORD

As part of the Federal Aviation Administration's (FAA) National Aging Aircraft Research Program (NAARP), the FAA William J. Hughes Technical Center, established a major center at Sandia National Laboratories (SNL): the Airworthiness Assurance NDI Validation Center (AANC). The AANC conducts numerous projects related to the validation of improved aircraft maintenance practices. The Center also supports technology development initiatives. To facilitate these activities, the AANC has set up a hangar facility at the Albuquerque International Airport.

One of the primary goals of NAARP is to foster new technology associated with the repair of civil aircraft. A typical aircraft can experience over 2,000 fatigue cycles (cabin pressurizations) and even greater flight hours in a single year. The unavoidable by-product of this use is that flaws develop throughout the aircraft's skin and substructure elements. These flaws can take the form of cracks, corrosion, disbonds, dents, and gouges. Composite doublers, or repair patches, provide an innovative repair technique which can enhance the way aircraft are maintained. Instead of riveting multiple steel or aluminum plates to facilitate an aircraft repair, it is possible to bond a single Boron-Epoxy composite doubler to the damaged structure.

Economic barriers to the purchase of new aircraft have created an aging aircraft fleet and placed even greater demands on efficient and safe repair methods. The use of bonded composite doublers offers the airframe manufacturers and airline maintenance facilities a cost effective technique to safely extend the lives of their aircraft. However, before this advanced aircraft repair technique could be accepted for commercial aircraft use, uncertainties surrounding the application, subsequent inspection and long-term endurance of composite doublers had to be addressed.

This document is one in a series of reports covering the AANC's comprehensive evaluation of composite doublers for commercial aircraft use. The development and validation effort addressed the full array of engineering issues including design, material allowables, installation, damage tolerance, quality assurance, in-service surveillance (nondestructive inspection), and FAA/industry requirements. The full suite of reports, each containing a similar foreword section, are:

1. *Development and Validation of Nondestructive Inspection Techniques for Composite Doubler Repairs on Commercial Aircraft (SAND98-1014)*
2. *Damage Tolerance Assessment of Bonded Composite Doublers for Commercial Aircraft (SAND98-1016)*
3. *Full-Scale Structural and NDI Validation Tests on Bonded Composite Doublers for Commercial Aircraft Applications (SAND98-1015)*

Report #1: "Development and Validation of Nondestructive Inspection Techniques for Composite Doubler Repairs on Commercial Aircraft" - The purpose of this report is to document the NDI techniques and procedures which have been assessed to inspect bonded composite doubler installations on aircraft structures. The intent of the inspections are to detect: 1) disbonds, delaminations, and porosity in the composite laminate, and 2) cracks in the parent aluminum material. An array of conventional and advanced NDI techniques were evaluated. Flaw detection sensitivity studies were conducted on applicable eddy current, ultrasonic, X-ray and thermography based devices. The pulse-echo ultrasonic technique deployed in this program uses the traditional A-scan approach as its basis, however, significant improvements are realized through the adoption of C-scan imaging. An X-ray inspection was modified from its original specification in the L-1011 NDT Manual. A series of tests were performed in order to: 1) verify that composite doublers do not impede X-ray inspections, and 2) study X-ray optimization when inspecting through composite doublers. This study concluded that a team of NDI techniques can identify flaws in composite doubler installations well before they reach critical size. The development of appropriate inspection reference standards, critical to performing proper inspections, is also discussed.

Report #2: "Damage Tolerance Assessment of Bonded Composite Doublers for Commercial Aircraft" - This report focuses on a series of fatigue and strength tests which were conducted to study the damage tolerance and fatigue life enhancement associated with Boron-Epoxy composite doublers. Tension-tension fatigue and ultimate strength tests attempted to grow engineered flaws in coupons with composite doublers bonded to aluminum skin. An array of design parameters, including various flaw scenarios, the effects of surface impact, and other "off-design" conditions, were studied. The structural tests were used to: 1) assess the potential for interply delaminations and disbonds between the aluminum and the laminate, and 2) determine the load transfer and crack mitigation capabilities of composite doublers in the presence of severe defects. A series of specimens were subjected to ultimate tension tests in order to determine strength values and failure modes. Coupon test configurations, the loads applied, the test procedures, and all associated results are documented in this report.

Report #3: "Full-Scale Structural and NDI Validation Tests on Bonded Composite Doublers for Commercial Aircraft Applications" - This report describes a series of structural and nondestructive inspection (NDI) tests which were conducted to investigate the performance of Boron-Epoxy composite doublers. Full-scale tests were conducted on fuselage panels cut from retired aircraft. These full-scale tests studied stress reductions, crack mitigation, and load transfer capabilities of composite doublers using simulated flight conditions of cabin pressure and axial stress. Also, structures which modeled key aspects of aircraft structure repairs were subjected to extreme tension, shear and bending loads to examine the composite laminate's resistance to disbonds and delaminations especially in high peel stress regions. Nondestructive inspections were conducted throughout the test series in order to validate pertinent techniques on actual aircraft structure.

The test results were also used to verify design and analyses methodologies for composite doubler technology. The primary test article was a large fuselage section cut from a retired All Nippon Airways (ANA) L-1011 aircraft. The fuselage test article included a passenger door cut-out and contained all substructure frame, longeron, and stringer elements. Several other test configurations - consisting of composite doublers mounted on simulated aircraft panels - were examined in order to assess the response of composite doublers in worst-case shear and bending load scenarios. These two test configurations were loaded to failure in order to determine safety factors associated with current doubler design methodologies.

Background and Deliverables - The Federal Aviation Administration sponsored this project at the AANC to determine the viability of bonded composite doublers and to gain FAA approval for their use on commercial aircraft. A specific application was chosen - reinforcement of an L-1011 door frame - in order to provide the proof-of-concept driving force behind this test and analysis project. In addition to the AANC, other project team members included Lockheed-Martin, Delta Air Lines, and Textron Specialty Materials. Appropriate FAA oversight was provided through the Atlanta Aircraft Certification Office (ACO) and the FAA's William J. Hughes Technical Center. The project deliverables will assist the FAA in developing guidance which assures the continued airworthiness of composite doublers.

The data stemming from this study serves as a comprehensive evaluation of bonded composite doublers for general use. The associated documentation package provides guidance regarding the design, analysis, installation, damage tolerance, quality assurance, and nondestructive inspection of these doublers. Although an initial aircraft application was pursued in parallel to this investigation, the overall goal was to provide results that are pertinent to any use of Boron-Epoxy doublers for commercial aircraft reinforcement or repair. In order to streamline the use of composite doublers in other applications, the documentation package for this validation effort resides in the public domain. The FAA's Atlanta ACO maintains the documents under the FAA project number SP1798AT-Q. The documentation package includes:

Report	Report Number
1. Boron-Epoxy Material Allowables	LG95ER0193
2. Damage Tolerance Assessment	SNL96ER0189
3. Full-Scale Structural and NDI Testing	SNL96ER0006
4. Boron-Epoxy Doubler Installation Process Specification	TSM 2000,008-001
5. Design and Analysis of L-1011 Composite Doubler	LG95ER0157
6. L-1011 Composite Doubler Drawing (Upper Fwd. Corner, P-3 Passenger Door)	LCC-7622-378
7. Nondestructive Inspection Procedures	AANC-PEUT-Comp-5521/4-004

The first use of the above documentation package was to support the installation of an FAA-approved Boron-Epoxy composite repair on a Lockheed L-1011 aircraft. The repair has been installed on the upper forward corner of a P3 passenger door frame. The aircraft is currently operating in the Delta Air Lines fleet. Three post-installation inspections, spanning one year of aircraft operation, have shown the doubler to be free of flaws. A second important product of the results cited above is the Lockheed-Martin Service Bulletin 093-53-278 which allows the door corner composite doubler to be installed on all L-1011 aircraft. With the successful completion of the L-1011 door corner application, the FAA and AANC are now conducting a program with Boeing and Federal Express to develop, certify, and install a more generic set of composite doubler applications for a variety of common aircraft repairs.

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Development and Validation of Nondestructive Inspection Techniques for Composite Doubler Repairs on Commercial Aircraft

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1.0 Background

In 1991, the FAA's William J. Hughes Technical Center established The Airworthiness Assurance NDI Validation Center (AANC) at Sandia National Laboratories. Its primary mission is to support technology development, validation, and transfer to industry in order to enhance the airworthiness and improve the aircraft maintenance practices of the U.S. commercial aviation industry. The Center conducts projects in a myriad of engineering disciplines. The results are placed in the public domain so that the industry at-large can reap the benefits of FAA-funded R & D efforts. To support the Center's goals, the FAA/AANC has set up a hangar facility at the Albuquerque International Airport which contains a series of transport and commuter aircraft. The facility replicates a working maintenance environment by incorporating both the physical inspection difficulties as well as the environmental factors which influence maintenance reliability. Sandia's charter with the FAA includes a wide array of airworthiness assurance disciplines such as nondestructive inspection, structural mechanics, computer science, fire safety, and corrosion. However, the development and assessment of nondestructive inspection (NDI) technology is the primary focus of the AANC.

One of the primary goals of the Federal Aviation Administration's (FAA) National Aging Aircraft Research Program (NAARP) is to foster new technology associated with the repair of civil aircraft. A typical aircraft can experience over 2,000 fatigue cycles (cabin pressurizations) and even greater flight hours in a single year. The unavoidable by-product of this use is that flaws develop throughout the aircraft's skin and substructure elements. These flaws can take the form of cracks, corrosion, disbonds, dents, and gouges. Composite doublers, or repair patches, provide an innovative repair technique which can enhance the way aircraft are maintained. The high modulus of Boron-Epoxy composite material enables a doubler to pick up load efficiently and effectively when bonded to a metal structure. The load transfer occurs by shear through the adhesive. Figure 1 is a schematic of a typical composite doubler repair highlighting the basic design principles. The AANC team completed a comprehensive technology development, validation, and application program which established the performance of composite doublers as an improvement over metallic doublers.

As the commercial airline industry responds to calls for the ensured airworthiness of global airline fleets, inspection reliability is of growing importance. The development and application of new Nondestructive Inspection (NDI) techniques needs to keep pace with the growing understanding of aircraft structural aging phenomena. In this role as validator of NDI techniques, the AANC's main objective is to perform comprehensive, independent, and quantitative evaluations of new and enhanced inspection techniques. Some peripheral NDI development activities are pursued and formal NDI procedures are produced by these projects.

AANC and Inspection of Bonded Composite Doublers - The use of composite doublers in commercial aviation must address issues such as installation, subsequent inspection and long-term endurance. 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.

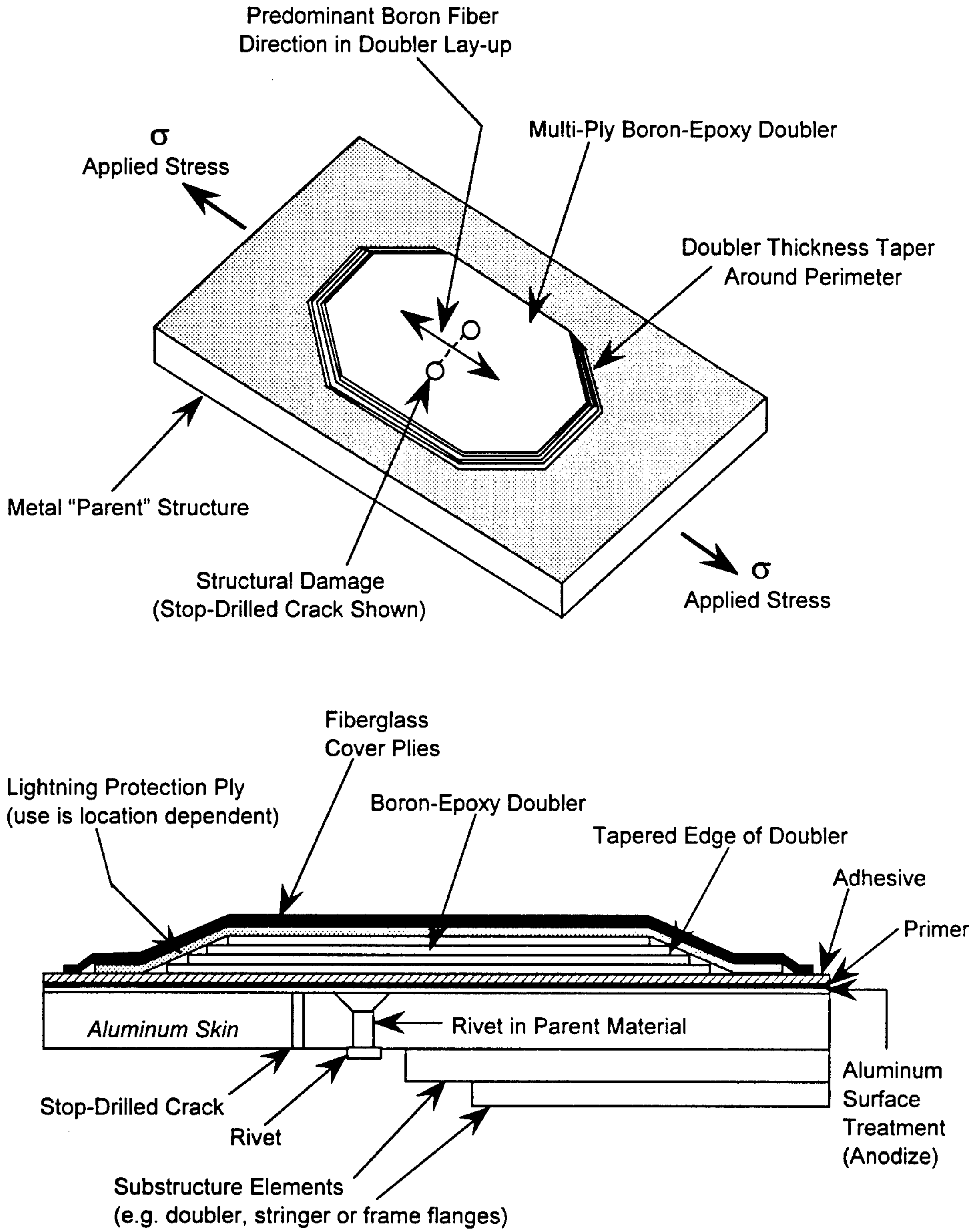


Figure 1: Schematic of Bonded Composite Doubler Installation on an Aluminum Skin

Efforts to bring newly developed technology to the field can encounter some obstacles. Field personnel may be reluctant to accept new repair practices and associated NDI procedures for several reasons. The technology may not be fully field tested; there may not be enough experience under field conditions. It may require the purchase of new equipment and aircraft maintenance facilities want proof that the capital outlay is justified. Further, it may require retraining personnel. The AANC was set up to comprehensively address these obstacles and reduce the risks involved in introducing new maintenance practices to the field. The Center does this by evaluating the performance of new hardware, software, and NDI procedures; by demonstrating and documenting the performance of systems; and by supporting the economic analyses of new maintenance practices.

The reliability and efficiency of composite doubler inspection operations are key to ensuring the continued airworthiness of these doublers. The AANC used comprehensive validation exercises to quantify the reliability and implementation costs of a complete inspection methodology. The validation process takes into account a number of specific issues ranging from human factors to the construction of suitable, flawed test specimens to the need for comprehensive and uniform validation exercises. It considers the numerous factors which affect the reliability of an inspection methodology including the individual inspector, his equipment, his procedures and the environment in which he is working. The approach is based on the use of real-life Validation Assemblies which are full-scale structural assemblies containing known, realistic defects.

This report describes the utilization of conventional and advanced NDI techniques to detect flaws in bonded composite doublers and their parent aluminum material. In this project, close consultation with the FAA and the air transport industry was pursued in order to meet the necessary requirements. Active industry involvement was essential to the efficient execution of the AANC activities and ensured the relevance of any resulting recommendations.

Bonded Composite Doublers on Aircraft Structure - 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 safely extend the lives of their aircraft. Flight 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]. Reference [5] describes a series of analytical models which were developed to study the stress field in and around composite doublers and the crack growth life extension resulting from composite doubler use.

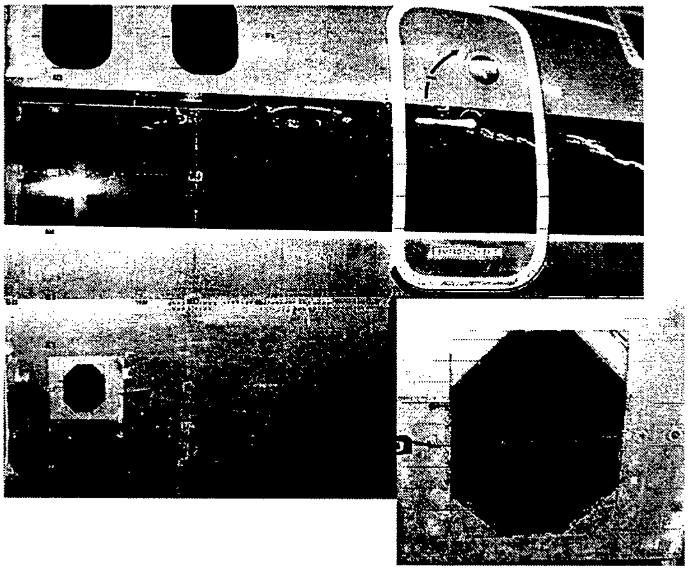
The AANC is conducting a series of projects which are introducing composite doubler technology to the U.S. commercial aircraft fleet. The comprehensive goal of the validation efforts are to address any remaining uncertainties about composite doublers and thus, assure: 1) proper design and installation processes, and 2) the continued safe operation of the doublers over time. To pursue this goal and to demonstrate the technology using a proof-of-concept installation, a specific composite application was chosen on an L-1011 aircraft. Through the use of laboratory test structures and flight demonstrations on an in-service L-1011 airplane, this study investigated general composite doubler design, fabrication, installation, structural integrity, and nondestructive evaluation.

Repairs and reinforcing doublers using bonded composites have numerous advantages over mechanically fastened repairs. Adhesive bonding eliminates stress concentrations, and new potential crack initiation sites, caused by additional fastener holes. Composites are readily formed into complex shapes permitting the repair of irregular components. Also, composite doublers can be tailored to meet specific anisotropy needs thus eliminating the undesirable stiffening of a structure in directions other than those required. Other advantages include corrosion resistance, a high strength-to-weight ratio, and potential time savings in installation. The economic advantages stem primarily from time savings in installation and the secondary effect of reduced aircraft downtime. Exact dollar values depend on the complexity of the repair installation and the number of repairs installed.

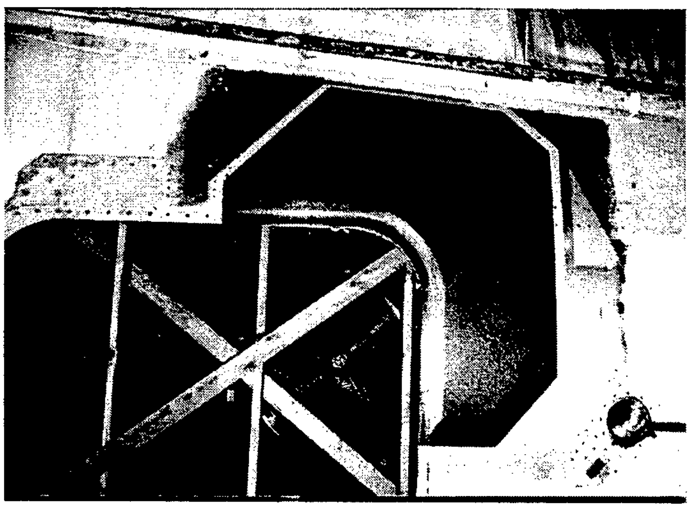
Typical Composite Doubler Installation and NDI - Figure 1 shows a typical bonded composite doubler repair over a cracked parent aluminum structure. Sample composite doubler installations, showing two families of potential aircraft repair applications, are shown in Figure 2. The number of plies and fiber orientation are 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.

The taper at the edge of the doubler is used to produce a gradually increasing stress gradient in the area of primary load transfer. In some applications, such as the L-1011 door corner doubler 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. 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 affected 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. Furthermore, the lightning protection ply creates an undesirable side effect by disrupting the eddy current signals. The laminate taper, which may occur over changing thicknesses within the parent structure, creates a need for careful, and possibly multiple, equipment set-ups and inspections. The discussion which follows will present the host of NDI impediments and will describe how NDI techniques can be implemented to overcome these obstacles.



(a) Sample Fuselage Skin Repair
(composite doubler approx. 12" X 10")



(b) Sample Door Corner Repair
(composite doubler approx. 5 ft.^{2} footprint)

Figure 2: Sample Bonded Composite Doubler Installations Showing Two Families of Potential Repair Applications

In this program, all doublers were installed using the Phosphoric Acid Non Tank Anodize (PANTA) surface preparation procedure and the Phosphoric Acid Containment System (PACS) equipment. The complete installation procedure is provided in Ref. [6] and is Textron Specification No. 200008-001 (may also be referenced as the Boeing

Specification D658-10183-1). Specification 200008-001 references a series of FAA-approved Boeing Aircraft Corporation (BAC) processes and Boeing Material Specifications (BMS) which are widely used by Boeing on commercial aircraft. The key installation steps are summarized below.

1. Aluminum Surface Preparation - solvent clean per Boeing Aircraft Specification (BAC) 5750; alkaline clean per BAC 5749; oxide removal per BAC 5514; phosphoric acid anodize as per BAC 5555; anodize is implemented in the field using a Phosphoric Acid Containment System (PACS).
2. Primer and Adhesive Process - aluminum surface prime per Boeing Materials Specification (BMS) 5-89 using Cytec BR-127 primer (or equivalent); co-cure the Cytec FM-73 (or equivalent: AF163) structural adhesive per BMS 5-101 simultaneously with the Boron-Epoxy doubler.
3. Boron-Epoxy Doubler Installation and Cure - lay up the 5521/4 Boron-Epoxy doubler in accordance with the application design drawing; cure for 90 to 120 minutes at 225°F to 250°F at 0.5 atm vacuum bag pressure; computer-controlled heater blankets are used to provide the proper temperature cure profile in the field.

The Air Force installation procedure [3, 7-8] is very similar to the process described above except that the Air Force surface preparation step uses a grit blast and silane chemical application.

1.1 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 for widespread use in the civil aviation industry, it is imperative that methods be developed which can quickly, easily, and reliably assess the integrity of a doubler. The validation effort must include carefully engineered flaw specimens which mimic the structures of interest and provide all inspection impediments. Blind studies must be performed to arrive at quantitative evaluations of NDI performance [9].

Primary among inspection requirements for these doublers is the identification of disbonds, between the composite laminate and aluminum parent material, and delaminations between adjacent composite laminate plies. Detection of voids, or porosity, is also critical since these defects can reduce the strength of the doubler. The absence of disbonds, delaminations, and porosity in an installation quality assurance check indicates that the doubler is able to perform its duty [10-14]. However, due to the relative 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 are 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 were applied by the AANC to aid NDI development, produce NDI procedures, and to perform formal validation of new composite inspection technologies.

NDI requirements (sensitivity and inspection intervals) are driven by Damage Tolerance Analyses (DTA). However, the stack of metal parent material (isotropic), composite lamina (anisotropic), and adhesive layers makes the analysis quite complex and hinders the calculation of an exact DTA. It is difficult to determine the effects of flaw size and the point at which a flaw size/location becomes critical. This is especially true of disbond, delamination, and porosity flaws. NDI is often asked to compensate for this analysis uncertainty and consequently, the thresholds for flaw detection can become quite conservative. Also, an increased emphasis is placed on quantifying the probability that a flaw of a particular size and location will be detected by a piece of NDT equipment.

The difficulties associated with analyzing the stress fields and flaw tolerance of various composite doubler designs and installations are highlighted in references [4], [12], and [18]. Numerous doubler design and analysis studies [4-5, 13-15] have led to computer codes and turn-key software [16, 17] for streamlining the analyses. These developments have taken great strides to eliminate the approximations and limitations in composite doubler DTA. Section 1.4 discusses NDI requirements as they relate to the ability of composite doublers to operate in the presence of doubler and metal flaws. The test results summarized in Section 1.4 and presented in detail in references [20] and [22] supplement these composite doubler analysis efforts and provide a basis of comparison with computational models. Analysis improvements, however, must be validated by successful flight performance of operational doublers. This can only be accumulated over a long period of time. Continued surveillance of installed doublers will provide quantitative flight performance history and produce a conservative safety factor. Thus, NDI will continue to play a critical role in the use of composite doublers.

Several NDI techniques, primarily ultrasonic-based and thermography methods, are currently being used by the Air Force [19] and in the introductory commercial aircraft effort described in this document. However, continued structural and inspection validation efforts are being conducted to further clarify NDI flaw detection requirements and inspection device sensitivities over a wide array of installation variables. These efforts are also aimed at optimizing NDI deployment through improved procedures and the use of better calibration standards.

1.1.1 Application Dependent NDI Issues

1.1.1.1 Test Specimen Considerations - Need for Array of Test Articles and Full Aircraft Structure

Specimen Types - Test specimen design and utilization are key considerations in producing relevant NDI assessments. The specimens should possess statistically relevant flaw densities and profiles. In order to provide realistic, comprehensive, and yet controlled flaw scenarios it is necessary to include a mix of test specimens from all four of the following categories:

Type	Specimen Category Description
1	Reference Standards - used to set-up equipment at maintenance depots; provide immediate feedback through knowledge of flaw locations/types
2	Engineered Test Specimens - representative flaws in realistic structures; well characterized flaws used for blind NDI performance studies
3	Full-Scale Aircraft Sections - sections cut from aircraft which provide exact structure and natural flaws
4	Complete Aircraft Test Beds - allows deployment issues to be addressed using actual structure and geometry

This approach avoids a complete dependence on any one type of structure. The sections cut from aircraft provide the most realistic specimens, however, since the flaw profiles cannot be determined until post-experiment disassembly, the engineered specimens provide a necessary element of experimental control.

Shape/Geometry - The test specimens should represent the shape and geometry of the structures being inspected. Initially, a generic approach is used to represent "common" doubler installations and substructure elements. This is followed by focused testing using the exact structure for the application of interest. These specimens contain both front and back geometries to produce the proper NDI responses. Worst case conditions can be generated by selecting specimens with geometries that pose special manipulation problems or produce NDI responses that obscure flaw signals.

Flaw Sizes and Numbers - Quantitative assessments require that a statistically relevant number of flaw sites and detection opportunities exist in the test specimens. Flaw sizes should not be so large that they are always found or so small that they are always missed - the flaw sizes should cover the expected range of increasing reliability. The human vigilance factor can only be assessed if there are sufficient unflawed inspection sites in the test specimens. A specimen design goal is to make the number of unflawed sites large enough to permit some estimate of false call rate.

Composite Doubler Repairs with Disbonds and Delaminations - As a result of this FAA/AANC project, a series of bonded composite doubler specimens have been developed. The specimens represent a wide array of composite doubler installations on an assortment of aircraft structure. Installation features which were varied in the test specimens include: footprint of doubler, number of Boron-Epoxy plies, taper ratio around the perimeter of the doubler, doubler lay-up (quasi-isotropic vs. uniaxial), use of protective fiberglass cover plies, and cure cycle (temperature and pressure variations within allowable limits). A separate study was performed in order to determine the most realistic and reliable methods for producing engineered flaws in the test specimens. The array of flaws include disbonds between the composite laminate and the aluminum skin, delaminations between adjacent plies (at various depths through 72 plies), corrosion in the parent aluminum material, and fatigue cracks in the parent aluminum material. The aircraft structures contain different skin thicknesses (0.040" th. to 0.071" th.), bonded aluminum doublers and triplers, substructure elements such as stringers, frames, and longerons, and different fastener types. Full-scale aircraft structure included a complete 737 aircraft, two fuselage barrel sections from a DC-9 aircraft, two L-1011 fuselage sections, and three C-141 wing planks. Each of these test articles include bonded composite doublers with controlled flaw profiles.

1.1.1.2 Inspection Considerations - Deployment Issues and NDI Impediments

During the course of this investigation, a series of inspection impediments and considerations were highlighted. Not all of these will be present in each installation, however, they are worth noting at the beginning of any NDI application study.

Ultrasonic Considerations:

1. Taper in composite lay-up may require multiple equipment calibrations (probably after each ten to twenty ply drop off) in order to interpret the signal.
2. Substructure elements may create some shadowing and interpretation difficulties - experimentation and proper calibration standards should alleviate this difficulty.
3. Vacuum bag cure of thick laminate may result in considerable porosity. An extensive debulk process may reduce porosity considerably, however, it may not eliminate it. The question then becomes: what is an acceptable level of porosity? Inspection for disbonds below delaminations or porosity will require a shear wave ultrasonic technique since the initial delamination will prevent a normal wave from investigating any deeper into the structure. This adds time and complexity to the inspection process.
4. The sensitivity of resonance mode techniques decreases with increasing thickness of the doubler. In laminates with more than 20 plies, it may be difficult to detect individual disbonds and delaminations due to their decreased overall effect on resonance-based devices.
5. If a scanning system is used, all deployment obstacles and accessibility limitations must be addressed.
6. Proper UT coupling, via water or other agent, must be produced and maintained throughout the inspection.

Thermography Considerations:

1. Deployment activities must include the application of a high-emissivity coating to obtain an acceptable thermographic image.

2. Damage to layers deep within a structure is more difficult to detect than damage in surface layers because the larger mass of material tends to dissipate the applied heat energy. In addition, substructure elements create heat sinks which affect the thermographic image. Preliminary testing will establish the resolution for different inspection depths.
3. The infrared camera and heat source must be placed on the surface being inspected. Thus, there may be accessibility concerns when this assembly must be located in confined spaces.

Eddy Current Considerations:

1. Eddy current inspections must be carried out "blind" where the inspector has no visual indications of rivet or substructure element locations. These features can create signals which may be misinterpreted as flaws. Thus, it may be necessary to produce a map of the entire area covered by the doubler. The map will indicate the locations of all rivets or other structures which can distort the signal. It can be used as a template for all inspections after the doubler is installed.
2. Each layer in the overall lay-up thickness (including Boron-Epoxy, fiberglass, and lightning protection plies) creates additional probe liftoff artifacts. As in normal eddy current deployment into multi-level structures, this decreases the sensitivity of the technique. Lower frequencies can be used to produce a greater depth of EC penetration, however, this requires a larger probe diameter which is not as sensitive as the higher frequency probes. The larger probes also make it harder to negotiate small scan areas.
3. Wire mesh, or other conductive lightning protection layer, will distort the EC signal. Minimal and acceptable distortions may be achieved by using lower probe frequencies. It is the combination of this difficulty, coupled with the thickness/liftoff effects described in item (2), which determines the viability of applying the EC technique.
4. The combination of parent structure and doubler geometry may restrict external access to inspection areas of interest. This may create a need to perform inspections from inside the aircraft. These inspections can only be performed when the aircraft is sufficiently disassembled (probably only during "D" checks).
5. Crack detection in substructure elements (2nd and 3rd layer) becomes difficult when inspecting through thicker crossections. The total liftoff impediment, which now includes any aluminum layers which must be penetrated, must be considered. Section 3.2 addresses both surface and interlayer crack detection.

X-Ray Considerations:

1. This technique may show cracks which are in inaccessible areas for EC. Proper location (angle) for the source and target film are key. Case-by-case experimentation to assess limitations is necessary.
2. Shadowing from substructure elements may make flaw identification difficult.

3. Requires access to front and back of structure thus, inspections can only be performed when the aircraft is sufficiently disassembled (probably only during "D" checks).
4. Because of the potential hazards and personnel protection issues associated with this type of inspection, airlines may resist adding X-ray inspections to their maintenance programs.
5. Unless this can be applied in lieu of EC, X-ray adds another technique to the process thus adding time and complexity to the total inspection.

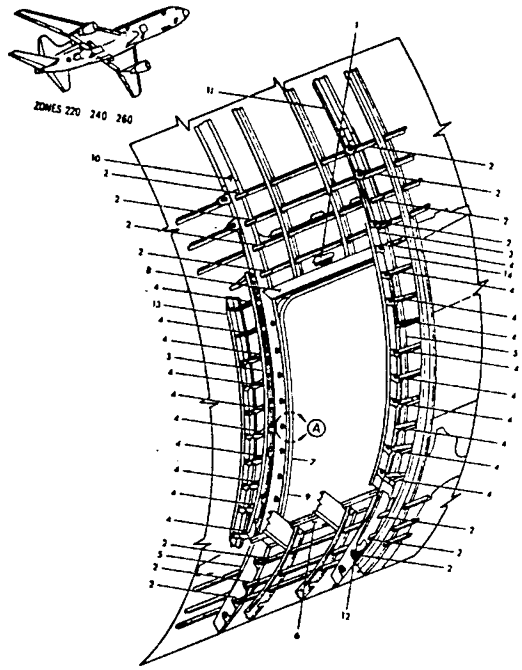
As discussed in Section 1.1.1.1, the actual effects from the issues outlined above can only be determined through experimentation with an array of specimens containing realistic flaws in representative aircraft structure. In addition to using "generalized" composite lay-ups of various thicknesses, the complete lay-up of the proposed composite doubler design must be studied to determine if there are any unique difficulties associated with the ply orientations. Finally, appropriate calibration standards must be developed to support uniform and optimum use of NDT equipment. The design and use of calibration, or reference standards is discussed in Section 4.0.

1.1.2 NDI Assessment Through a Specific Application

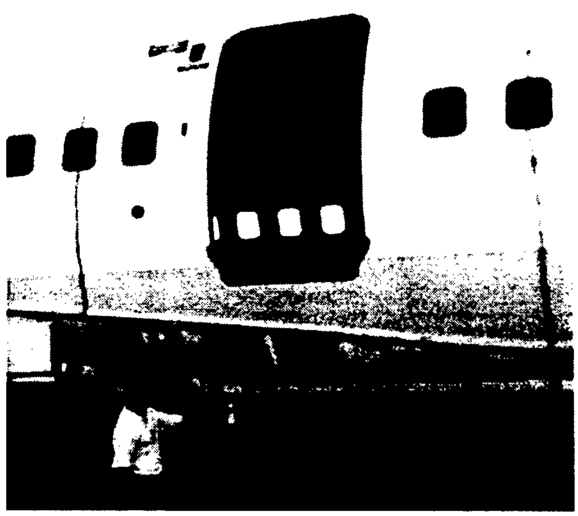
The overall goal of this FAA/AANC program was to establish the viability of composite doubler technology and validate NDI for necessary flaw detection. In order to drive the project tasks and to produce a comprehensive demonstration of these items, a proof-of-concept application was pursued. All activities were approached in a generic fashion, however, special emphasis was placed on the needs of the selected aircraft application. The AANC conducted the initial technology evaluation project with Delta Air Lines, Lockheed-Martin, Textron, and the FAA [20-23]. By focusing on a specific commercial aircraft application - reinforcement of the L-1011 door frame - and encompassing all "cradle-to-grave" tasks, this program objectively assessed the capabilities of composite doublers. Through the use of laboratory test structures and a fuselage section cut from a retired L-1011 aircraft, this study evaluated composite doubler design, fabrication, installation, structural integrity, and non-destructive inspection. The final phase of this project included the installation of a composite doubler on an L-1011 in Delta's fleet. An overview of the NDI carried out on L-1011 composite doublers (Delta aircraft and L-1011 fuselage sections cut from retired L-1011) is provided here as a foundation for the detailed NDI discussions which follow.

1.1.2.1 L-1011 Door Surround Structure

The primary test articles were large fuselage sections cut from retired All Nippon Airways (ANA) L-1011 aircraft. The fuselage test article included a passenger door (P3 passenger door) cut-out and contained all substructure frame, longeron, and stringer elements. Figure 3 shows a photograph of one of the door surround structure sections prior to being cut from the L-1011 fuselage. Each test article, which matched the P3 door configuration chosen for the on-aircraft installation, had planform dimensions of approximately 141" H (151" arc length in the hoop direction) X 114.75" W. NDI assessments were completed prior to and after the doubler installation on the Delta aircraft.



(a) Structural Configuration of Passenger Door Area



(b) Section Cut from Retired L-1011 Aircraft for Full Scale Tests

Figure 3: L-1011 Door Surround Structure Test Article

Figure 4 shows structural details of the upper, forward corner of the door surround structure. It contains a close-up of the door corner area and the footprint of the composite doubler used to reinforce the area. The drawing also highlights three potential crack origins (listed as "crack ref") at the corners of the passenger door and emergency door handle release cut-outs.

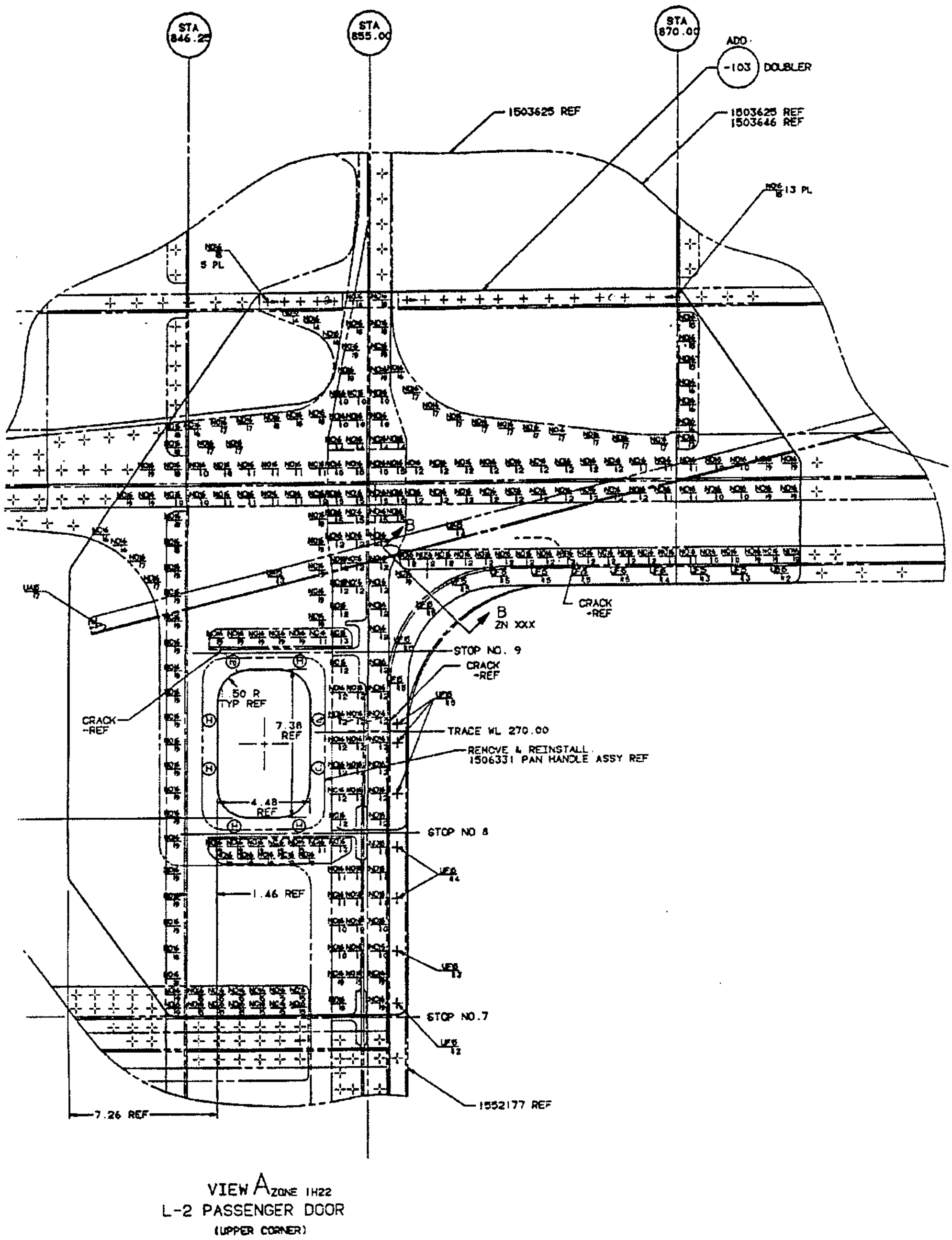


Figure 4: Structural Detail of Area Repaired by Composite Doubler

1.1.2.2 Summary of Doubler Installation

Figure 5 shows the Delta aircraft undergoing maintenance and the doubler installation staging area at the right side, P3 passenger door. Figure 6 shows the aircraft skin section which was cleaned and anodized - via a phosphoric acid non-tank anodize (PANTA) process - to support the doubler bonding process [6]. The doubler was placed in an autoclave (150°F, 80 psi) to debulk/densify the doubler and to bleed out excess resin. The 72 ply Boron-Epoxy composite laminate (post-debulk) is shown in Figure 7. The contour around the door corner radius, the cut-out to accommodate the emergency door handle access port, and the tapered edges around the perimeter are evident. A fiberglass environmental protection ply and a copper mesh lightning protection ply were installed on top of the Boron-Epoxy laminate. The doubler was placed on the fuselage followed by bleeder cloths, heater blankets, insulation and a vacuum bag assembly. Figure 8 shows the vacuum bag arrangement and the Heat Con blanket controller during the cure process. Figure 9 shows overall views of the door corner composite doubler immediately following its installation and after the application of the Delta paint scheme.

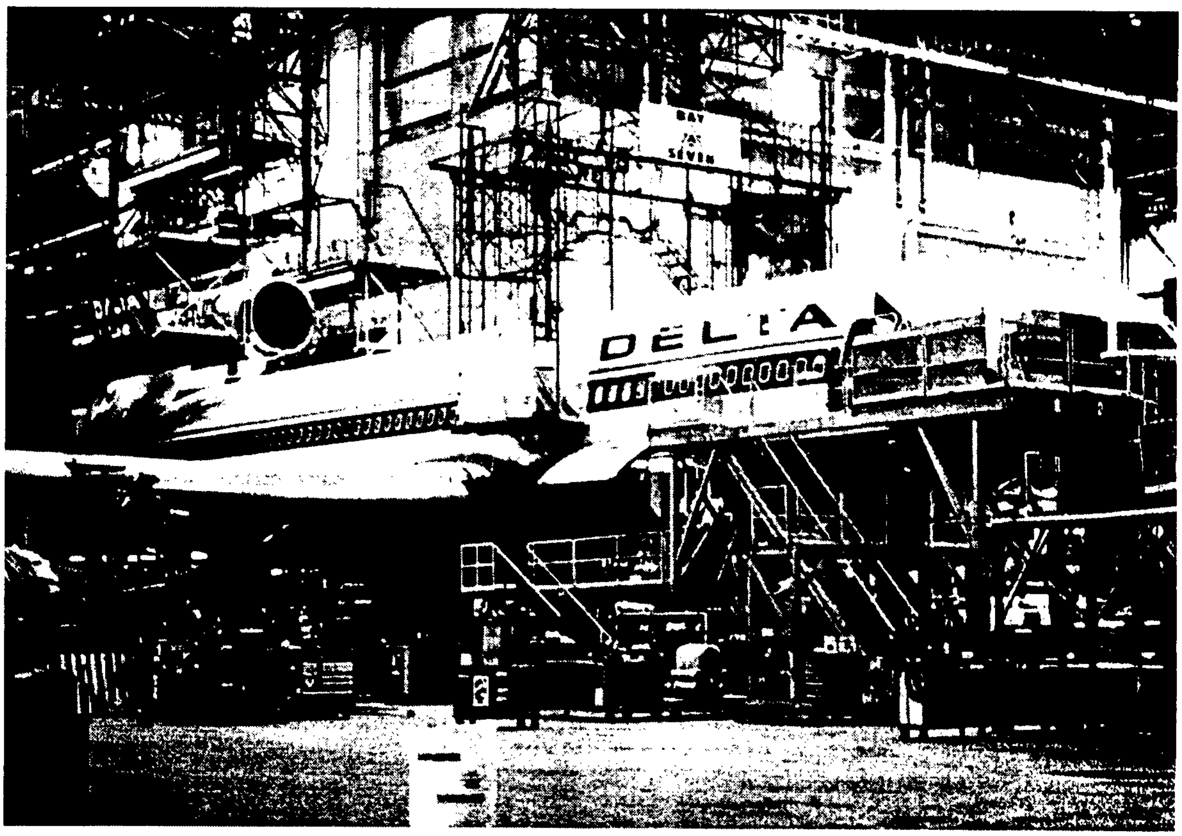


Figure 5: Delta L-1011 Aircraft During Installation of Composite Doubler

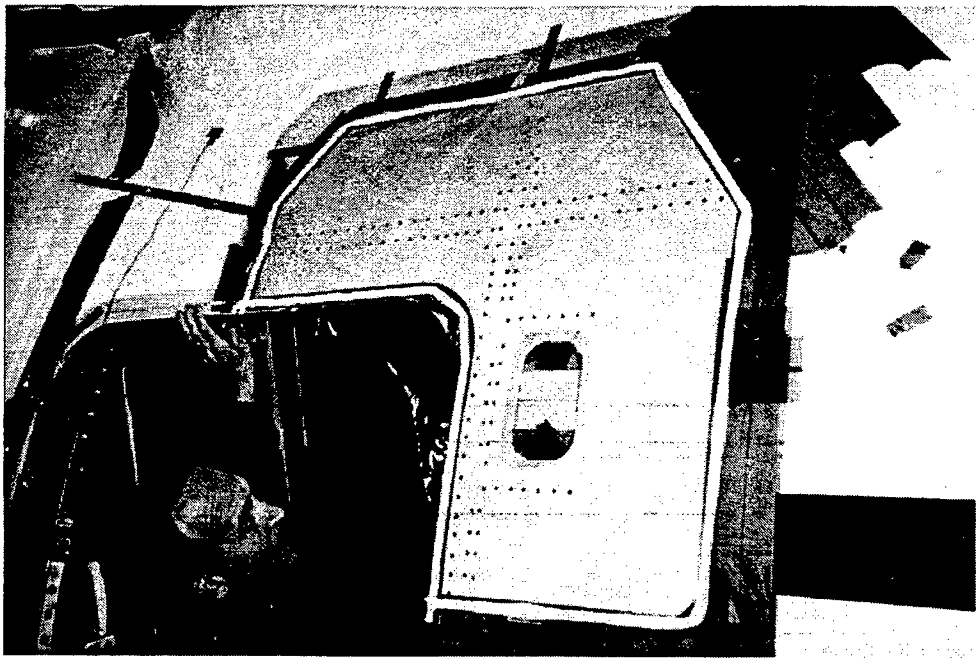


Figure 6: Anodized Door Corner Prepared for Doubler Bonding Process

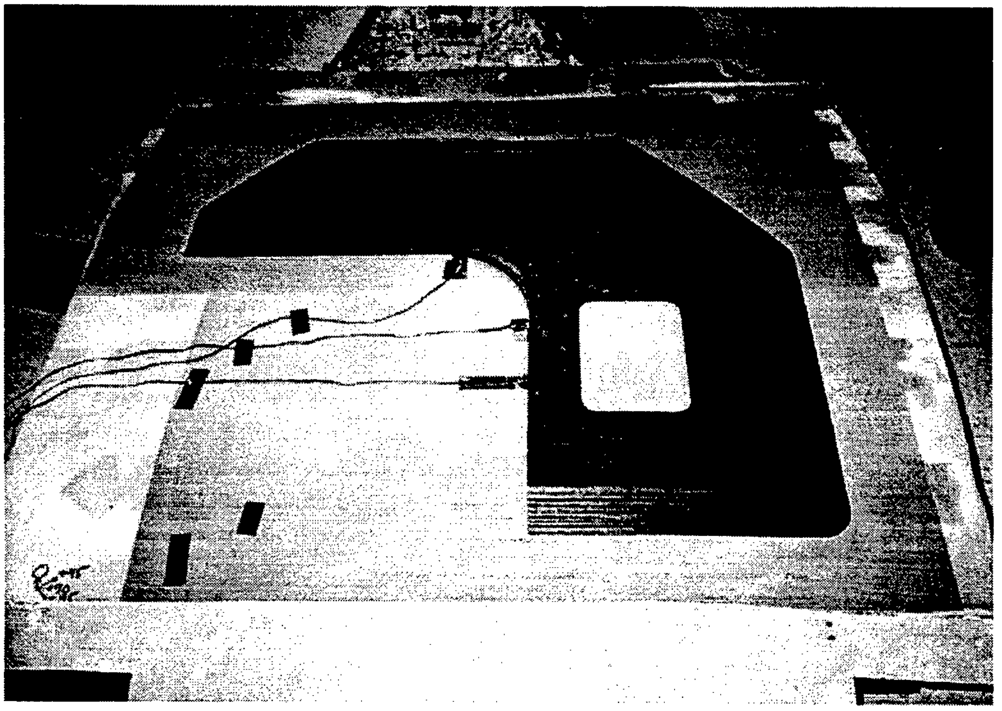
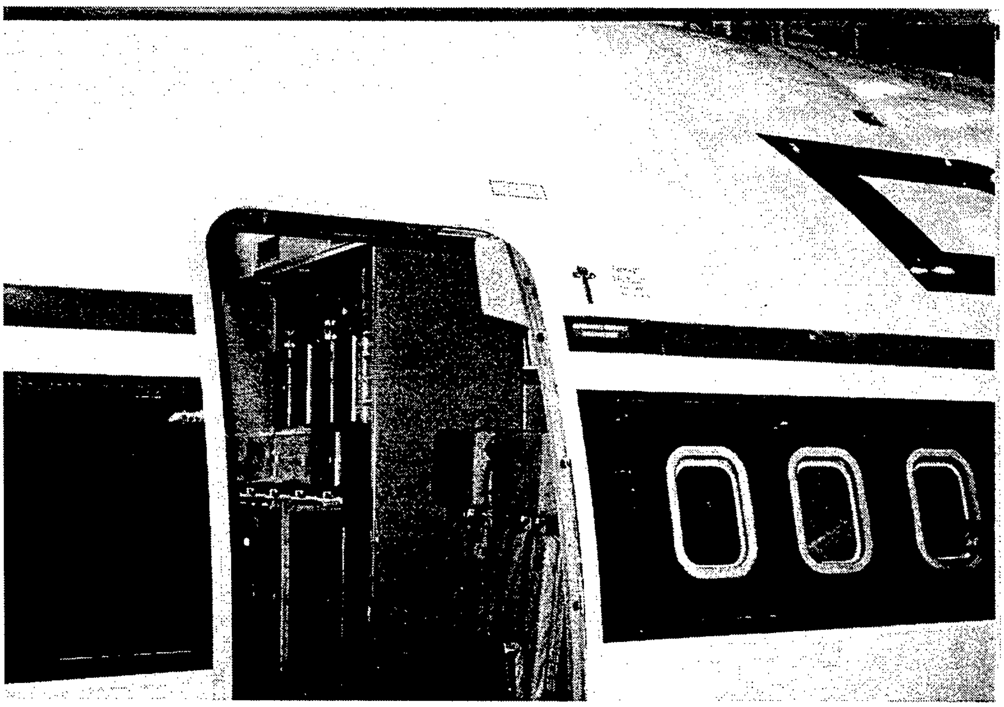


Figure 7: Boron-Epoxy Laminate Following Debulk Process

Figure 8: Doubler Cure Process - Heat Blanket, Insulation, and Vacuum Bag Assembly

(a) Door Corner Doubler Prior to Application of Delta Paint Scheme



(b) View of Doubler After First 45 Days of Operation

Figure 9: Overall View of Composite Doubler on Delta Aircraft Fuselage

1.1.2.3 Nondestructive Inspection of Door Surround Structure and Composite Doubler

The NDI techniques deployed in this effort were capable of detecting disbonds, delaminations, and porosity in the composite doubler (ultrasonics), as well as cracks in the parent aluminum material [22, 24-26]. The door surround structure was inspected with visual (optical magnification), ultrasonic (UT), X-ray and eddy current (EC) NDI techniques before and after the composite doubler installation. Before the doubler was installed, a drawing was made of the area covered by the doubler footprint. It included the location of all rivets or surface structures which could provide a source of false flaw indications. This drawing was then used as a "template" map to aid the inspections performed after the doubler was installed.

Inspections for cracks in the parent material were carried out using an eddy current procedure applied to both the inside and outside of the structure. Bolt hole eddy current (BHEC) and eddy current surface scan (ECSS) inspections were performed prior to the doubler installation. The aluminum material adjacent to the doubler was also inspected using ECSS after the doubler was installed. Both EC procedures followed existing call-outs in the L-1011 Nondestructive Testing Manual [27]. X-ray inspections, currently in use in the door corner region, were also conducted using the procedure listed in the L-1011 NDT manual.

After the doubler was installed, disbond and delamination inspections were performed using the Sandia Labs AANC ultrasonics inspection procedure for bonded composite doublers, AANC-UT-Comp-5521/4-004 [28]. This procedure is required by reference [29] for the L-1011 application. The doubler was inspected using pulse-echo ultrasonics (UT) and an X-Y scanner system (Section 2.1 provides the details). Most of the flaw detection effort was focused on the critical 2" wide strip around the perimeter of the doubler. The allowable flaw size in this load transfer region is 0.5" in diameter. Scans were also produced in the internal region to assure that there were no flaws in excess of the damage tolerance allowables. Figure 10 shows the ultrasonic scanner system inspecting the upper, tapered region of the door corner doubler. A typical scan obtained during the doubler inspection is shown in Figure 11. A disbond flaw would show up as a red area on the scan corresponding to a loss of signal. The inspection did not reveal any flaws in the L-1011 doubler. Contrast Figure 11 (no flaws) with the Figure 35 UT scan of a doubler test specimen containing engineered flaws. The specimen was one of several developed to support this inspection. In Figure 35, the flaws are clearly seen as distinct color variations (signal loss) in the C-scan image.

1.2. Quality Assurance

An overall approach to managing the implementation of composite doubler technology is proposed in reference [30]. Reference [30] suggests the use of an Engineering Standard to guide all design, analysis, and QA issues. A series of quality assurance (QA) measures were included in this project's composite doubler installation process [6] to assure:

1) sufficient strength in the adhesive layer, 2) sufficient strength in the Boron-Epoxy laminate, 3) proper surface preparation to allow the best opportunity for complete adherence of the doubler, and 4) the detection of any flaws in the composite doubler. The first four QA devices involve test specimens which are generated at the same time the doubler is installed. All test specimens are produced using the same temperature and pressure profile as the aircraft doubler cure. The final QA mechanism is nondestructive inspection which is used for the initial acceptance of a composite doubler installation and for continued surveillance over the life of the doubler.

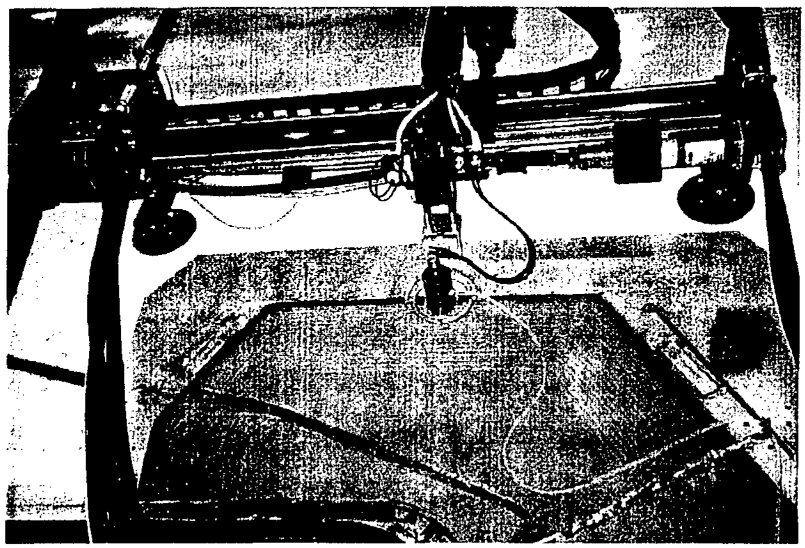


Figure 10: Ultrasonic Scanner System Inspecting a Tapered Region of the L-1011 Door Corner Doubler

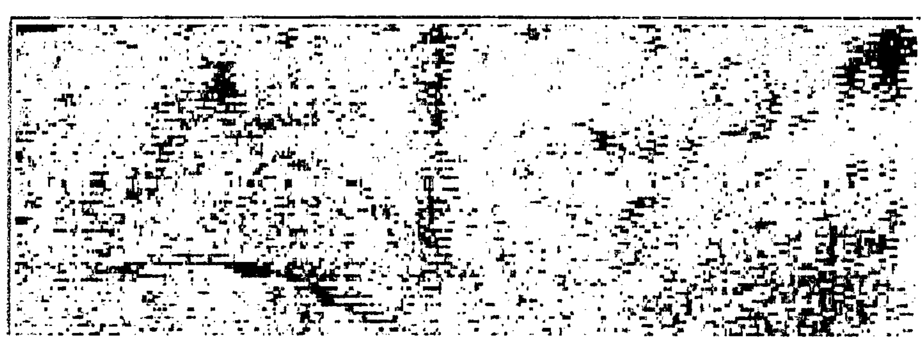


Figure 11: Sample Ultrasonic C-Scan from Doubler Inspection (approx. 14" X 4" scan window) - Bright Red Patches, Not Seen Here, Would Indicate Flaws

a. Wedge Test - Two aluminum strips are bonded to the parent structure immediately adjacent to the doubler. A phenolic wedge is used to pry the strips off the aircraft. If adhesive is found on both the aluminum strip and the aircraft skin, this indicates that the adhesive fractured (cohesive failure) rather than disbonded (adhesive failure). Thus, the surface preparation is good and the full adhesive strength has been achieved. Figure 12 depicts this surface preparation QA test and the two potential failure modes.

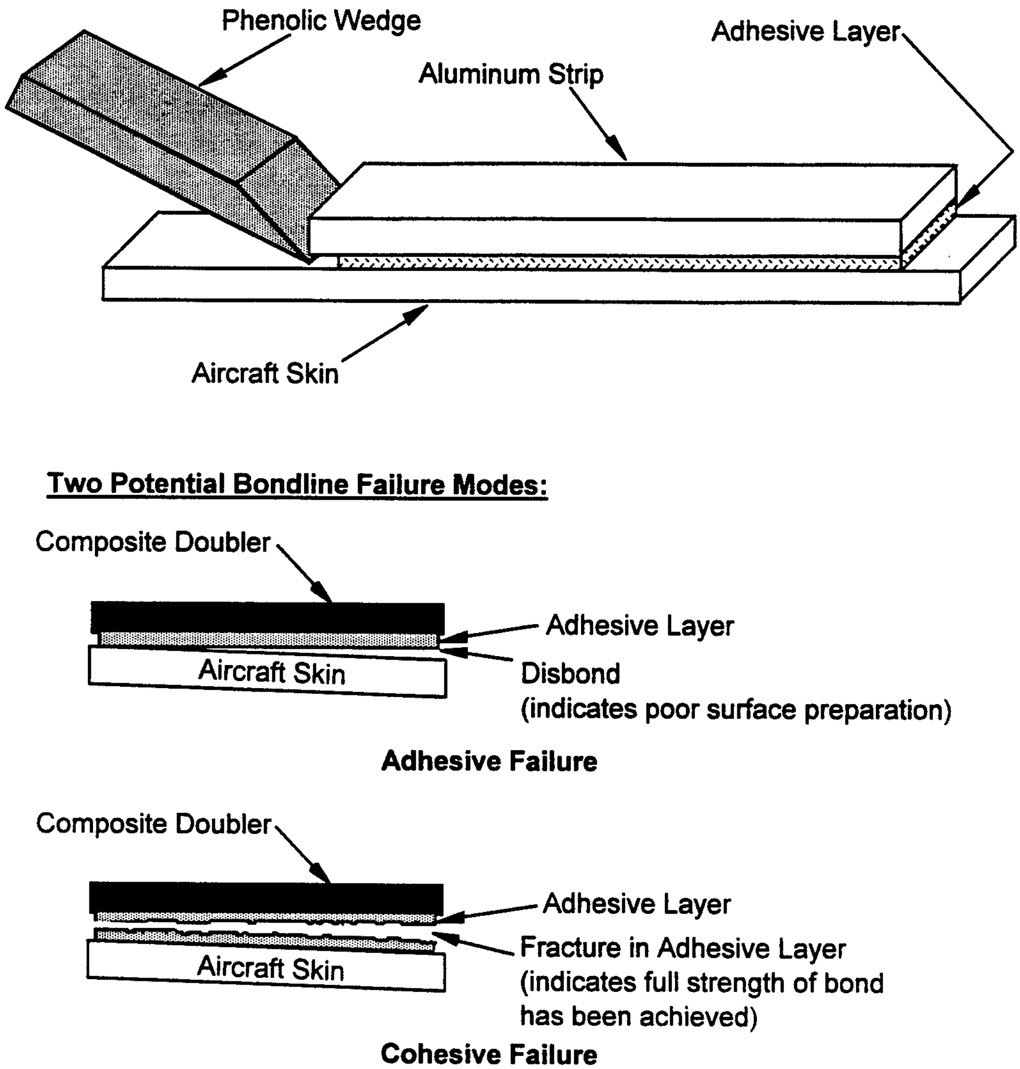


Figure 12: Quality Assurance Wedge Test for Surface Preparation

b. Lap Shear Test - These tests utilize one inch wide aluminum coupons with a bonded lap joint. The specimens are pulled to failure to determine the ultimate strength of the adhesive layer. The minimum strength requirement is 3,000 psi. Six specimens were tested for the L-1011 door corner doubler. They produced the following strength values: 1) 4,720 psi, 2) 4,500 psi, 3) 4,440 psi, 4) 4,880 psi, 5) 4,740 psi, and 6) 4,390 psi.

c. Short Beam Shear - One inch wide Boron-Epoxy laminate coupons (15 ply unidirectional lay-up) are tested for laminate shear strength as per ASTM specifications. Three specimens were tested for the L-1011 laminate and an average shear value of 10.7 ksi was determined. The cured Boron-Epoxy shear strength should be at least 10.5 to 11.0 ksi.

d. Four Point Bend - One inch wide Boron-Epoxy laminate coupons (15 ply unidirectional lay-up) are tested for ultimate tensile strength as per ASTM specifications. Three specimens were tested for the L-1011 laminate and an average tensile strength of 212 ksi was determined. The established minimum strength requirement is 180 ksi.

e. Nondestructive Inspection - The tests outlined above determine the strength properties of the installation. However, it is still necessary to detect any flaws in the installation. Initially, the status of flaws in the doubler and bondline must be ascertained to accept the installation. Thereafter, the flaw status of the doubler, bondline, and parent material must be periodically measured. Nondestructive inspection provides the last line of defense in this regard. NDI is the only means for determining if the structural integrity of the repair area changes over time.

1.3 Inspection Requirements and Intervals for Continued Surveillance

In any surveillance of aircraft structure there are three main aspects to the inspection requirements: 1) the damage tolerance analysis (DTA) which determines the flaw onset and growth data (especially critical flaw size information), 2) the sensitivity, accuracy, and repeatability of NDI techniques which, in concert with the DTA, establishes the minimum inspection intervals, and 3) the impediments which the NDI techniques must contend with while achieving the required level of sensitivity. Detailed discussions on damage tolerance assessments for composite doubler installations are presented in references [12, 15, 18, 20-21]. An overview of damage tolerance for bonded composite doublers is provided in Section 1.3.1 in order to present NDI needs in light of damage tolerance issues. The bulk of this document addresses items (2) and (3). NDI studies strive to detect flaws "as small as possible", however, in order to avoid unnecessary maintenance, and possibly harmful structural modifications, the NDI techniques should be directed at flaw levels as determined by DTA.

Fatigue cracks occur in structures that have been subjected to repeated stress cycles. These cracks typically initiate where the design or surface conditions provide points of stress concentration. Obviously, composite doublers are intended to reduce these conditions and thus eliminate crack growth. However, inspection techniques must evaluate the success of each composite doubler in achieving this goal. The techniques should inspect large areas while still retaining the ability to resolve small details through composite materials.

Flaw Sensitivity Requirements and L-1011 Door Corner Doubler - Inspection requirements for existing composite doublers vary significantly from one aircraft application to the next. Some of this variation is due to the difference in doubler design, location, and structure being repaired. Some of the variation is simply due to the uncertainty in the analysis which determined key flaw parameters. Ultimately, conservative envelopes are drawn around flaw tolerance and the associated sensitivity requirements for NDI. In the case of the L-1011 doubler installed in this study, analysis [21], test [20], and other pertinent composite doubler experience [31] was used to arrive at the inspection requirements. In the critical 2" band around the perimeter of the doubler, inspections must accurately detect disbonds, delaminations, or porosity as small as 0.5" in diameter. In the area of maximum doubler thickness (away from tapered region), the allowable disbond, delamination, or porosity flaws could be as large as 5% of the full-thickness footprint. Furthermore, it was specified that adjacent flaws must be separated by at least 3 inches. Cracks in the parent material beneath the doubler must be detected by the time they reach 1" in length. The conservatism of this requirement can be contrasted with the typical conventional, metallic repairs where post-repair inspections of existing cracks beneath the metal doubler are usually eliminated.

Inspection Intervals for L-1011 Aircraft - One of the major outputs from the doubler design effort was the determination of the inspection intervals to accompany the composite doubler installation. The existing inspections, X-ray, bolt hole EC, and surface scan EC outside the doubler footprint [27], were retained with the following inspection intervals:

NDI Technique	Critical Crack Length (in)	Inspection Interval
1) X-ray	1.00	after 1st yr. and 4,500 flights
2) ECSS	0.35	after 1st yr. and 5,690 flights
3) BHEC	0.07	after 1st yr. and 10,657 flights

These inspections detect cracks in the aluminum structure. An ultrasonic (UT) inspection is used to locate interply delaminations in the composite laminate and laminate-to-aluminum disbonds in the doubler installation. The reference [21] analysis determined the following UT inspection intervals for the composite doubler:

NDI Technique	Critical Disbond or Delamination (in)*	Inspection Interval
Ultrasonic	0.50" diameter	after 1st 30 days
Visual, Tap Test	5% of total area	after 1st 6 months
Ultrasonic	0.50" diameter	after 1st year
Ultrasonic	0.50" diameter	every 4,500 flights

* The maximum allowable flaw size of 0.5" diameter pertains to the perimeter of the doubler footprint within two inches of an edge of the doubler. Away from the doubler edge taper region, the maximum allowable contiguous flaw is equal to 5% of the total, full-thickness area of the doubler.

The close scrutiny of the doubler indicated by the frequent inspections (short intervals) listed above is due to the newness of this composite doubler technology in commercial aircraft applications. It is believed that with the accumulation of successful flight history, the inspection intervals will be extended and, in some cases, removed altogether. Note that after the initial close surveillance of the doubler (through first year following installation), the inspection interval reverts back to every major overhaul of the aircraft (i.e. D-check or heavy maintenance visit every 4,500 flights). Extensive testing has shown that if a composite doubler installation survives its first 6 months to 1 year of operation without any flaw growth, then a good installation has been achieved and little or no flaw growth is expected over the doubler's lifetime [10, 12, 20, 33].

1.4 NDI Needs in Light of Damage Tolerance

A series of fatigue and strength tests were conducted to study the damage tolerance of Boron-Epoxy composite doublers. Tension-tension fatigue and ultimate strength tests attempted to grow engineered flaws in coupons with composite doublers bonded to aluminum skin. An array of design parameters, including various flaw scenarios, the effects of surface impact, and other "off-design" conditions, were studied. The structural tests were used to: 1) assess the potential for interply delaminations and disbonds between the aluminum and the laminate, and 2) determine the load transfer and crack mitigation capabilities of composite doublers in the presence of severe defects. A series of specimens were subjected to ultimate tension tests in order to determine strength values and failure modes.

One of the primary concerns surrounding composite doubler technology pertains to long-term survivability, especially in the presence of non-optimum installations. This test program demonstrated the damage tolerance capabilities of bonded composite doublers. The fatigue and strength tests quantified the structural response and crack abatement capabilities of Boron-Epoxy doublers in the presence of worst case flaw scenarios. The engineered flaws included cracks in the parent material, disbonds in the adhesive layer, and impact damage to the composite laminate. Environmental conditions representing temperature and humidity exposure were also included in the coupon tests. After discussing the damage tolerance of composite doublers, it is possible to better understand the demands placed on NDI to detect damage. This section provides the foundation for the NDI sensitivity topics presented in sections 2 and 3 of this document.

1.4.1 Relationship Between Inspection Needs and Damage Tolerance

Establishing Damage Tolerance - Damage tolerance is the ability of an aircraft structure to sustain damage, without catastrophic failure, until such time that the component can be repaired or replaced. The U.S. Federal Aviation Requirements (FAR 25) specify that the residual strength shall not fall below limit load, P_L, which is the load anticipated to occur once in the life of an aircraft. This establishes the minimum permissible residual strength $\sigma_P = \sigma_L$. To varying degrees, the strength of composite doubler repairs are affected by crack, disbond, and delamination flaws. The residual strength as a function of flaw size can be calculated using fracture mechanics concepts. Figure 13 shows a sample residual strength diagram. The residual strength curve is used to relate this minimum permissible residual strength, σ_P, to a maximum permissible flaw size a_P.

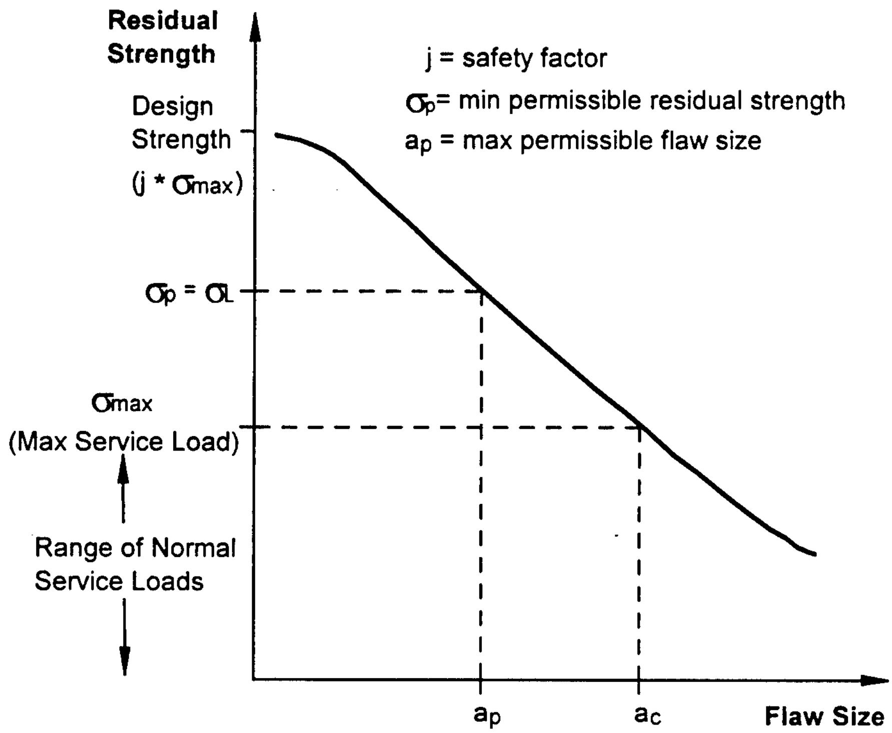


Figure 13: Residual Strength Curve

A fracture control plan is needed to safely address any possible flaws which may develop in a structure. Nondestructive inspection is the tool used to implement the fraction control plan. Once the maximum permissible flaw size is determined, the additional information needed to properly apply NDI is the flaw growth versus time or number of cycles. Figure 14 contains a flaw growth curve. The first item of note is the total time, or cycles, required to reach a_P. A second parameter of note is a_d which is the minimum detectable flaw size. A flaw smaller than a_d would likely be undetected and thus, inspections performed in the time frame prior to n_d would be of little value. The time, or number of cycles, associated with the bounding parameters a_d and a_P is set forth by the flaw growth curve and establishes *H(inspection).* Safety is maintained by providing at least two inspections during *H(inspection)* to ensure flaw detection between a_d and a_P.

Inspection Intervals - An important NDI feature highlighted by Fig. 14 is the large effect that NDI sensitivity has on the required inspection interval. Two sample flaw detection levels $a_{d\,(1)}$ and $a_{d\,(2)}$ are shown along with their corresponding intervals $n_{d\,(1)}$ and $n_{d\,(2)}$. Because of the gradual slope of the flaw growth curve in this region, it can be seen that the inspection interval H_1*(inspection)* can be much larger than H_2*(inspection)* if

NDI can produce just a slightly better flaw detection capability. Since the detectable flaw size provides the basis for the inspection interval, it is essential that quantitative measures of flaw detection are performed for each NDI technique applied to the structure of interest. This quantitative measure is represented by a Probability of Detection (PoD) curve such as the one shown in Figure 15. Regardless of the flaw size, the PoD never quite reaches 1 (100% possibility of detection). Inspection sensitivity requirements normally ask for a 90-95% PoD at a_P. For any given inspection task, the PoD is affected by many factors such as: 1) the skill and experience of the inspector, 2) accessibility to the structure, 3) exposure of the inspection surface, and 4) confounding attributes such as underlying structure or the presence of rivets. Thus, the effects of circumstances on PoD must be accounted for in any NDI study. Figure 16 shows how increasingly difficult circumstances can degrade the PoD of an NDI technique. Much of the rest of this document is spent addressing NDI resolution, sensitivity, and the measurement of probability of flaw detection for composite doubler NDI.

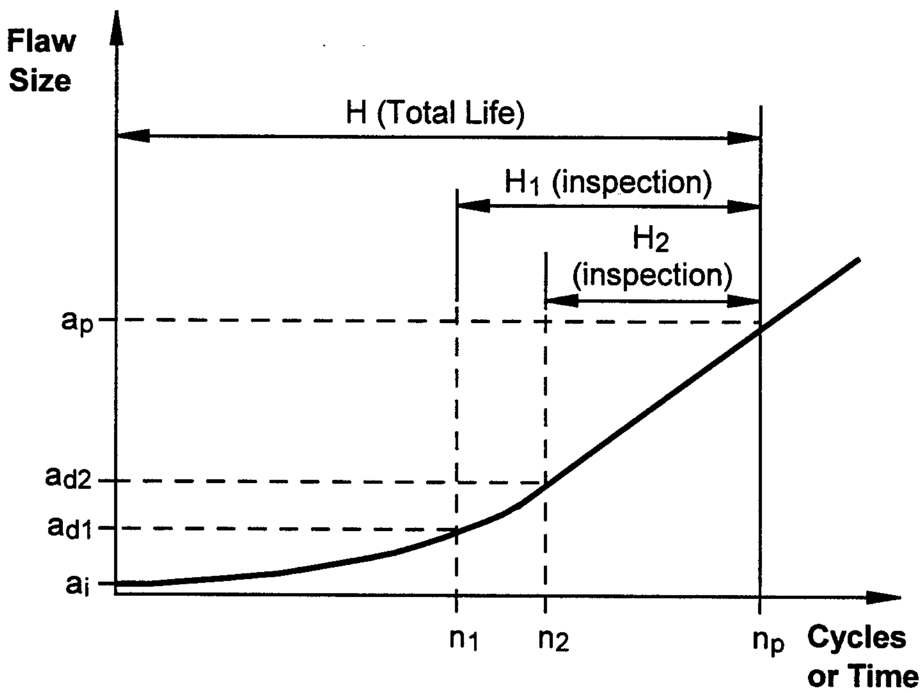


Figure 14: Crack Growth Curve Showing Time Available for Fracture Control

As an example of the DTA discussed above, reference [21] describes the design and analysis process used in the L-1011 program. It presents the typical data - stress, strength, safety factors, and damage tolerance - needed to validate a composite doubler design. The design was analyzed using a finite element model of the fuselage structure in the door region along with a series of other composite laminate and fatigue/fracture computer codes. Model results predicted the doubler stresses and the reduction in stress in the aluminum skin at the door corner. Peak stresses in the door corner region were reduced by approximately 30% and out-of-plane bending moments were reduced by a factor of 6. The analysis showed that the doubler provided the proper fatigue enhancement over the entire range of environmental conditions. The damage tolerance analysis indicated that the safety-limit of the structure is increased from 8,400 flights to 23,280 flights after the doubler installation (280% increase in safety-limit). It established an inspection interval for the aluminum and composite doubler of 4,500 flights.

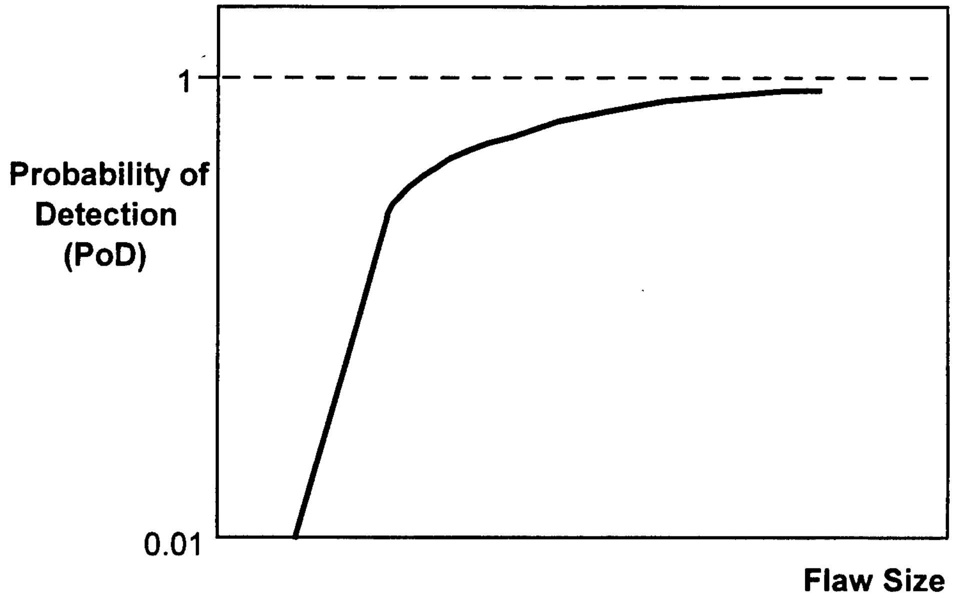


Figure 15: Probability of Flaw Detection vs. Flaw Size

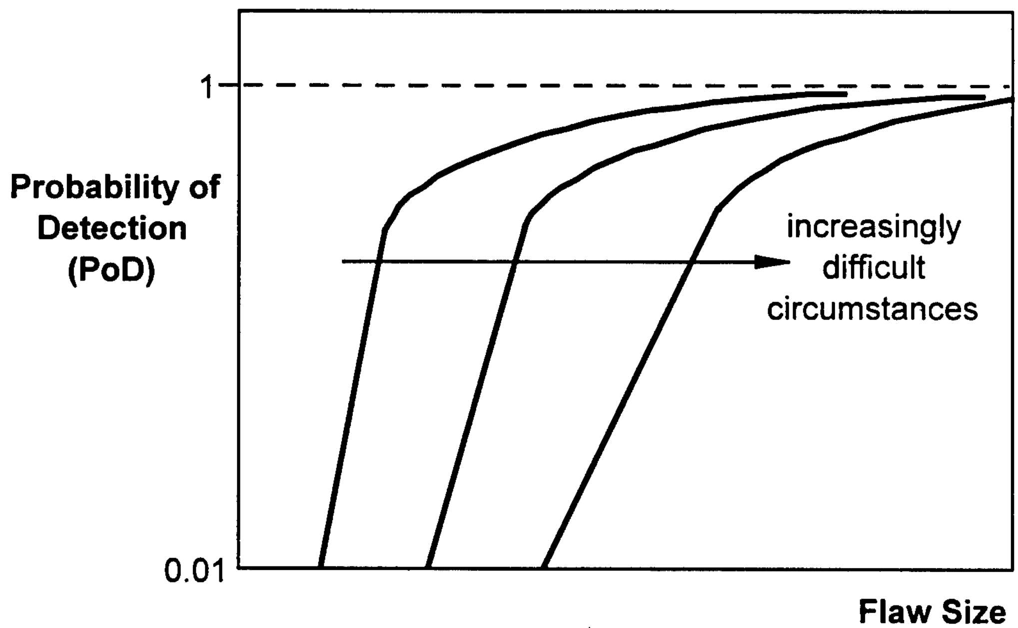


Figure 16: Effect of Circumstances on Probability of Detection

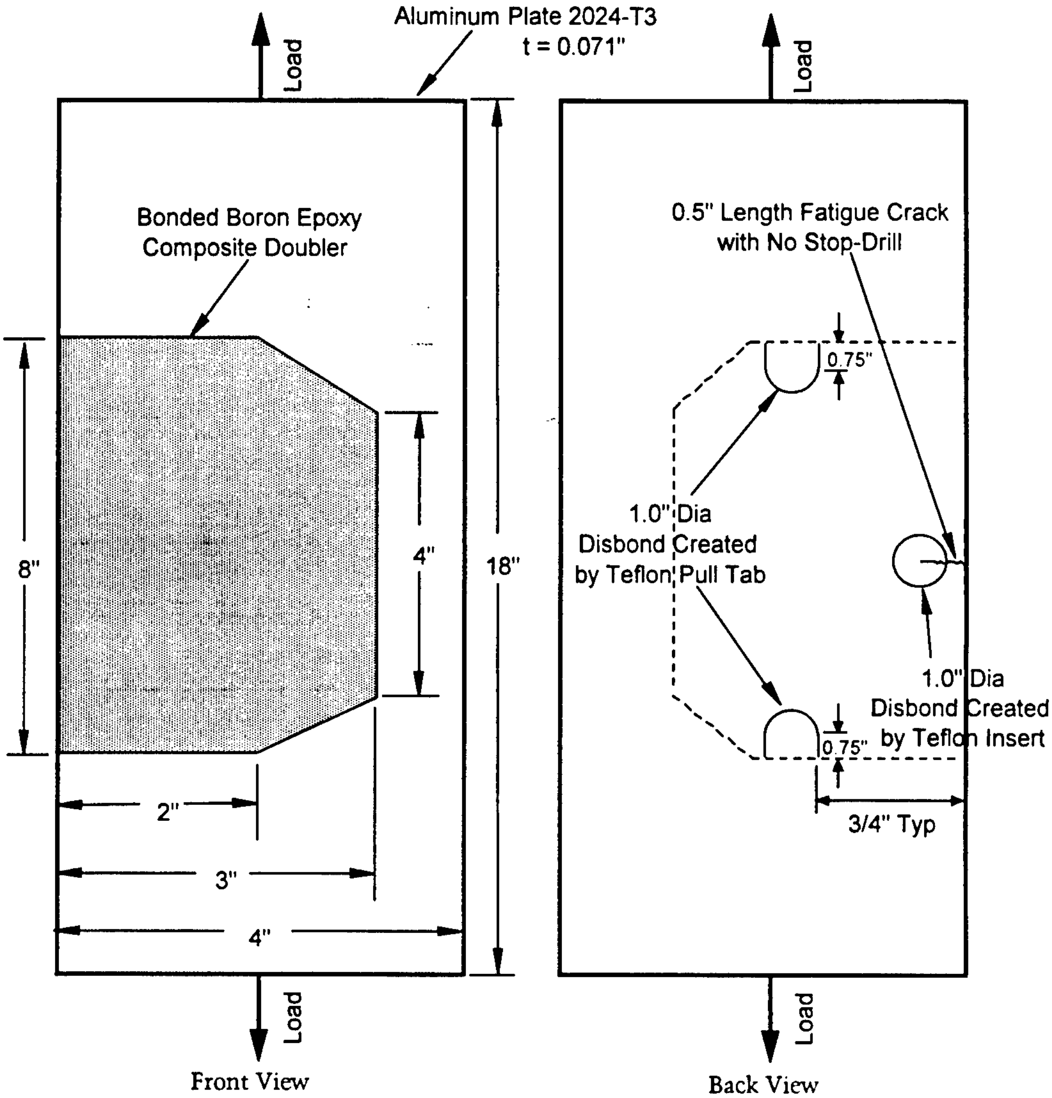
1.4.2 Damage Tolerance Testing

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, 1" diameter disbonds in the critical load transfer region of the doubler perimeter. Figure 17 shows one of the test specimens with engineered flaws. Tension-tension fatigue and residual strength tests were conducted on the laboratory specimens. The entire damage tolerance assessment program and the test results are presented in reference [20]. Thru-transmission ultrasonics, resonance UT, and eddy current inspection techniques were interjected throughout the fatigue test series in order to track the flaw growth.

General Use of Results - The objective of this test effort was to obtain a generic assessment of the ability of Boron-Epoxy doublers to reinforce and repair cracked aluminum structure. By designing the specimens using the nondimensional stiffness ratio, it is possible to extrapolate these results to various parent structure and composite laminate combinations. The number of plies and fiber orientations used in these tests resulted in an extensional stiffness ratio of 1.2:1 $\{(Et)_{BE} = 1.2\ (Et)_{Al}\}$. Independent Air Force [31] and Boeing studies [32-33] have determined that stiffness ratios of 1.2 to 1.5 produce effective doubler designs. Lockheed-Martin has also used this range of stiffness ratios in military composite doubler designs.

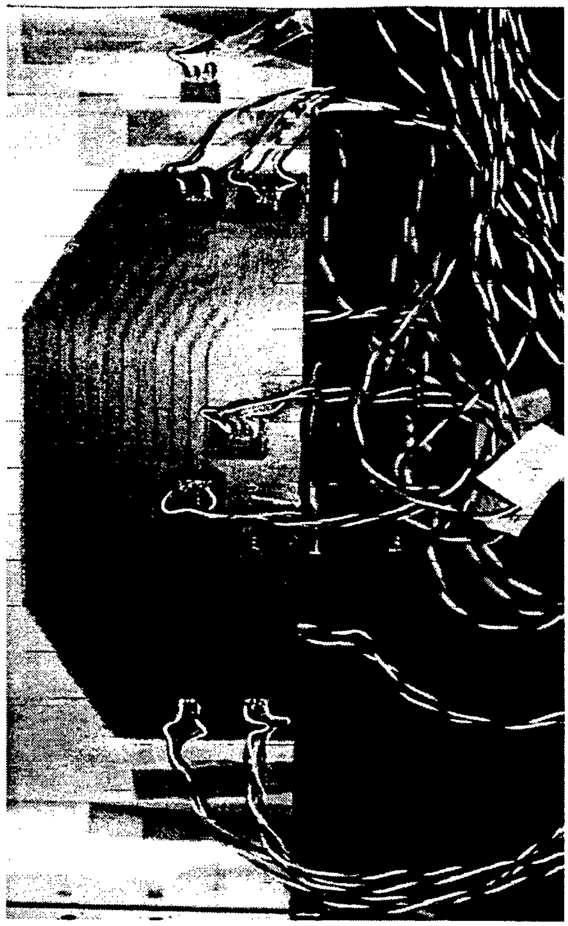
1.4.3 Damage Tolerance Results and Inspection Requirements

Large strains measured immediately adjacent to the doubler flaws emphasized the fact that relatively large disbond or delamination flaws (up to 1" diameter) in the composite doubler have only localized effects on strain and minimal effect on the overall doubler performance (i.e. undesirable strain relief over disbond but favorable load transfer immediately next to disbond). This statement is made relative to the inspection requirement to detect disbonds/delaminations of 0.5" diameter or greater [28]. Obviously, disbonds will effect the capabilities of composite doublers once they exceed some percentage of the doubler's total footprint area. The point at which disbonds become detrimental depends upon the size and location of the disbond and the strain field around the doubler. This study did not attempt to determine a "flaw size vs. effect" relation. Rather, it used flaws which were twice as large as the detectable limit to demonstrate the ability of composite doublers to tolerate potential damage.



1. **13 Ply Boron/Epoxy doubler**
2. **$[0, +45, -45, 90]_3$ lay-up (fiber orientation to the load) plus a 0° cover ply on top; longest ply on bottom**
3. **30:1 taper ratio drop off**
4. **Stiffness Ratio, $(Et)_{BE} = 1.2\ (Et)_{Al}$**
5. **Fatigue crack with 1.0" Dia co-located disbond centered over crack tip**
6. **1.0" Dia disbonds in load transfer region of composite doubler (edges of the bondline)**

(a) Coupon Schematic Showing Embedded Flaws



(b) Photo of Coupon During Fatigue Test

Figure 17: Composite Doubler Damage Tolerance Test Coupon with Engineered Flaws

Similarly, the crack mitigation capabilities of Boron-Epoxy doublers were evaluated using crack sizes which exceeded the inspection threshold. The current inspection requirement calls for inspection intervals and sensitivity to detect cracks of 1" length [21]. The damage tolerance tests presented in reference [20] looked at crack growth beneath doublers of up to 3". The doublers were able to mitigate the crack growth by a factor of 20 versus the unrepaired aluminum. Test results showed that it would take two to three L-1011 fatigue lifetimes (72,000 - 108,000 cycles) for a crack to propagate 1" beneath a reinforcing composite doubler. Finally, these tests showed that Boron-Epoxy composite doublers are able to achieve this performance level (i.e. reinforce and mitigate crack growth) even in the presence of extreme worst-case flaw scenarios. This is the strongest evidence of the damage tolerance of bonded Boron-Epoxy doublers. The two main crack growth mitigation curves are shown in Figures 18 and 19. Important details of these curves and the ref. [20] study are described below.

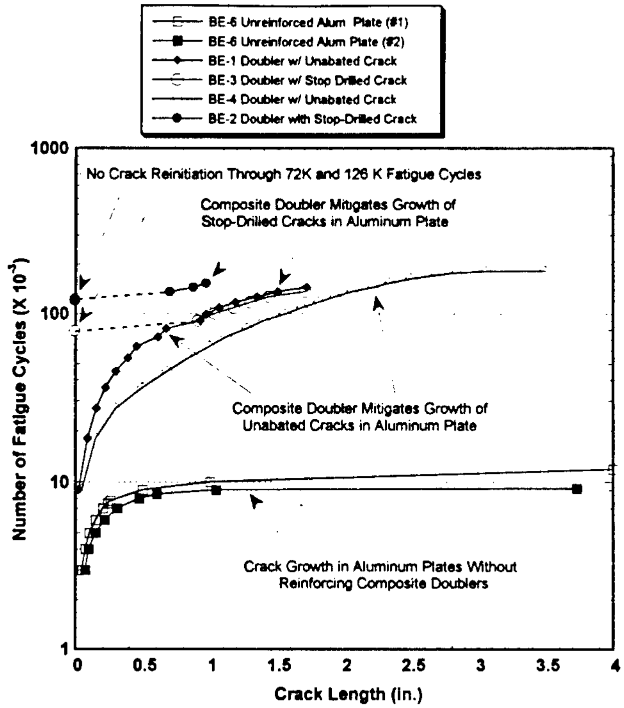


Figure 18: Fatigue Crack Growth in 2024-T3 Skin With and Without Composite Doubler Repairs (set #1)

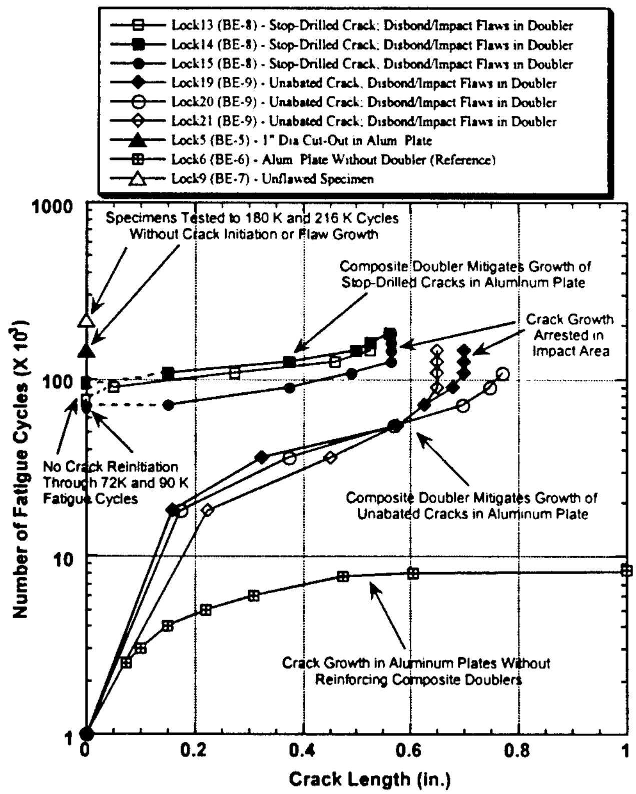


Figure 19: Fatigue Crack Growth in 2024-T3 Skin With and Without Composite Doubler Repairs (set #2)

Fatigue Tests: Flawed Specimens - The composite doublers produced significant crack growth mitigation when subjected to simulated pressure tension stress cycles. Even specimens with unabated fatigue cracks and collocated disbonds and impact damage were able to survive 144,000 fatigue cycles without specimen failure (less than 2" crack growth). During the course of fatigue cycling, all crack growth occurred in the aluminum plates. No fractures were found in any of the composite laminates. Comparisons with control specimens which did not have composite doubler reinforcement showed that the fatigue lifetime was extended by a factor of 20.

Fatigue Tests: Baseline (Unflawed) Specimens - The best basis of comparison for the performance characteristics discussed above was provided by specimens with normal installation and no flaws. These unflawed specimens showed that crack growth and disbonds/delaminations could be eliminated for at least 216,000 fatigue cycles (tests were discontinued at this point).

Adhesive Disbonds - The fatigue specimens contained engineered disbonds of 3 to 4 times the size detectable by the doubler inspection technique [24]. Despite the fact that the disbonds were placed above fatigue cracks and in critical load transfer areas, it was observed that there was no growth in the disbonds over 144,000 to 216,000 fatigue cycles (four to six L-1011 lifetimes). In addition, it was demonstrated that the large disbonds, representing almost 30% of the axial load transfer perimeter, did not decrease the overall composite doubler performance.

Performance of Adhesive Layer - Previous analyses of bonded doublers have demonstrated that the most critical part of the repair installation is the adhesive [3-4,10-14, 31-33]. It must transfer the load to the composite doubler and hold up under many load cycles. The adhesive must also resist moisture and other environmental effects. In order to obtain the optimal adhesive strength and assure a satisfactory performance over time, it is essential to strictly comply with the installation process [6]. Surface preparation is one of the key steps in the installation process. This study demonstrated the ability of the accepted adhesives (AF-163 and FM-73) to transfer loads over multiple fatigue lifetimes of a commercial aircraft. Strain field analyses and fatigue tests showed that large disbonds - in excess of those which will be detected by NDI - and Boron-Epoxy water absorption did not effect the performance of the adhesive layer.

Stress/Strain Fields - The maximum doubler strains were found in the load transfer region around the perimeter (taper region) of the doubler. The strains monitored in this area were 45% - 55% of the total strain in the aluminum plate. This value remained constant over four fatigue lifetimes indicating that there was no deterioration in the bond strength. During crack propagation, the stresses in the doubler increased to pick up the loads released by the plate. Data acquired during failure tests showed that the composite doubler was able to transmit stresses in the plastic regime and that extensive yielding of the aluminum was required to fail the installation. Also, stress risers, normally observed around flaws, were eliminated by the doubler.

Residual Strength - Post-fatigue load-to-failure tests produced residual strength values for the composite-aluminum specimens. Comparisons of the test results with tabulated values for 2024-T3 ultimate tensile strength, which do not use flawed specimens, should be conservative. Even the existence of disbonds and fatigue cracks did not prevent the doubler-reinforced-plates from achieving static ultimate tensile strengths in excess of the 70 ksi Mil handbook listing for 2024-T3 material. Thus, the composite doubler was able to restore the structure to its original load carrying capability.

Ultimate Strength - The ultimate strength values for each of the specimens tested was essentially the same regardless of the flaw scenario. Ultimate strengths in excess of Mil handbook values were produced by the doubler-reinforced plates. The high strain levels experienced during the failure tests did not produce disbond growth in the specimen. The failure mode was extensive aluminum yielding followed by fracture in the adhesive layer. This indicates that the installation was successful and that the full strength of the adhesive was achieved.

1.4.4 Overall Evaluation of Bonded Boron-Epoxy Composite Doublers - Crack Mitigation and Damage Tolerance

By combining the ultimate strength, disbond growth, and the crack mitigation results, it is possible to truly assess the capabilities and damage tolerance of bonded Boron-Epoxy composite doublers. In this test series, relatively severe installation flaws were engineered into the test specimens in order to evaluate Boron-Epoxy doubler performance under worst case, off-design conditions. The engineered flaws were at least two times larger than those which can be detected by NDI. It was demonstrated that even in the presence of extensive damage in the original structure (cracks, material loss) and in spite of non-optimum installations (adhesive disbonds), the composite doubler allowed the structure to survive more than four design lifetimes of fatigue loading. Installation flaws in the composite laminate did not propagate over 216,000 fatigue cycles. Furthermore, the added impediments of impact - severe enough to deform the parent aluminum skin - and hot-wet exposure did not affect the doubler's performance. Since the tests were conducting using extreme combinations of flaw scenarios (sizes and collocation) and excessive fatigue load spectrums, the performance parameters were arrived at in a conservative manner.

This damage tolerance assessment indicates that the inspection requirements discussed in Section 1.3 are very conservative. Furthermore, inspection mandates to detect 0.25" or 0.125" diameter disbonds, set forth in other composite doubler programs, may be overly conservative and, as will be discussed in section 2.0, not reliably achievable in the field. Even in view of these encouraging doubler performance results, the cautious NDI approach is necessary in order to accumulate data on the operation of bonded doublers in actual flight environments. A strong history of success may allow the inspection intervals on these repairs to be lengthened or eliminated.

1.5 Applicable Conventional and Advanced NDI Equipment

The main goals in the application of NDI techniques to composite doubler installations are: 1) proper detection accuracy and reliability, 2) increased speed and decreased cost of inspection, 3) improved scanning techniques, 4) improved flaw imagery (signal processing), and 5) upgrading existing techniques and procedures as new technology becomes available. New technology need not be a completely different approach and/or a new device used to perform an inspection. It could merely be an advanced probe or signal readout equipment which is integrated into an existing technique.

Reference [34] identifies and describes emerging nondestructive inspection methods that can be potentially applied to inspect aircraft. The categories of NDI techniques are: acoustic emission, X-ray, computed tomography, backscatter radiation, advanced electromagnetics, coherent optics, advanced ultrasonics, advanced visual, and infrared thermography. The physical principals, generalized performance characteristics, and typical applications associated with each method are described. In addition to studying the use of conventional NDI equipment on composite doublers, several emerging techniques were explored.

For crack detection beneath doublers, the validation efforts focused on eddy current and X-ray techniques. It was found that the basic deployment methods presently used on aircraft could be retained, however, equipment settings needed to be adjusted to account for the presence of the doubler. These issues, along with quantitative performance results, are presented in Section 3.0.

Ultrasonic methods have shown a tremendous potential for assessing the structural integrity of the doubler laminate and its adherence to the parent aluminum structure. The AANC has used ultrasonics to detect both interply delaminations as well as disbonds at the laminate-to-aluminum interface. A UT scanning system, the Ultra Image IV, was used to conduct many of the inspections, however, it should be noted that the inspections are not considered to be equipment sensitive. Other scanners, such as the Mobile Automated Scanner (MAUS) system [35] or the Dripless Bubbler [36], may be equally suited to composite doubler inspections. Key features of a scanner system will be elaborated upon in Section 2.1. This includes items such as the sophistication of the data acquisition/reduction software and ease of hardware deployment. Section 2 discusses 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.

Another advanced NDI technique which is gaining recognition and use in the aviation industry is thermography. Since the desire of this initial study was to utilize conventional NDI and equipment currently possessed by the majority of aircraft maintenance depots, the application of thermography to bonded composite doublers was not comprehensively studied. However, some preliminary tests were performed which clearly demonstrated the capabilities of thermography for composite doubler structures. These initial results are presented along with a description of more focused testing which was conducted at the AANC.

1.6 Cost Benefits

A complete validation process must also include an assessment of the cost effectiveness of the new maintenance technique in light of the engineering advantages. This includes an analysis of the implementation costs represented by dollars, time, and resources that are used to carry out the maintenance practice (in this case aircraft repair and subsequent inspection). The aircraft repair process using bonded composite doublers has numerous advantages over conventional, mechanically fastened repairs. Following is a summary of the engineering and economic advantages.

Engineering Advantages:

1. adhesive bonding eliminates stress concentrations caused by additional fastener holes
2. crack mitigation performance (improved fatigue life of structure)
3. strength-to-weight ratio (modulus and strength values are three times that of aluminum yet material is 50% lighter and doublers can be up to 50% thinner than metal repairs)
4. flexibility in design (composite doublers can be tailored to meet specific directional strength needs)
5. corrosion resistance (Boron-Epoxy material does not corrode and will not induce corrosion in the parent material)
6. formability (composite laminates are easily formed to fit the contour of fuselage sections and tight radii).

Economic Advantages:

The economic advantages stem primarily from time savings in installation and the secondary effect of reduced aircraft downtime. Exact dollar values depend on the complexity of the repair installation and the number of repairs installed. In general, data accumulated to date using demonstration installations have indicated that it may be possible to realize a 50% - 60% savings in labor when applying composite doublers.

One of the most common aircraft repairs is the application of a doubler to a cracked, corroded, or dented surface skin (scab repairs). Composite doublers are particularly well suited to these type of repairs. Many of these repairs can be completed without accessing the inside of the aircraft structure. This can produce a large time savings if the comparable metallic doubler requires inside access to install the fasteners. These type of surface skin scab repairs can be found many times on a single aircraft. Thus, economies of scale come into play and the cost savings can be substantial when applied over a carrier's entire fleet.

An important by-product of the reduced man-hours needed to effect a composite doubler repair is that it may be possible to return an aircraft to service earlier. In some cases, a composite doubler may allow for an overnight repair and eliminate any loss of service for an aircraft. Revenue loss for aircraft down time can be upwards of $80,000 per day. With approximately 6,000 aircraft flying in the U.S. commercial fleet, reduced aircraft downtime may represent the greatest potential for cost savings.

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2.0 Inspections for Disbonds and Delaminations

The two main potential causes of structural failure in composite doubler installations are cracks in the aluminum and adhesive disbonds/delaminations. When disbonds or delaminations occur, they may lead to joint failures. By their nature, they occur at an interface and are, therefore, always hidden. A combination of fatigue loads and other environmental weathering effects can combine to initiate these types of flaws. Periodic inspections of the composite doubler for disbonds and delaminations (from fabrication, installation, fatigue, or impact damage) is essential to assuring the successful operation of the doubler over time. The interactions at the bond interface are extremely complex, with the result that the strength of the bond is difficult to predict or measure. Even a partial disbond may compromise the integrity of the structural assembly. Therefore, it is necessary to detect all areas of disbonding or delamination, as directed by DTA, before joint failures can occur.

The overall goals of this effort was to: 1) utilize suitable NDI techniques to detect interply delaminations and aluminum interface disbonds, and 2) generate an inspection procedure for use by NDT technicians in aircraft maintenance depots. This included the development of appropriate equipment calibration standards. The first goal was aimed at general validation of NDI for composite doublers while the second goal was focused on facilitating the L-1011 doubler installation.

2.1 Pulse-Echo Ultrasonics

Ultrasonic (UT) inspection is a nondestructive method in which beams of high frequency sound waves are introduced into materials for the detection of surface and subsurface flaws in the material. The sound waves, normally at frequencies between 0.1 and 25 MHz, travel through the material with some attendant loss of energy (attenuation) and are reflected at interfaces. The reflected beam is displayed and then analyzed to define the presence and location of flaws.

The degree of reflection depends largely on the physical state of the materials forming the interface. Cracks, delaminations, shrinkage cavities, pores, disbonds, and other discontinuities that produce reflective interfaces can be detected. Complete reflection, partial reflection, scattering, or other detectable effect on the ultrasonic waves can be used as the basis of flaw detection. In addition to wave reflection, other variations in the wave which can be monitored include: time of transit through the test piece, attenuation, and features of the spectral response.

The principal advantages and disadvantages of UT inspection as compared to other NDI techniques are:

Advantages

- superior penetrating power for detection of deep flaws
- high sensitivity permitting the detection of extremely small flaws
- accuracy in determining size and position of flaws

- only one surface needs to be accessible
- nonhazardous operations with no effect on personnel and equipment nearby
- portability
- output can be digitally processed.

Disadvantages
- operation requires careful attention by experienced personnel
- extensive technical knowledge is required for the development of inspection procedures
- couplants are needed to provide effective transfer of ultrasonic wave energy into parts being inspected
- suitable reference standards are needed both for calibrating equipment and for characterizing flaws.

In UT pulse-echo inspections, short bursts of ultrasonic energy are interjected into a testpiece at regular intervals of time. In most pulse-echo systems, a single transducer acts alternately as the sending and receiving transducer. The mechanical vibration (ultrasound) is introduced into a testpiece through a couplant and travels by wave motion through the testpiece at the velocity of sound, which depends on the material. If the pulses encounter a reflecting surface, some or all of the energy is reflected and monitored by the transducer. The reflected beam, or echo, can be created by any normal (e.g. in multi-layered structures) or abnormal (flaw) interface. Figure 20 is a schematic of the pulse-echo technique and the interaction of UT waves with various interfaces within a structure. Sometimes it is advantageous to use separate sending and receiving transducers for pulse-echo inspection. The term pitch-catch is often used in connection with separate sending and receiving transducers.

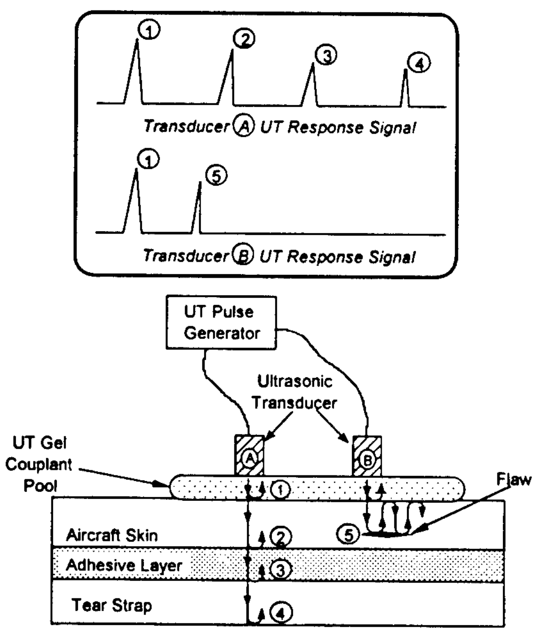


Figure 20: Schematic of Pulse-Echo Ultrasonic Inspection and Reflection of UT Waves at Assorted Interfaces

2.1.1 A-Scan vs. C-scan Mode

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. Flaw size can be estimated by comparing the amplitude of a discontinuity signal with that of a signal from a discontinuity of known size and shape. Flaw location (depth) is determined from the position of the flaw echo along a calibrated time base.

Figure 21 shows a Quantum device being used to perform a pulse-echo UT inspection of a composite doubler bonded to an L-1011 fuselage structure. Figure 22 contains two A-scan signals produced by the hand-held transducer inspection (gel couplant) of another doubler specimen which contained intentional, engineered flaws at discrete locations. Changes in the A-Scan signal (i.e. lack of reflected signal from aluminum back wall), caused by the presence of the disbond, are clearly visible. Key portions of the signal in Figure 22 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 and which indicates a good bond, and 2) the absence of signature waveforms indicating a disbond.

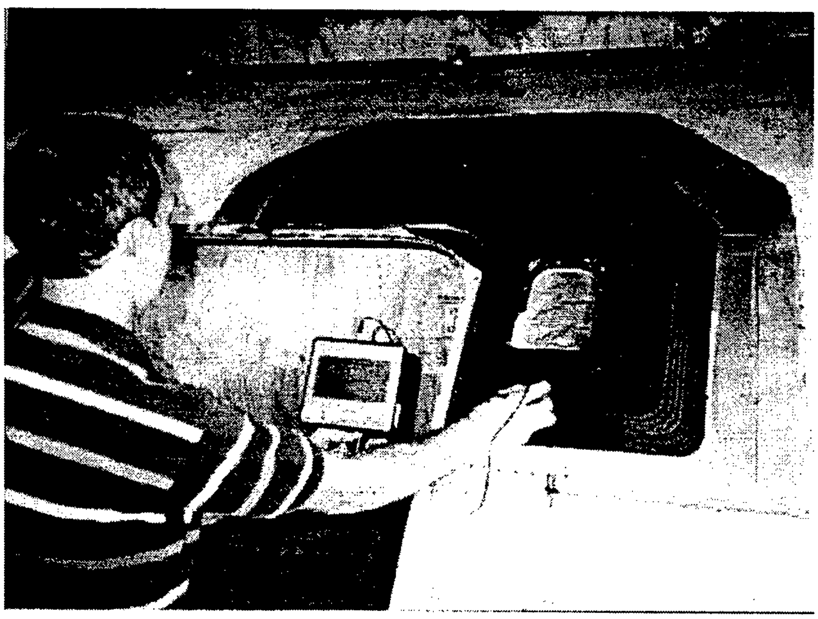


Figure 21: Pulse-Echo Ultrasonic Inspection of Door Corner Composite Doubler Using a Quantum A-Scan Device

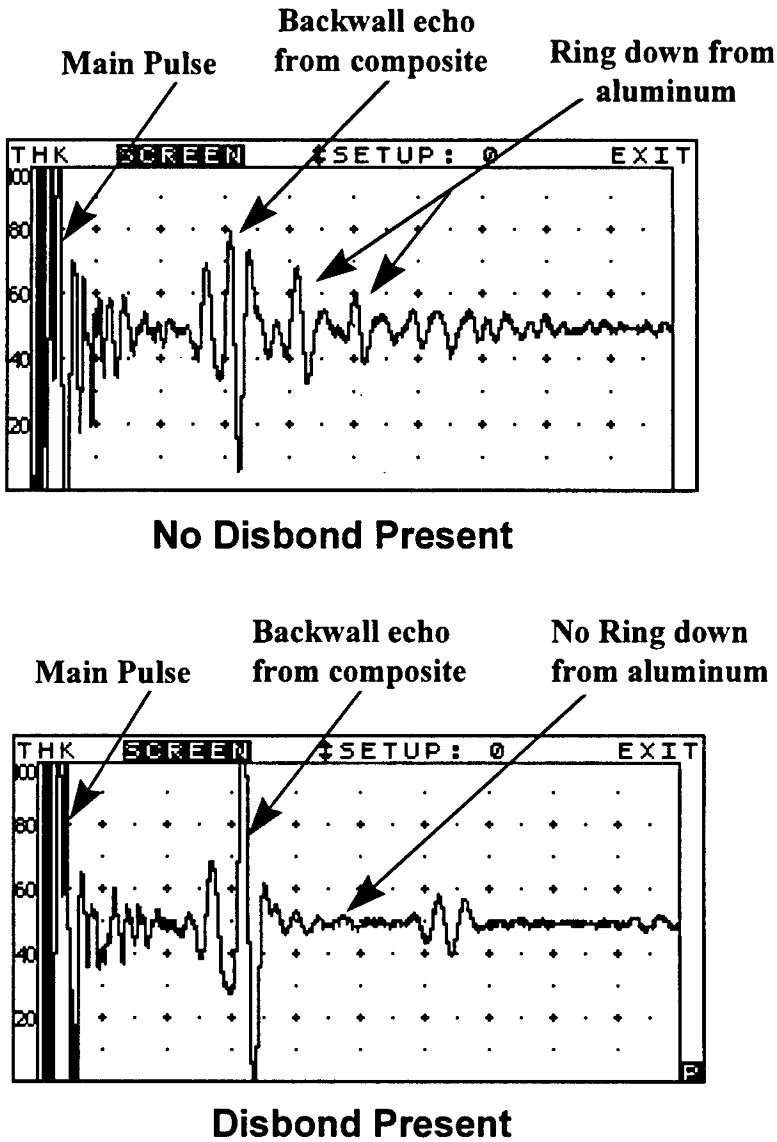


Figure 22: A-Scan Waveform from Bonded and Disbonded Portions of a Composite Doubler Test Specimen

<u>C-Scan Mode: Use of UT Scanning Technology</u> - 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. These inspection impediments are primarily troublesome in thicker composite laminates which exceed 20 plies. Significant improvements in disbond and delamination 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. This format provides a quantitative display of signal amplitudes or time-of-flight data obtained over an area. The X-Y position of flaws can be mapped and time-of-flight data can be converted and displayed by image processing-equipment to provide an indication of flaw depth. A variety of PC-based manual and automated scanning devices can provide position information with digitized ultrasonic signals [35]. Specific emphasis can be placed on portions of the UT signal - and highlighted in the color-mapped C-Scan - based on user specified amplitude gates, time-of-flight values and signal waveforms.

2.1.2 Use of Scanning Technology

In recent years, fieldable, portable, NDI scanner systems have made great inroads into aircraft maintenance practices. The scanners are used to generate C-scan images of eddy current, ultrasonic, or bond tester inspection data. Scanner designs include manual scanners, semiautomated scanners, and fully automated scanners. Reference [35] contains information on the usability and performance of commercially available scanner systems as they apply to aircraft NDI. Several of the ref. [35] scanner systems are discussed here as they pertain to composite doubler inspections. When addressing scanner system capabilities and limitations, key performance factors include: design, portability, deployment, articulation and access to enclosed areas, speed of coverage, accuracy, usability (human factors), and computer hardware/software.

Mechanics of C-Scan System - The basic C-Scan system used by the AANC to inspect bonded composite doublers is shown schematically in Figure 23. 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 characteristics of the sum total of signals received. The particular scanner system used by the AANC in these inspections was the Ultra Image IV manufactured by SAIC/Ultra Image Inc. Figure 24 shows the Ultra Image IV interconnection diagram for its various components. This set-up is typical for most scanner devices. Both manual and automated (motorized) scanners were utilized in this study.

A photograph of the automated (motorized) Ultra Image scanner inspecting a composite doubler on an aircraft fuselage is shown in Figure 25. The entire ultrasonic C-Scan device is attached to the structure using suctions cups connected to a vacuum pump. The unit is tethered to a remotely located computer for control and data acquisition. Pneumatic pressure is used to maintain a constant transducer force against the part being scanned. This is superior to a spring loaded scanner arm where the transducer deployment pressure varies with the spring displacement (i.e. degree of out-of-plane irregularity). In order to better accommodate the specific needs of composite doubler inspections, a series of devices were added to the inspection system. First, a gimbal device was developed to: 1) adapt to surface irregularities and varying slopes, and 2) maintain the transducer perpendicularity with the inspection surface. This minimizes loss of coupling and misdirection/loss of UT energy between the transducer and doubler. Figure 26 shows a close-up view of the transducer assembly in the gimbal positioning mechanism.

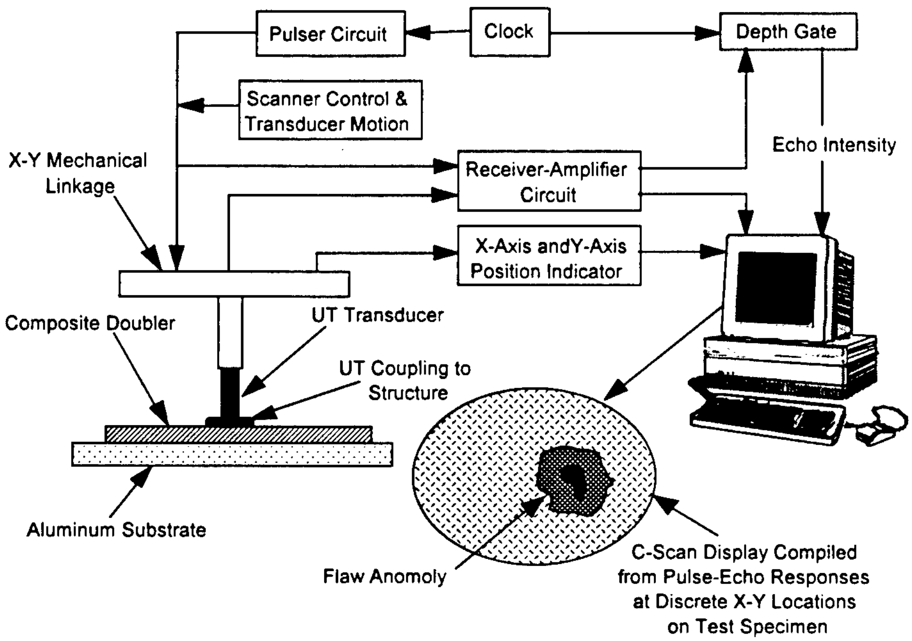


Figure 23: Schematic of C-Scan Setup for Pulse-Echo Ultrasonic Inspection

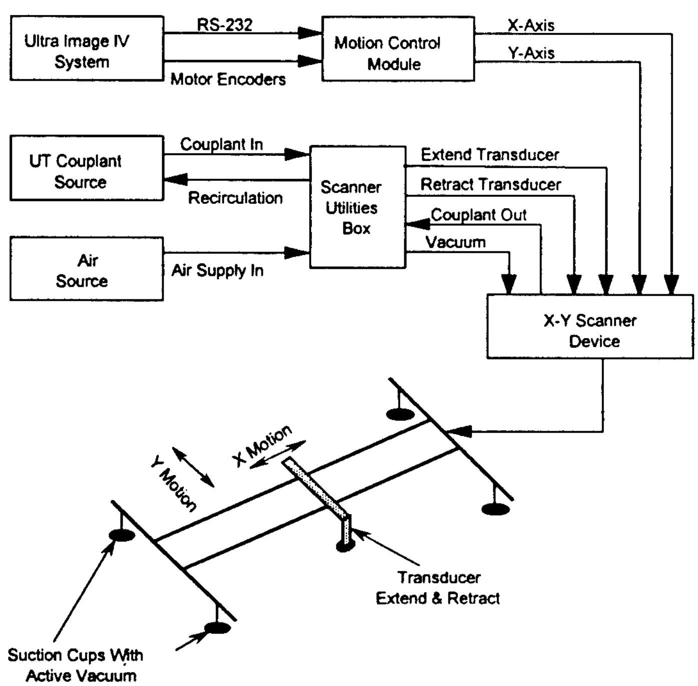


Figure 24: Interconnection Diagram for Components in Automatic Scanner System

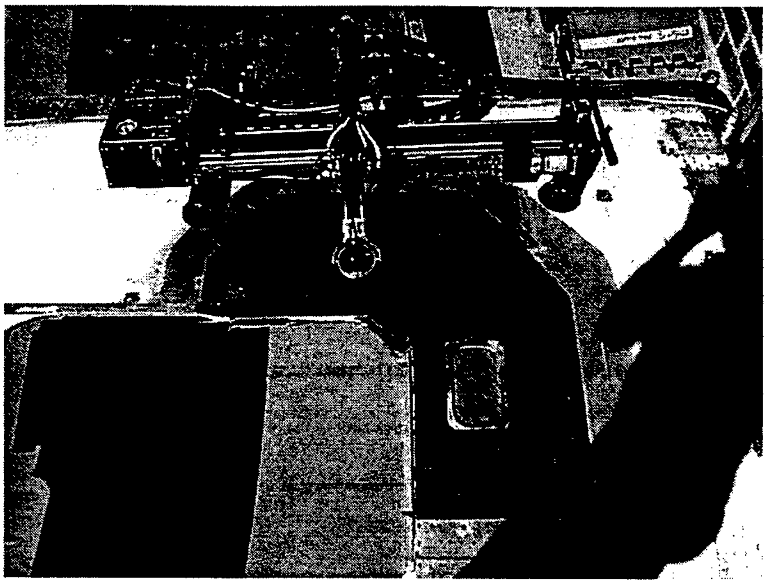


Figure 25: Automated Ultrasonic Scanner Inspecting a Composite Doubler on an Aircraft Fuselage

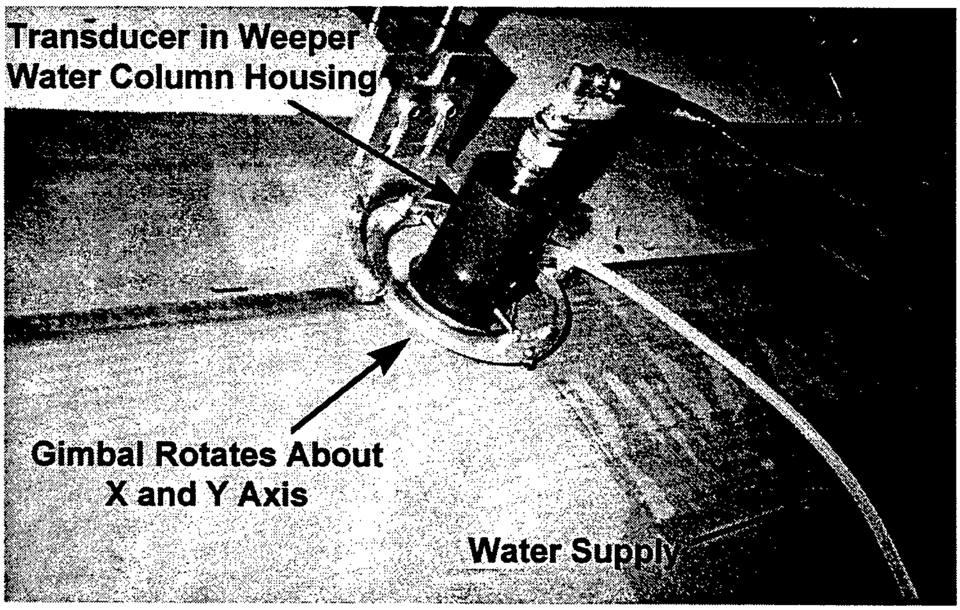


Figure 26: Close-Up View of Ultrasonic Transducer in Gimbal Positioning Mechanism

Optimizing UT Signal Through Improved Coupling - The second inspection system enhancement involved the use of a "weeper" system to optimize ultrasonic coupling into and out of the doubler. Normal UT coupling is achieved through the use of a gel or other liquid medium which can: 1) conform to the time varying gap between the UT transducer and the test surface, and 2) transmit acoustic energy with minimum attenuation. In most

UT inspections, this couplant is initially applied to the surface and then periodically replenished as the couplant is pushed away by the scanning motion. When proper coupling is lost, a corresponding loss of UT signal (signal "drop out") is observed. Once a scanner has been set in motion, a preset area is inspected and any signal drop-out areas must be revisited. In order to avoid this potentially time consuming process, an optimized and continuous source of UT coupling is highly desirable.

Reference [36] discusses a device - the Dripless Bubbler - developed by the FAA's Center for Aviation Systems Reliability (CASR) and Iowa State University which provides a uniform, self-contained water column for enhanced UT coupling. A photo of the Dripless Bubbler device inspecting an aircraft panel containing a bonded composite doubler is shown in Figure 27. The ultrasonic scanning performed in this AANC study used a similar idea, however, the water flow for coupling is not completely contained and recovered. Instead a weeper system, manufactured by TESTECH Inc., was integrated into the Ultra Image scanner. The Figure 28 photograph shows the array of parts which make up the complete assembly shown operating in Figure 26. A schematic is provided in Figure 29. The weeper system forms the transducer arm of the scanning unit and consists of a UT emitter/receiver transducer in a water column. The weeper body is a cylinder with a plastic membrane at the base. Within the weeper body, a column of water is contained between the membrane and the transducer as shown in Figure 29. The membrane is pierced several times to produce a suitable water flow between the membrane and the inspection surface. Water is continuously pumped into the weeper body in order to maintain the water column and the water couplant "pool" between the weeper body and the inspection surface (see Fig. 29). Water running away from the couplant "pool" can be recovered and returned to a reservoir to create a closed-loop pumping system. This water column and associated water pool beneath the membrane provides very uniform and consistent coupling for the ultrasonic waves moving into and out of the test article. This eliminates data irregularities, provides more energy at the inspection point, and produces better output signals (less dispersion). The end results are: 1) improved signal-to-noise (amplitude), 2) better time-of-flight data, and 3) greater flaw detection resolution.

Adjusting the UT Output Through the Use of a Scanner Shoe - Another design feature was added to the transducer deployment in order to aid the interpretation of the UT response signal. Figure 29 shows the use of a "scanning shoe" placed at the base of the weeper body. The purpose of this shoe was twofold. First, the outside of the shoe was made from a plastic material which helped the transducer assembly slide along the wetted inspection surface. Second, the shoe acted as a UT offset. It increased the distance traveled by the interrogating UT signal thus offsetting the peaks caused by interaction of the UT wave with interfaces such as the weeper plastic membrane and the doubler front surface (see Fig. 29). This allowed us to clearly establish the initial interface pulse, or echo, from the inspection surface which is essential in setting up the C-scan gates for data acquisition. The degree of peak offset was controlled by the thickness of a rubber-impregnated cloth washer which was placed inside the shoe. Use of foam material also allowed the transducer assembly to conform to local irregularities in the surface and the soft material prevented any scratching of the inspection surface.

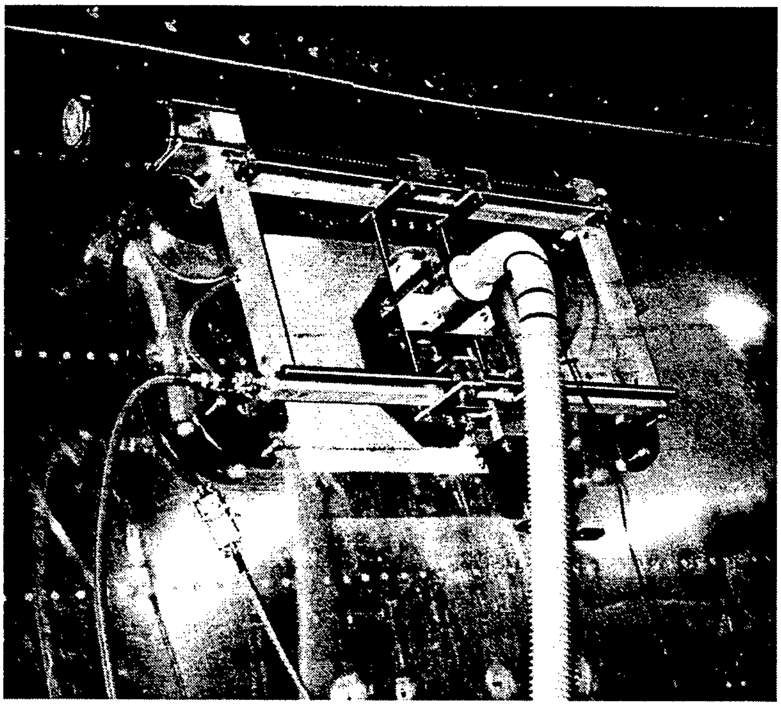


Figure 27: Ultrasonic Drippless Bubbler Scanning System Inspecting an Aircraft Panel

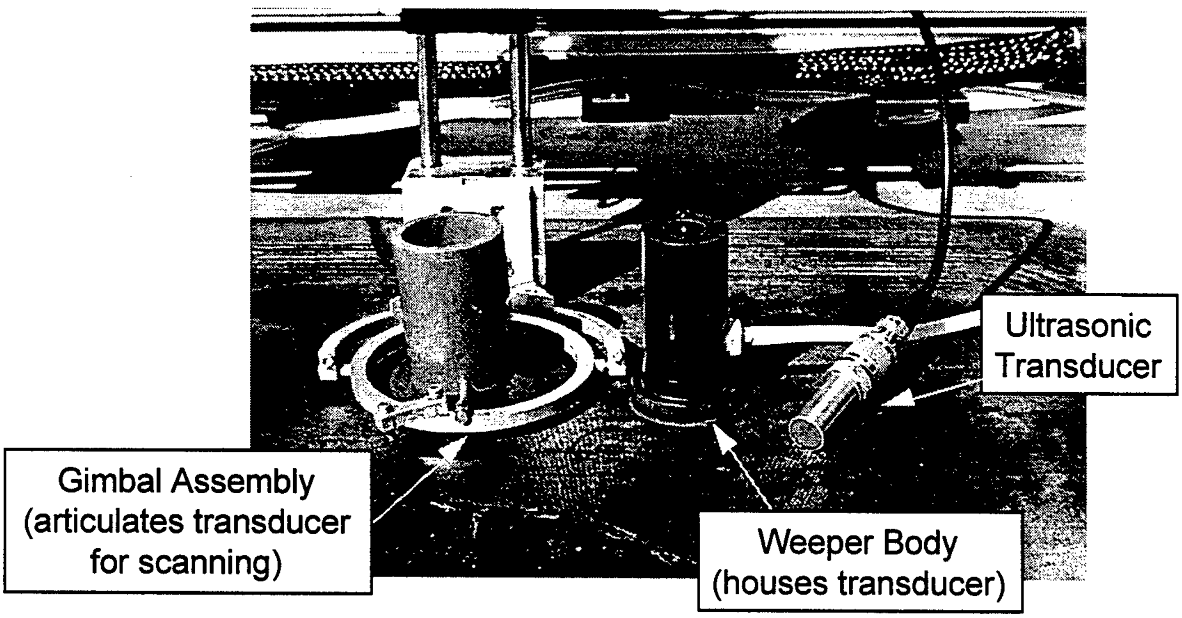


Figure 28: Transducer Deployment Assembly for Scanning (transducer fits inside the weeper body which is mounted in the gimbal assembly)

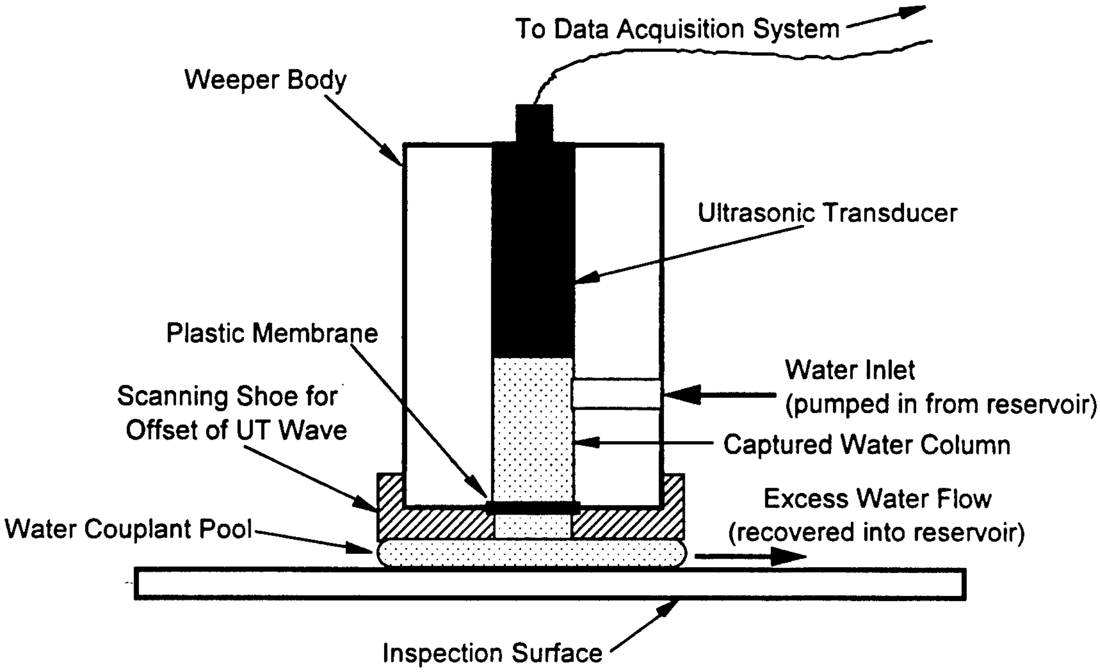


Figure 29: Schematic of Weeper System for Continuous Ultrasonic Coupling

Gating - 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. An electronic depth gate is an essential element in C-scan systems. The gates operate on the A-scan signals received during an inspection and allow users to focus on specific phenomenon in particular time frames (depths) within the structure. User-specified depth gates allow 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. The color coded C-scan reflects these focus areas.

Depth gates are adjustable. By setting a depth gate for a specific range of delay times, echo signals from key areas of the test article, parallel to the scanned surface, can be recorded. In these inspections, the gates were set so that front reflections from the doubler are de-emphasized in the display. Echoes from within the composite doubler and at the aluminum-to-composite bond interface were emphasized.

The Ultra Image IV system in use at the time of these inspections allowed up to four separate gates to be set and to trigger off either positive, negative, or both signal amplitudes. The gates were established by selecting the delay (time) and amplitude position. For the composite doubler inspections, three gates were set to collect: 1) delamination or porosity signals from within the doubler, 2) bond interface signal, and 3) the aluminum back surface echo. Figure 30 is a schematic showing the various ultrasonic wave interfaces and the time delay locations of the three gates. The operator must track the front surface of the doubler in order to appropriately set the time location (horizontal location) of the gates. Also, a representative calibration standard must be used to determine the proper amplitude settings (vertical location).

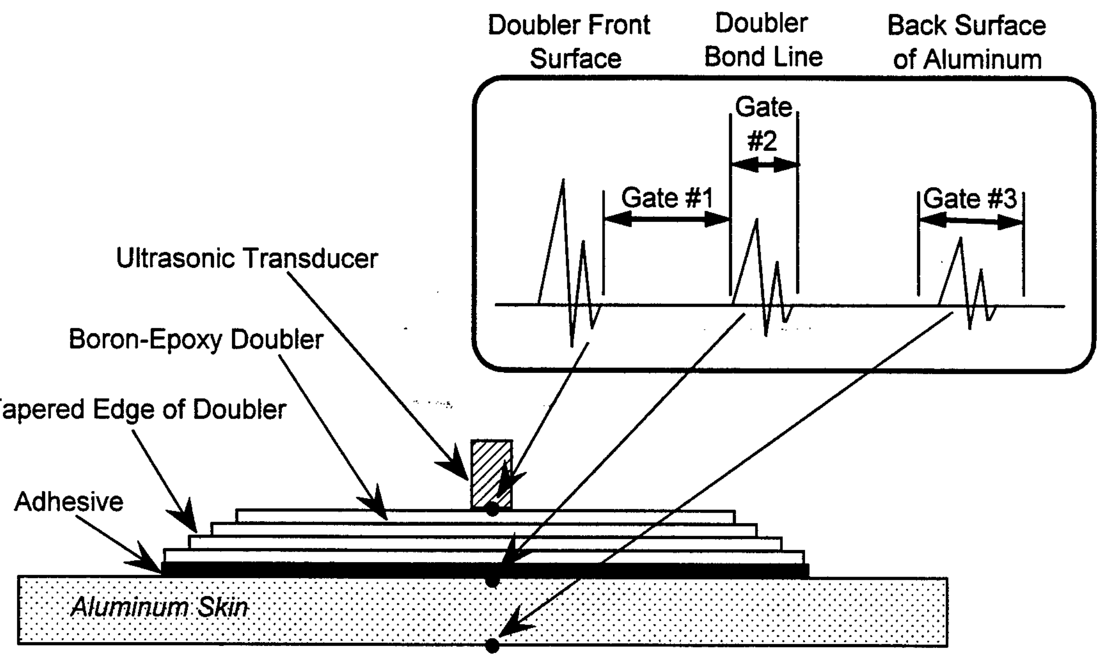


Figure 30: Ultrasonic Peaks Produced by Interfaces in Composite Doubler and Use of Single Scan with Three Gates to Perform Inspection

A typical A-scan trace from a composite doubler inspection is shown in Figure 31. It is labeled with the key UT wave interface areas and includes the three gates used in the inspections. Gate 1 is set up to detect delaminations, porosity, or other flaws within the composite laminate. Normally, the amplitude of the UT waveform should be relatively small compared with the adjacent peaks (labeled "C" and "D") shown in Figure 31. If, however, a flaw is present, a large amplitude signal, which exceeds the gate #1 level, will occur in this gate and create a delamination flaw map. Gates #2 and #3 are used to check the integrity of the bond layer in the installation. The loss of peak "D" at gate #2 or peak "E" at gate #3 would indicate a disbond at the laminate-to-adhesive interface or the adhesive-to-aluminum interface, respectively. Appendix A contains a pulse-echo ultrasonic inspection procedure for composite doublers using the Ultra Image IV device. It steps through the use of calibration standards, the set-up of the various gates, and the production of C-scans. 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. References [34-37] provide additional information on how the C-Scan technique can aid in the interpretation of composite inspections.

By employing a series of gates in one scan, it is possible to collect data over a range of depths (i.e. doubler thicknesses). However, to have complete coverage over a doubler with a wide range of thicknesses, several different scan set-ups, each containing their own unique set of gates, may be used. In the case of the L-1011 application where the composite doubler tapered from 4 plies to 72 plies, the gates were reset every 20 plies. This is due to the fact that the horizontal location (time) of the various peaks shown in Figure 31 change as the doubler gets thicker and the gates must slide accordingly. Pulse-echo UT tests showed that doublers less than 20 plies thick can be scanned with a single gate set-up.

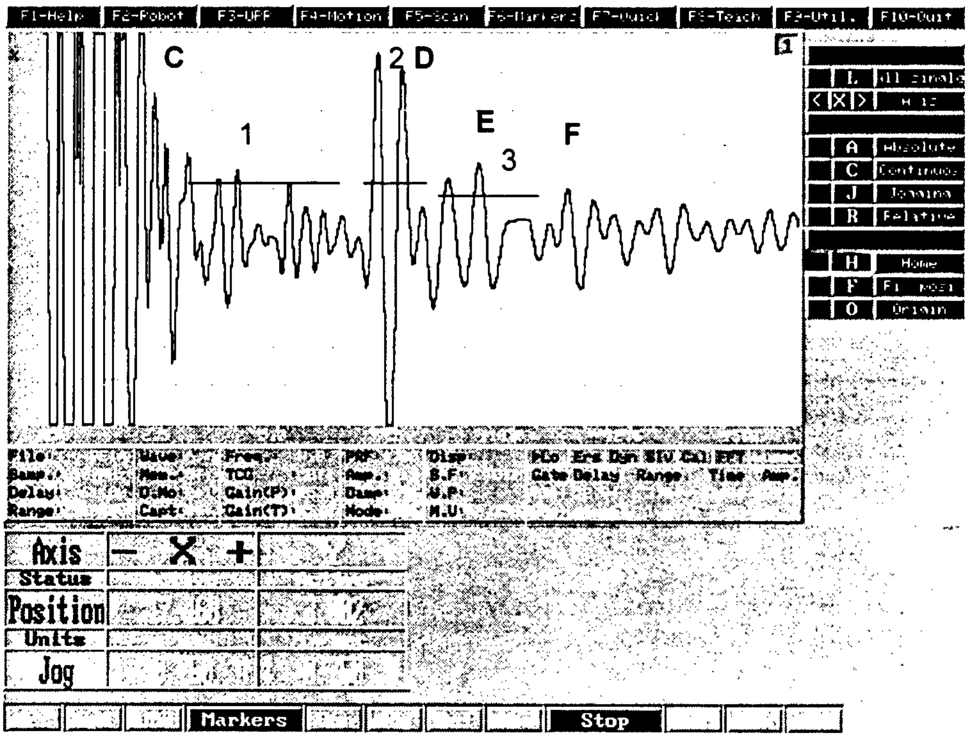


Figure 31: A-Scan Trace Showing Actual Response from Composite Doubler Inspection and Location of Gates to Detect the Following: Gate #1 - Delamination or Porosity Signals, Gate #2 - Bond Interface Signals, and Gate #3 - Backwall Echo from the Aluminum

Peak C = Front Surface Echo from Composite Doubler
Peak D = Echo from Composite Doubler Back Surface/Bond/Aluminum Front Surface
Peak E = Back Wall Echo from the Aluminum
Peak F = First Multiple Peak (Resonance) from the Aluminum

<u>Advantages of C-Scan Approach</u> - Automated systems offer the following 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. Quantitative data makes image interpretation of inspection results straightforward.

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

4. 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.

5. Human factors are improved; it eliminates tedium associated with hand held UT inspections. 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.

2.1.3 Use of Customized, Focused Transducers with Pulse Echo Ultrasonics

The detection of disbonds at the aluminum bond-line interface is often quite challenging. When using 1/2" diameter focus transducers, the echo amplitude change observed at the disbond may be only slightly different than that due to unflawed portions of the composite bond-line. A noticeable improvement in the bond-line echo response at a disbond can be obtained by using a 1" diameter, 2" focus transducer. The echo response can be further enhanced by placing a 3/8" diameter stop in the center of the transducer [38].

The diagram in Figure 32 shows ray traces, drawn from the 1.0 inch diameter transducer, which focus on the aluminum bond-line interface of the 72-ply boron-epoxy repair patch. The large refracted angles for the outer rays of the ultrasonic beam are due to the elastic anisotropy of the composite that changes significantly from the thickness direction to the transverse direction of the composite. The refracted angles in the composite shown in Figure 32 were calculated using L-wave velocity values that were measured in a small 72-ply Boron-Epoxy laminate coupon. The L-wave velocities for different angular orientations in the coupon are listed in Table 1.

Wave Propagation Direction	L-wave Velocity (mm/μs)
Thickness 0°	3.48
5°	3.43
10°	3.43
12.5°	3.51
14°	3.78
15°	4.14
Transverse 90°	6.73

Table 1: L-wave velocity values measured in the boron-epoxy composite

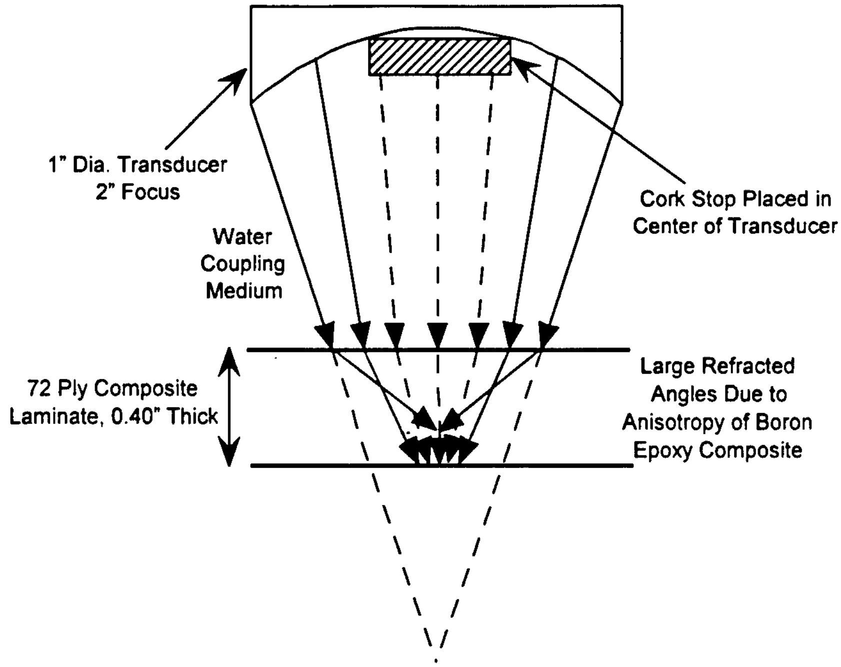


Figure 32: Ray traces for a 1.0 inch diameter, 2 inch focus transducer and a 72-ply boron-epoxy sample.

From Figure 32, it is seen that by placing a stop (3/8 inch diameter and 1/4 inch thick cork button) in the center of the transducer, the zero degree ray together with all low angle rays are blocked so that only the faster velocity rays are transmitted in the sample at large refracted angles. The faster velocity rays interact with the bond-line interface in a way to enhance the difference of the echo response between bonded and non-bonded conditions of the interface.

Improvements in Flaw Detection - C-scan images generated using the modified 1" diameter, 2" focus transducer on 72-ply and 8-ply sections of a calibration test sample are shown in Figure 33. The range gate was set on the positive half cycle amplitudes of the bond-line echo. Also shown in Figure 33 are waveforms recorded at the locations of the disbond and at a "normal" bonded area. The echo response using the modified focus transducer clearly displays an apparent phase reversal and increase in the positive half cycles of the echo at the bondline (disbond location). By setting a Time-of-Flight gate for only negative cycles of the echoes, a robust and unambiguous C-scan image of the disbonded areas in the Boron-Epoxy/aluminum interface are produced as illustrated in Figure 34.

The results presented in Figures 33 and 34 were recorded by an ultrasonic data acquisition system with the samples placed in a water immersion tank. However, the modified focus transducer described here can be deployed in the portable ultrasonic data acquisition and display systems described above. For the portable system, the immersion focus transducer can be placed into the body of the weeper or Dripless Bubbler transducer holder.

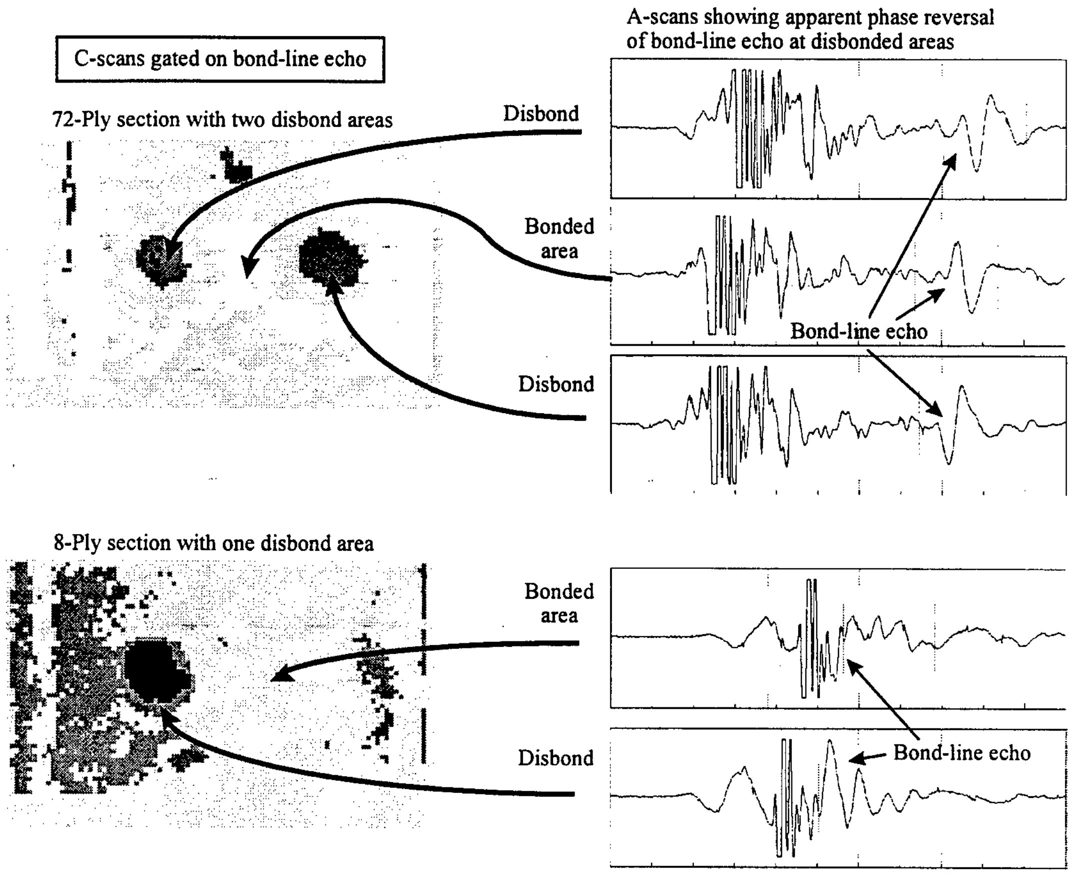


Figure 33: C-Scans and UT Waveforms Recorded at Bond and Disbond Regions for Two Extreme Laminate Thicknesses of a Calibration Test Sample

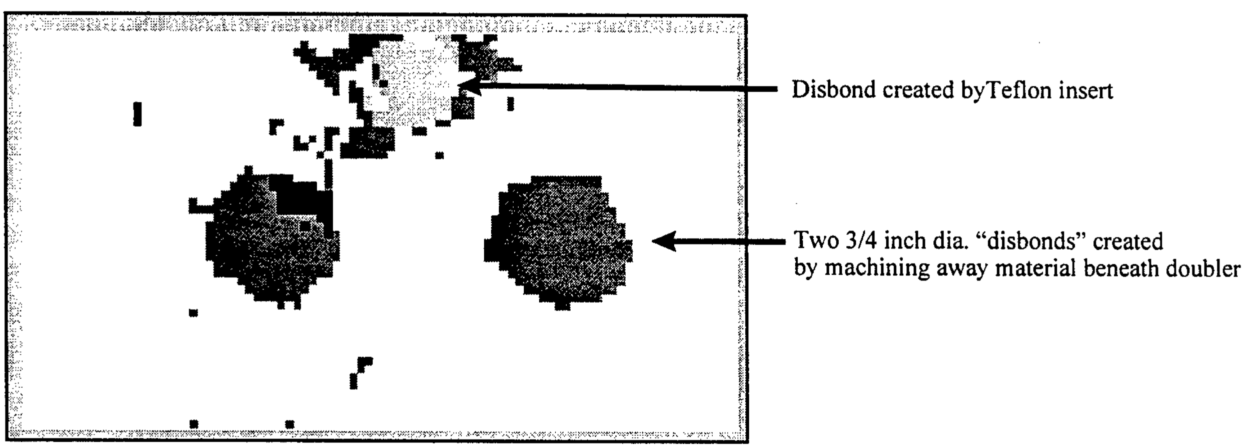


Figure 34: Time-of-Flight Plot of Two Disbonds in a 72 Ply Section of a Calibration Test Sample

2.1.4 Results from Pulse-Echo Ultrasonic Inspections

Using the ultrasonic scanner system and enhancements described above, a series of NDI validation tests were performed. The tests used the complete array of aircraft and bench top, engineered composite doubler specimens presented in Section 1.1.1.1 "Test Specimen Considerations." To review, the design variables which were studied include: footprint of doubler, number of Boron-Epoxy plies, taper ratio around the perimeter of the doubler, doubler lay-up (quasi-isotropic vs. uniaxial), use of protective fiberglass cover plies, and cure cycle (temperature and pressure variations within allowable limits). The specimens contained different skin thicknesses and substructure elements beneath the doublers while the doublers themselves ranged in thickness from 4 plies to 72 plies (approximately 0.027" to 0.410" th.).

1. Evaluation of Technique on Test Specimens with Engineered Flaws

A series of C-Scan images of various bonded composite doubler installations were obtained to evaluate the pulse-echo UT inspection technique and also to establish optimum gate settings for the actual L-1011 inspection. Figures 35-39 show C-scan images (based on amplitude) of bonded composite doublers with engineered flaws. Test specimen schematics are included with each NDI image to provide doubler lay-up information and profiles on the embedded flaws. Three-dimensional contour plots are also shown to demonstrate another means of displaying the data and interpreting the results. Disbond and delamination flaws are revealed by continuous and distinct signal loss areas which, depending on the color pallette chosen, are either relatively bright or dark compared to the surrounding colors. The figures are arranged in the order of increasing doubler thickness to display accurate pulse-echo UT output for a wide range of doubler designs (6 plies to 72 plies). It can be seen that: 1) the flaws are clearly visible when viewed side-by-side with adjacent, unflawed material, 2) flaws as small as 1/4" in diameter can be mapped even through 0.41" thick laminate, 3) inspections can be performed through impediments such as fiberglass cover plies or lightning protection mesh, and 4) the thickness and substructure configuration of the parent aluminum structure does not affect the inspections, although gate adjustments are necessary. In these images, the color scales can be adjusted to produce the greatest variation between flawed and unflawed material. In addition, time-of-flight information can also be displayed in image format to help locate the depth of the damage.

2. Evaluation of Technique on L-1011 Door Surround Structure Doublers

Ultrasonic Inspections on L-1011 Fuselage Test Article - In June, Delta Air Lines and Textron installed the Lockheed-designed composite doubler on a door surround structure fuselage section which was cut from a retired L-1011 aircraft (see Fig. 3). The fuselage section with composite doubler installed is shown in Figure 21. A UT inspection procedure was developed by the AANC and approved for use on L-1011 aircraft by Lockheed-Martin [29]. This procedure was applied to the doubler on the door surround

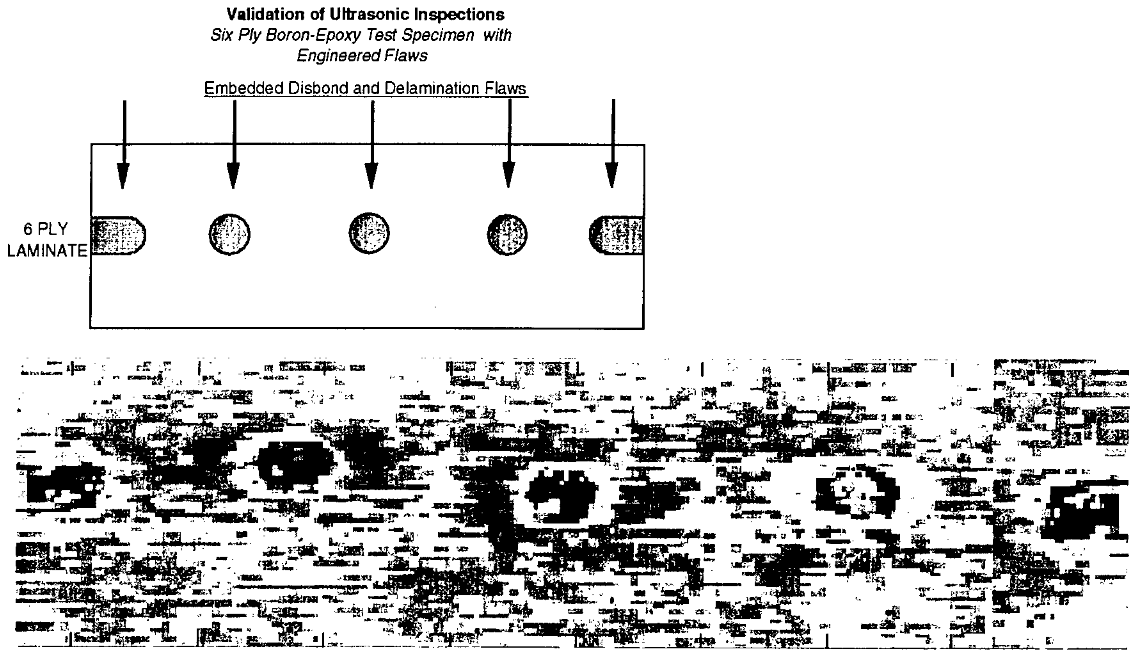


Figure 35: Pulse-Echo Ultrasonic C-Scan of 6 Ply Bonded Composite Doubler Specimen with Engineered Flaws

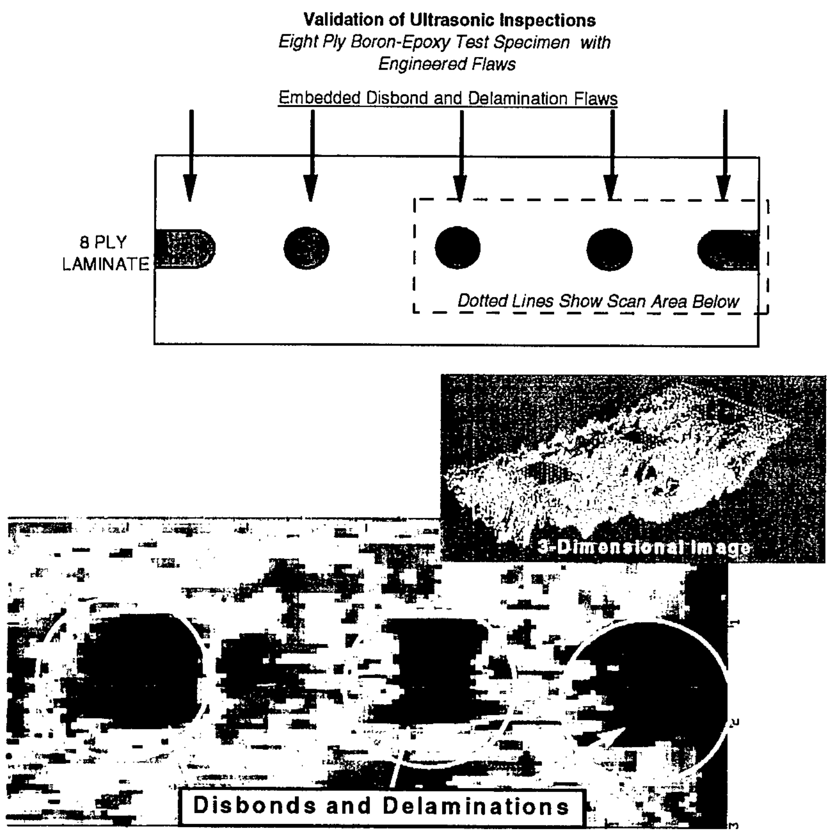


Figure 36: Pulse-Echo Ultrasonic C-Scan of 8 Ply Bonded Composite Doubler Specimen with Engineered Flaws

structure test article. Figure 40 contains a sample C-scan from an ultrasonic inspection of this composite doubler. Although no flaws were found in the L-1011 demonstration installation, it can be seen that a complete map of the composite doubler, which highlights any irregularities, can be obtained. Nonuniformities in the composite laminate and singular features, such as the Boron fibers, create color variations in the C-Scan. This demonstrates the sensitivity of the technique. The UT image in Figure 40 is from a uniform, full-thickness area on the doubler. Figure 41 contains a scan from a tapered region of the doubler. Once again, no flaws were found.

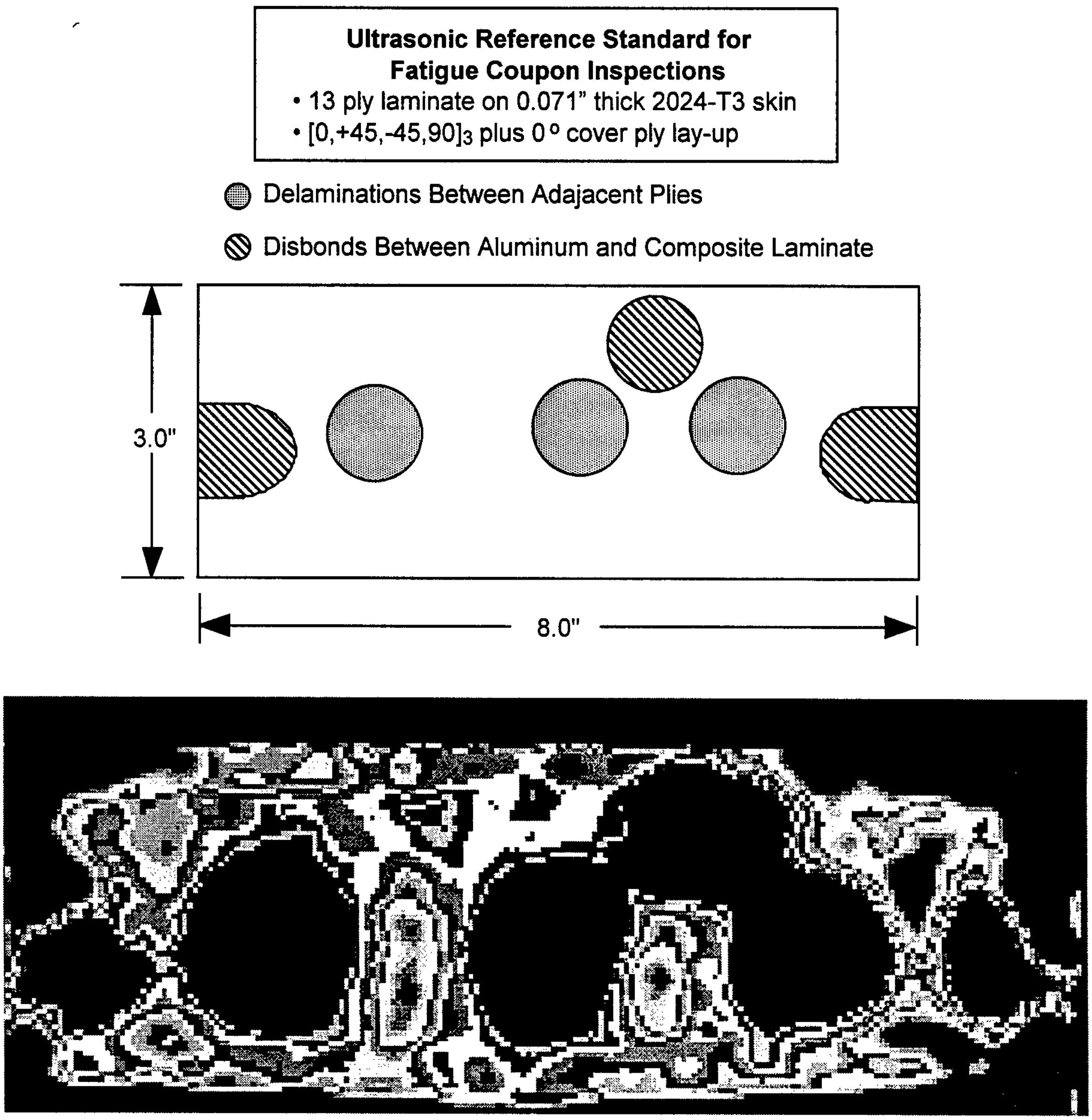


Figure 37: Pulse-Echo Ultrasonic C-Scan of 13 Ply Bonded Composite Doubler Specimen with Engineered Flaws

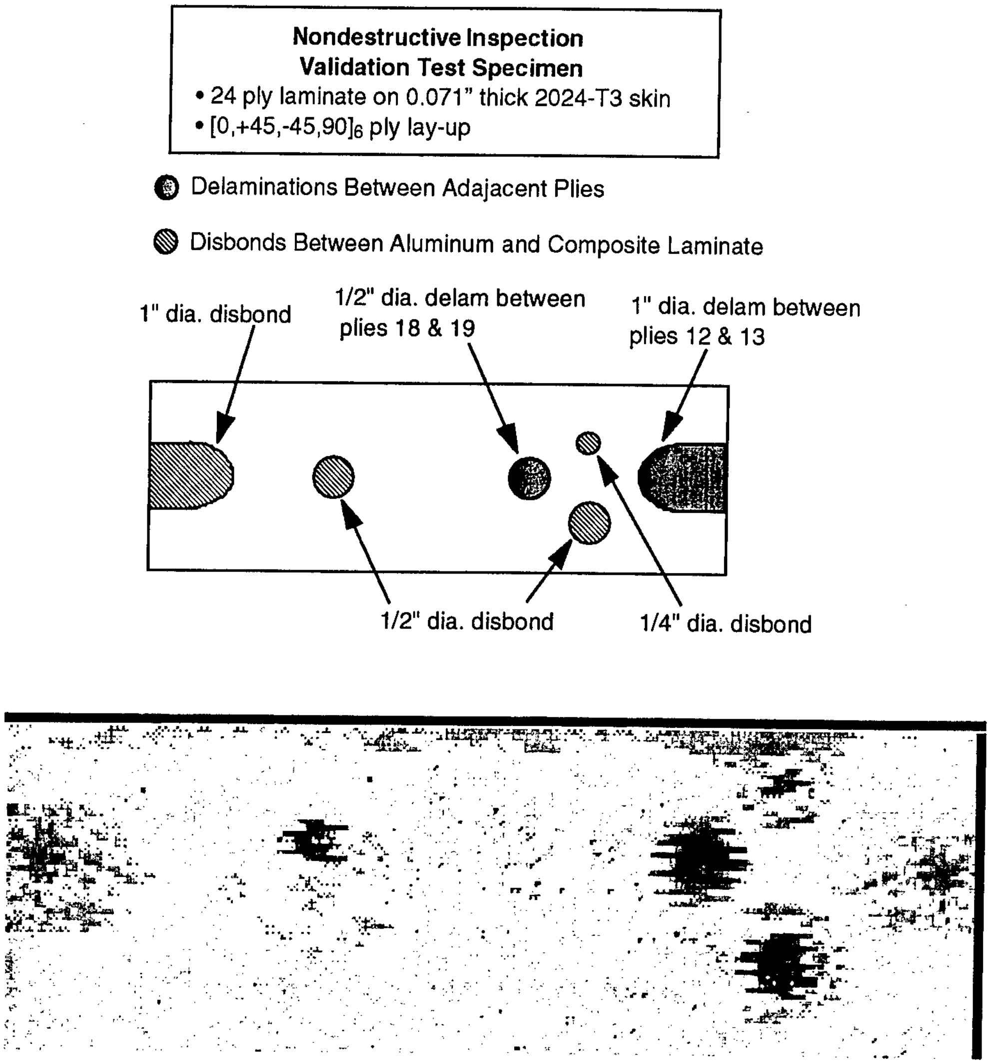


Figure 38: Pulse-Echo Ultrasonic C-Scan of 24 Ply Bonded Composite Doubler Specimen with Engineered Flaws

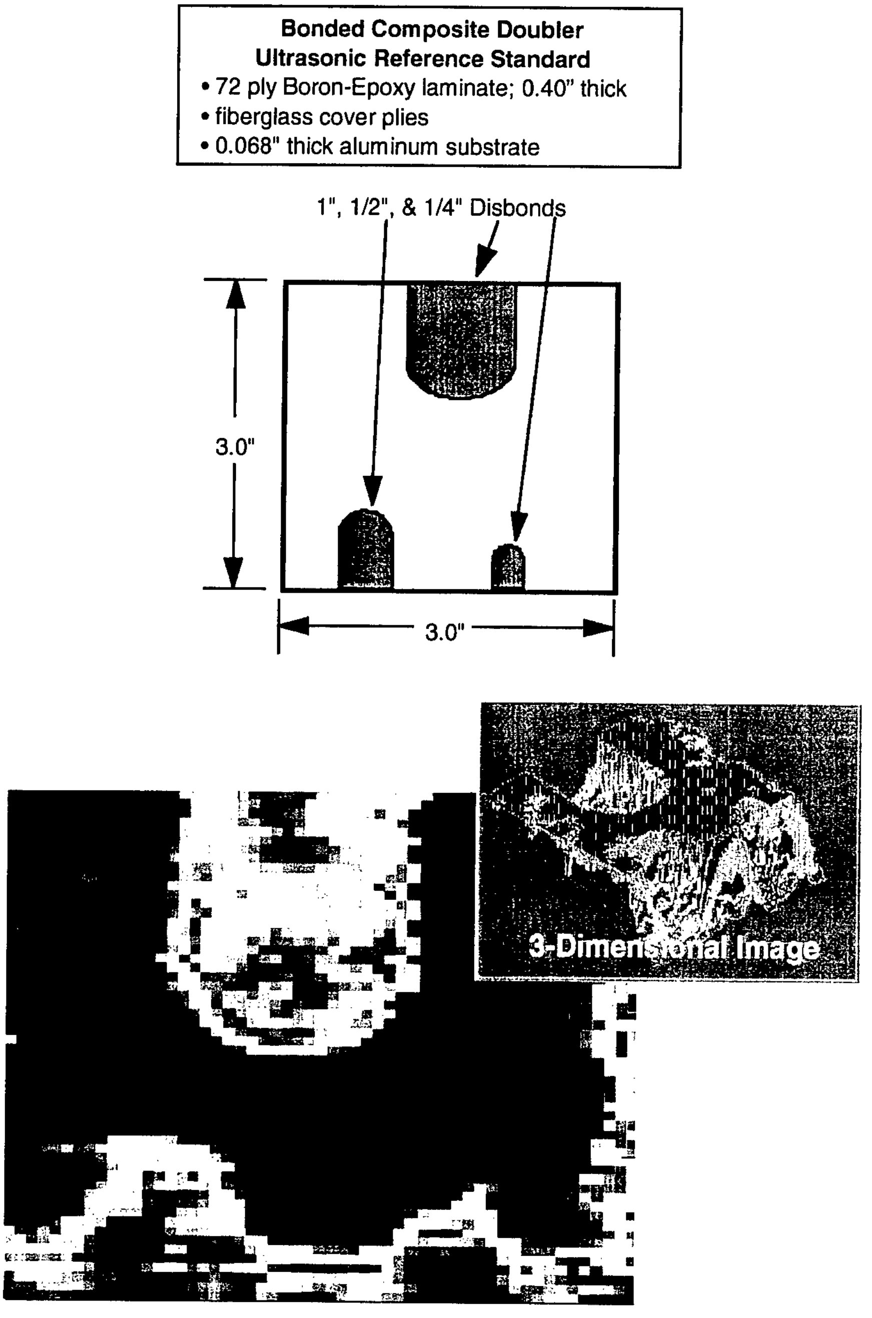
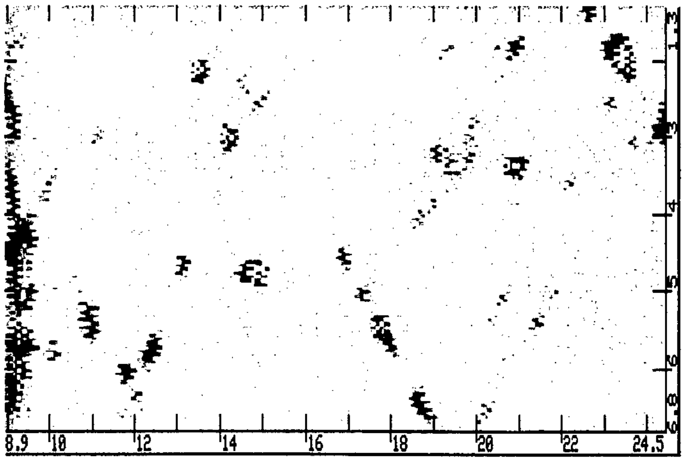


Figure 39: Pulse-Echo Ultrasonic C-Scan of 72 Ply Bonded Composite Doubler Specimen with Engineered Flaws



- No flaws (black signal loss areas) detected in full thickness region
- Color variations created by differences in signal strength (note: fiber directions are visible)

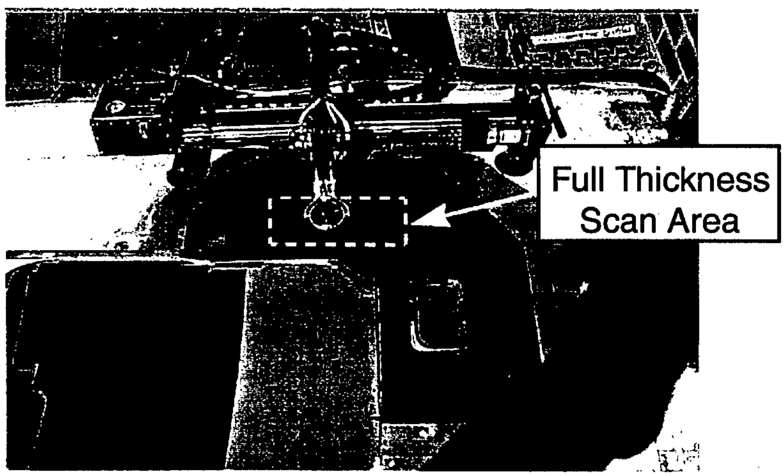


Figure 40: Pulse-Echo Ultrasonic C-Scan of Composite Doubler on L-1011 Fuselage Specimen - Constant Thickness Area Above the Door Cut-Out

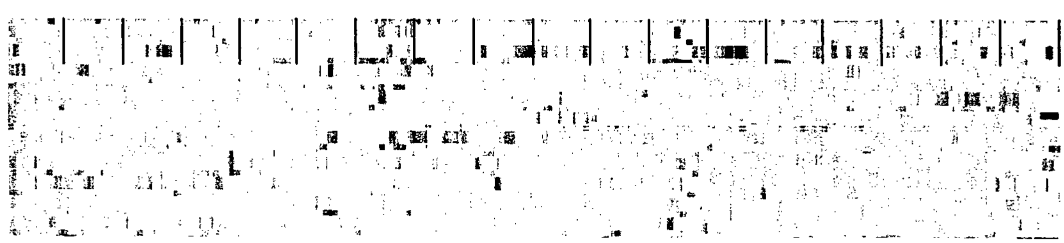


Figure 41: Pulse-Echo Ultrasonic C-Scan of Composite Doubler on L-1011 Fuselage Specimen - Tapered (Ply Drop-Off) Area at Outer Perimeter of Doubler

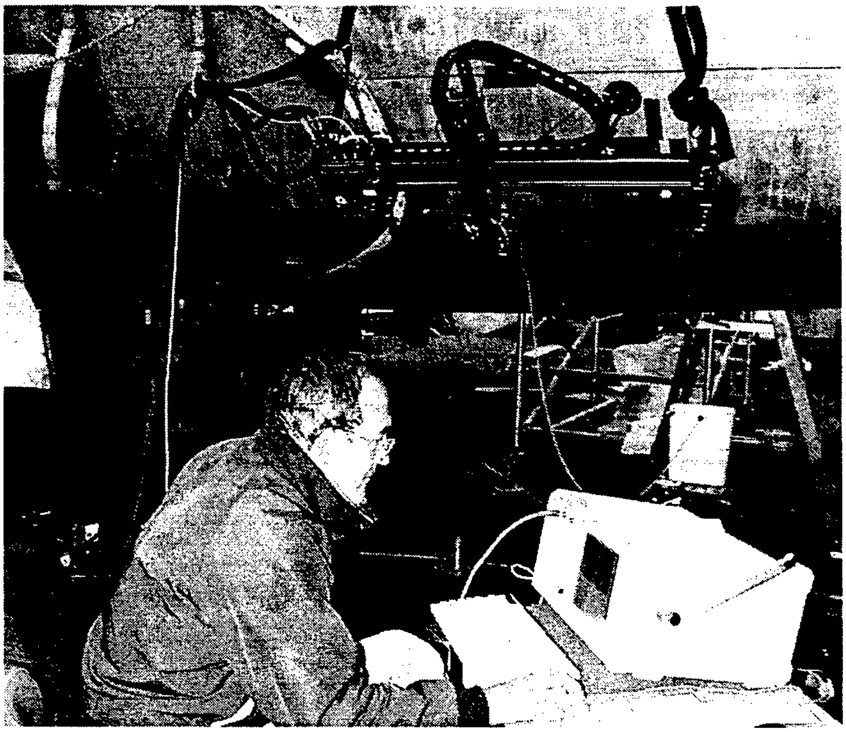
Ultrasonic Inspections on L-1011 Aircraft in Delta Fleet - In February, 1997, the door corner composite doubler was installed on an L-1011 aircraft operating in the Delta Air Lines fleet [22]. It was installed in lieu of the standard repair (as per SRM) of four, riveted metallic plates. The installation was considered a complete success by engineers from Lockheed, Delta, and the FAA and the aircraft was returned to its trans-Atlantic flight schedule. Three subsequent inspections have determined that the doubler is successfully operating without the initiation or growth of any flaws. The doubler was inspected using pulse-echo ultrasonics (UT), the Ultra Image scanner system, and the pulse-echo UT inspection procedure in reference [29]. Figure 10 shows the Ultra Image IV ultrasonic scanner system inspecting the composite doubler and a typical scan obtained during the doubler inspection is shown in Figure 11. The inspection did not reveal any flaws in the L-1011 doubler.

As per the doubler design specifications, in-service inspections took place following 45 days, six months, and one year of operation. The L-1011 (69,000 flight hours; 12,000 flight cycles) was brought in for an overnight check in April and August of 1997 and again in January of 1998. This close surveillance of the doubler allowed us to accumulate history regarding the doubler's long-term endurance under actual flight conditions. The inspections were successfully carried out during an overnight visit and the aircraft was returned to service the following morning.

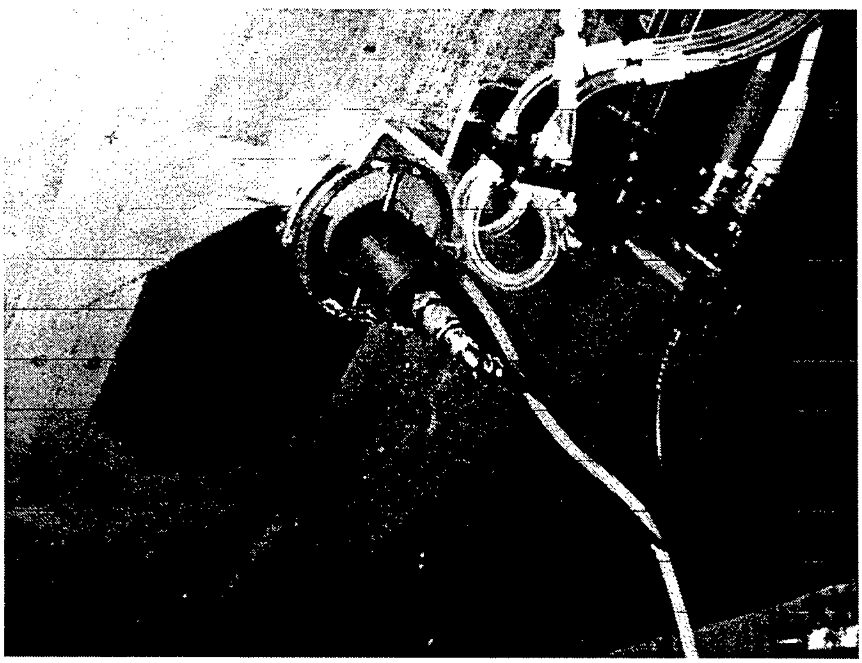
3. Evaluation of Technique on AANC 737 Test Bed (Composite Doubler with Engineered Flaws)

Ultra Image IV Device - Figure 42 shows an overall and close-up view of the Ultra Image scanner system being deployed on the 737 Transport Aircraft Testbed at the AANC hangar. It is inspecting an octagon shaped doubler that is six plies thick. Figure 43 is a schematic of the doubler revealing the size and location of the implanted flaws while Figure 44 shows the C-scan image produced by the Ultra Image scanner. In the gray-scale image, the flaws are shown as the brighter colored areas within the dark baseline. It can be seen that this inspection was able to detect flaws at a wide range of depths in a single image. Also, flaw imaging is most difficult at the edge of the doubler where the thickness is only one or two plies. This is because there is very little difference in UT transmission time between the front of a one ply doubler surface and the front of the aluminum surface beneath it. This makes it difficult, but still possible, to delineate differences which occur in this time frame.

Drippless Bubbler Device - Results from an inspection on the same 737 testbed doubler using the Dripless Bubbler device are shown in Figure 45. The inspections were performed using a ½" diameter, 2" focus, 15 MHz transducer. Again, all of the engineered flaws are visible and the disbond flaws around the thinnest portion of the doubler (tapered perimeter) are the most difficult to image.



(a) Overall View of Scanner Inspecting Fuselage Doubler



(b) Close-Up View of Transducer and Weeper System

Figure 42: Ultra Image Scanner System Deployed on AANC 737 Testbed

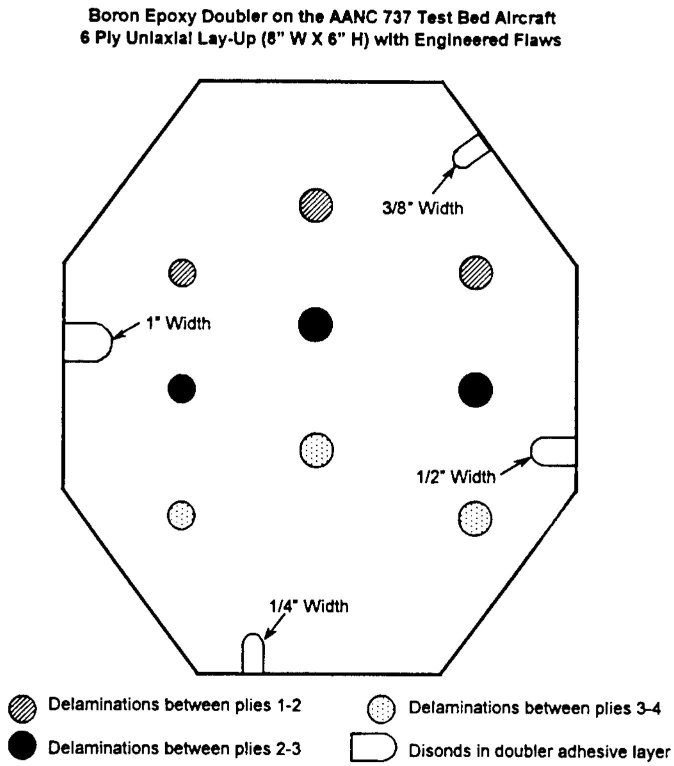


Figure 43: Schematic of 737 Testbed Doubler Showing Engineered Flaws

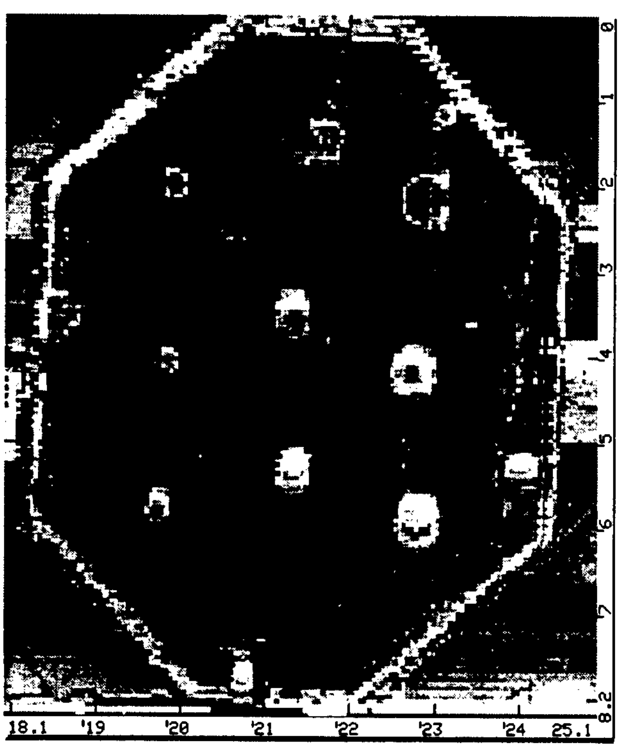


Figure 44: Gray-Scale C-Scan Image of 737 Doubler Produced by Ultra Image Device

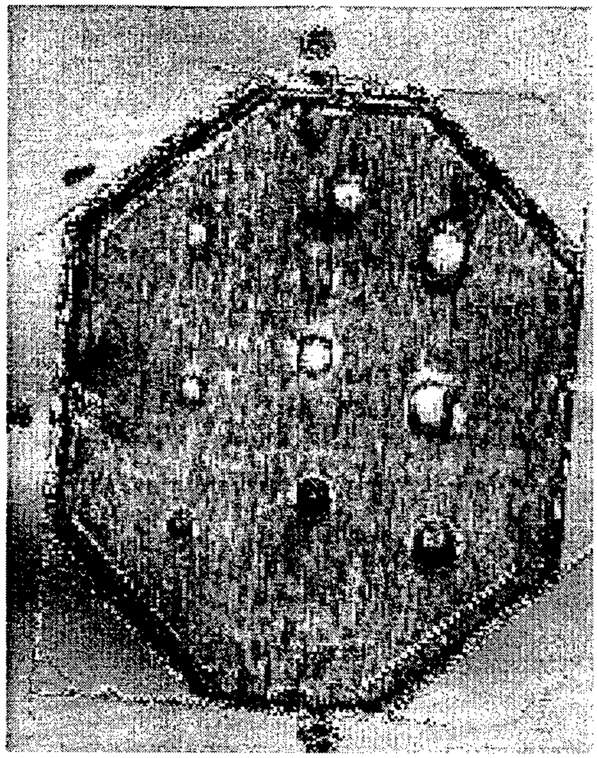


Figure 45: Gray-Scale C-Scan Image of 737 Doubler Produced by Dripless Bubbler Device

2.2 Through-Transmission Ultrasonics (TTU)

Background and Limitations - Through-transmission ultrasonics (TTU) passes a beam of sound energy through a component under test and, rather than interpreting the returned wave as pulse-echo UT does, it uses the signals which are transmitted through the test piece. The TTU method requires the use of two transducers, one transmitting the UT wave and one acting as a receiver. Figure 46 shows a schematic of a TTU ultrasonic inspection system. The transducers must be accurately aligned with each other on opposite sides of the component under test. Disbonds, delaminations, or porosity in the test piece will prevent all or part of the transmitted sound from reaching the receiver transducer. As in pulse-echo UT, the TTU inspection and data interpretation can be improved through the use of C-scan systems. The C-scan records the echoes from the internal structure of the composite doubler as a function of the position of each reflecting interface within the composite material boundaries. 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.

To perform an inspection using TTU, both sides of the test piece must be accessible. A water medium is used to provide the UT coupling. Inspections are performed with the test piece immersed in a water tank or positioned between water jets (UT squirter set-up).

When using the immersion method, the part and the transducers are submerged in water. The squirt method employs dynamic water columns that are squirted at the part while the transducers and the part are suspended (see Fig. 46). The transducers, which are not normally in contact with the inspection surface, are mounted on fixtures that automatically maintain alignment while scanning the entire test piece.

Because of the efficient UT coupling and the associated ability to optimize the amount of energy introduced to the test piece, automated, laboratory TTU immersion tanks or squirter systems are more accurate and sensitive than fieldable, hand scanning devices. The primary disadvantage is the need for parts to be removed from the aircraft in order to be inspected. 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. As a result, TTU was not deemed to be a viable inspection technique for composite doubler installations on aircraft. However, TTU is a very accurate NDI technique and was used primarily to establish a basis of comparison for other, more fieldable techniques. It was used in this project to evaluate basic UT phenomena and aid in the deployment of the pulse-echo UT scanner system.

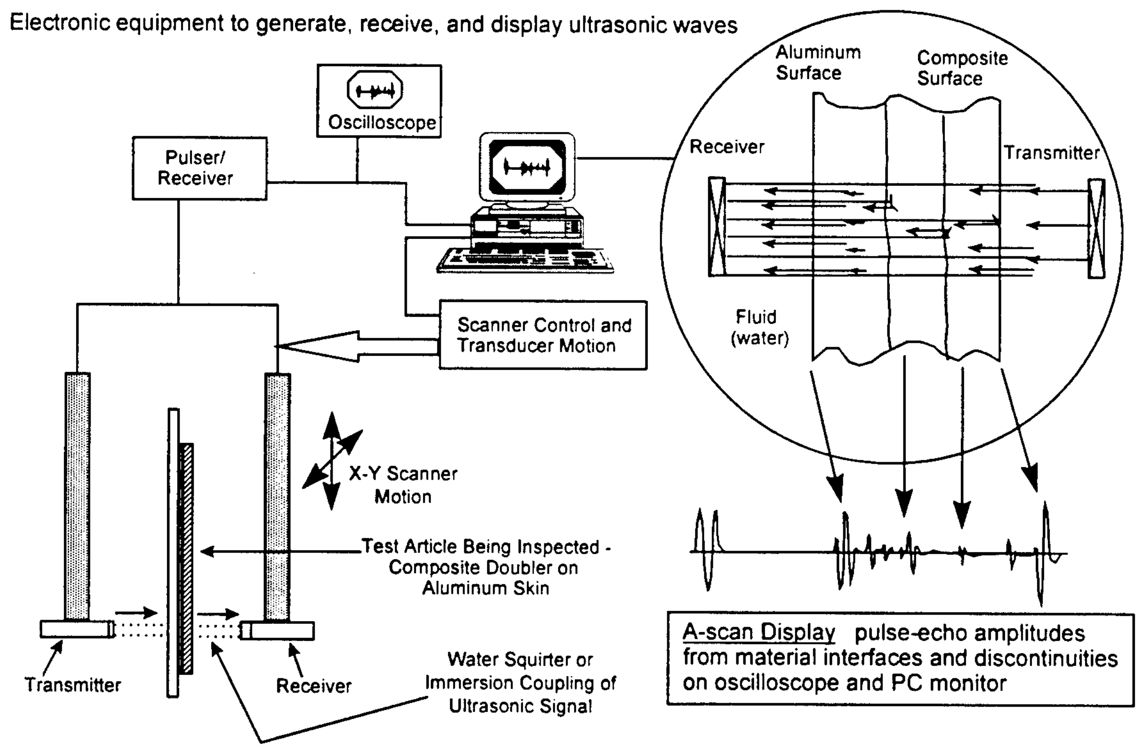


Figure 46: Thru-Transmission Ultrasonic Test Set-Up

TTU Composite Doubler Inspections - The damage tolerance fatigue coupons described in Section 1.4 and reference [20] were inspected using through-transmission ultrasonics. This provided an accurate assessment of flaw growth and a basis of comparison with conventional, fieldable NDI devices. This ultrasonic baseline used two 5 Mhz immersion transducers to produce a C-Scan image. Electronic gates, similar to those described above, were used during data collection, however, the primary information in TTU is the signal amplitude. Reference [39] provides related information on how ultrasonic TTU data can be presented and interpreted. Some results will be presented using one of the fatigue samples which included an unabated 0.5" long crack with a co-located 1" diameter disbond and 1" diameter disbonds in the edge of the doubler. Figure 17 shows a schematic of the test coupon and the locations of the engineered flaws. Figure 47 contains the C-scan results from the TTU inspection. Note the clear indication of the three 1" diameter disbonds. The validation testing revealed TTU resolution and sensitivity for flaws less than 1/4" in diameter.

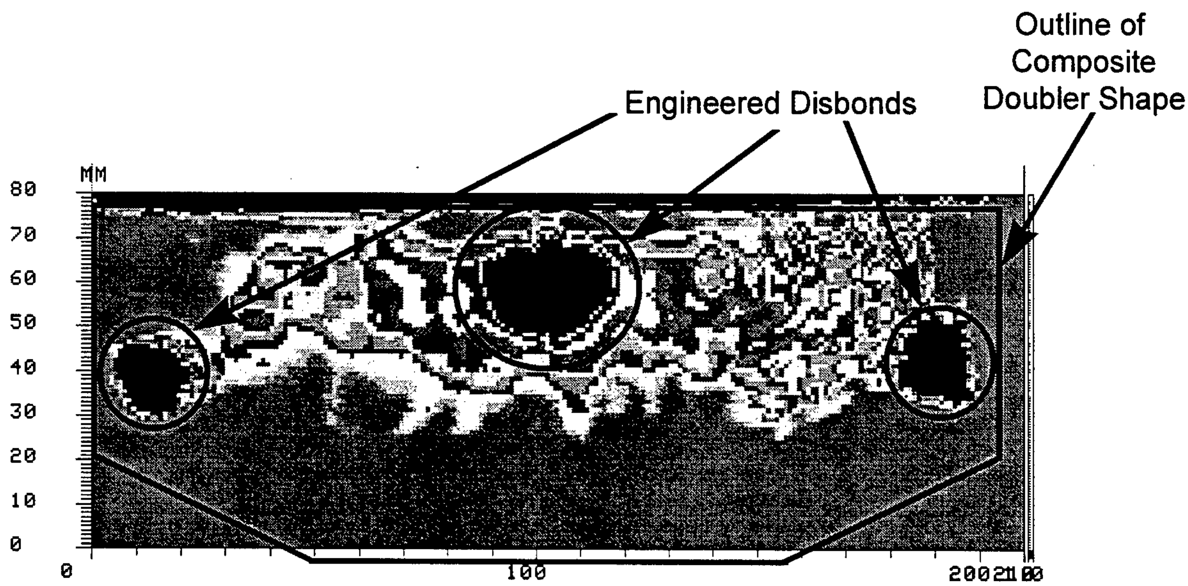


Figure 47: Thru-Transmission Ultrasonic Inspection Results of Composite Doubler Fatigue Specimen with Engineered Flaws

2.3 Resonance Test Inspection Method

General Operation - In high frequency bond testing (HFBT), often referred to as resonance testing, a transducer with a hard wear surface is acoustically coupled to the item under inspection using a liquid couplant. Inspection frequencies normally range from 25 to 500 kHz and are dependent on the thickness and type of material to be inspected. HFBT utilizes special narrow-bandwidth transducers, which, when coupled to the item under test, produce a continuous or standing UT wave in the material. The test material, in turn, has a damping effect on the transducer, increasing its bandwidth as well as changing its resonance frequency and signal amplitude. Anomalies, such as disbonds or delaminations in composite doublers, result in changes in the standing wave pattern of the material. These changes are detected as differences in ultrasonic or acoustic impedance at the surface of the material. It is these impedance changes that are monitored by the instrument and displayed in the form of amplitude/phase information on a meter or scope. HFBT has proved effective for inspecting multilayer metal and nonmetal laminates for the detection of disbonds as well as multi-ply composite structures for the detection of interply delaminations.

Resonance Inspection of Composite Doublers - In this study, high frequency ultrasonic resonant bond inspection was evaluated on the array of composite doubler test specimens. A Staveley Sonic Bondmaster instrument was used to perform the inspections. Figure 48 shows the Bondmaster being applied to the composite doubler fatigue coupons described in Section 1.4 and reference [20]. In this inspection, a narrow banded 0.5" diameter transducer was driven at its resonant frequency of 330 kHz. The transducer is placed on the composite doubler with the use of gel couplant. Reference [40] 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 on a calibration standard. The transducer is then moved to the composite doubler being inspected. Changes in the acoustic impedance of the transducer as it moves over a 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 affected by the relative size or 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 flawed and unflawed inspection sites.

Figure 49 shows some sample output from the Bondmaster device and how the screen plots are used to detect the presence of a flaw. Appendix B contains an inspection procedure for performing resonance mode inspections. Following is a brief summary of the high frequency bondtester inspection results on a composite doubler coupon 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. These signals did not exceed the alarm threshold so they were not classified as 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, however, to

accurately establish the presence and shape of the engineered disbond flaws over the duration of the fatigue tests using the resonance inspection technique.

Figure 48: Resonance Mode Inspection (Staveley Bondmaster Device) of Composite Doubler on Fatigue Coupon

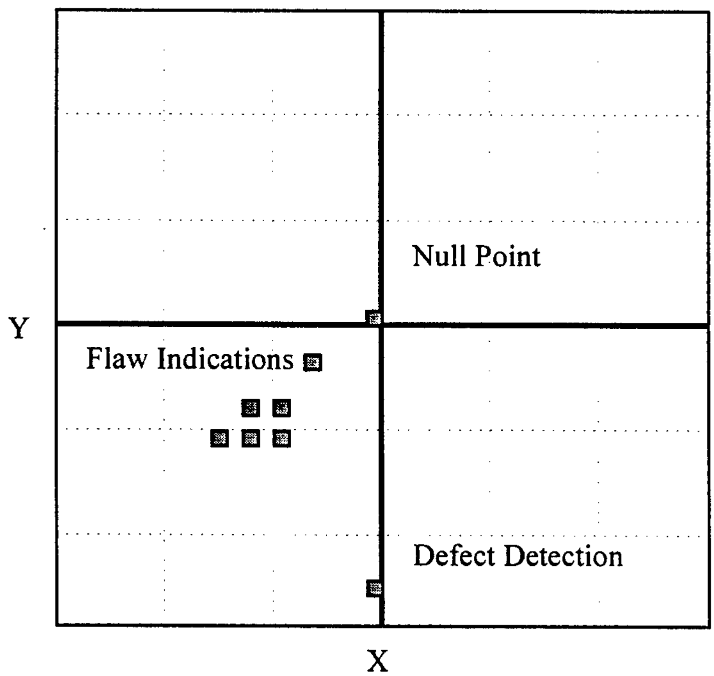


Figure 49: Representative Bondtester Output for Disbond and Delamination Inspections on 13 Ply Fatigue Coupons

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. Growth in the cohesive failure area matched the propagation of the aluminum crack. Using the resonance inspection technique, it was possible to monitor the changing boundaries of this adhesive fracture "strip" as the crack grew in length.

<u>Limitations and Difficulties Associated With HFBT</u> - As with other contact UT methods, the inspection surface must be relatively smooth to allow adequate acoustic coupling. This fact, combined with the need for a liquid couplant, can sometimes limit the application of HFBT and make large area inspections somewhat tedious. On painted surfaces, poor paint adhesion can increase the overall acoustic impedance of the structure and may cause erroneous indications. When inspecting relatively thick, multi-ply composite doublers, detection of delaminations in the bottom few plies can be difficult. This is due to the relatively small change in total material impedance seen by the probe. The use of well characterized calibration standards is essential to properly set-up the resonant UT device [41]. 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 0.115" thick (approximately 20 plies). In regions above this thickness, changes in the signal amplitude and phase occurred even during inspections of unflawed portions of the doubler. The signals at a single point continuously fluctuated from "unflawed" to "flawed" indications, thus, it was difficult to clearly interpret the readings. Additional experimentation may be able to alleviate these difficulties and expand the useable range of HFBT inspections.

2.4 Thermography

Thermography is a nondestructive inspection method that uses thermal gradients to analyze physical characteristics of a structure, such as internal defects. This is done by converting a thermal gradient into a visible image using a thermally sensitive detector such as an infrared camera or thermally sensitive film materials.

The temperature distribution on an aircraft skin or component can be measured optically by the radiation that it produces at infrared wavelengths. Many defects affect the thermal properties of materials. Examples are corrosion, disbonds, cracks, impact damage, panel thinning, and fluid ingress into composite or honeycomb materials. By the judicious application of external heat sources, these common aircraft defects can be detected by an appropriate infrared survey. Several organizations have demonstrated infrared structural inspection techniques on aircraft in field tests at maintenance facilities [42-46]. The Air Force is currently integrating thermography into the inspection of composite structures on its C-130, C-141, and F-15 aircraft. The applications include both composite honeycomb and bonded composite doubler structures. In the commercial aircraft arena, validation efforts are underway to certify thermography for select tear strap disbond and skin corrosion detection applications. In the AANC composite doubler study, a turn-key thermography inspection system developed at Wayne State University - the Thermal Wave Imager - was used to assess the merits of thermography to detect disbonds and delaminations in composite doublers. The discussion and results which follow pertain to the Thermal Wave Imager (TWI) system.

Thermal wave imaging is accomplished using high-power flash lamps, an infrared (IR) video camera, and image processing hardware and software, all of which are controlled by a personal computer. A schematic diagram of such a system is given in Figure 50. The flashlamps put out a short, high-power pulse of light, which raises the surface temperature of the aircraft approximately ten degrees when it is absorbed by the surface.

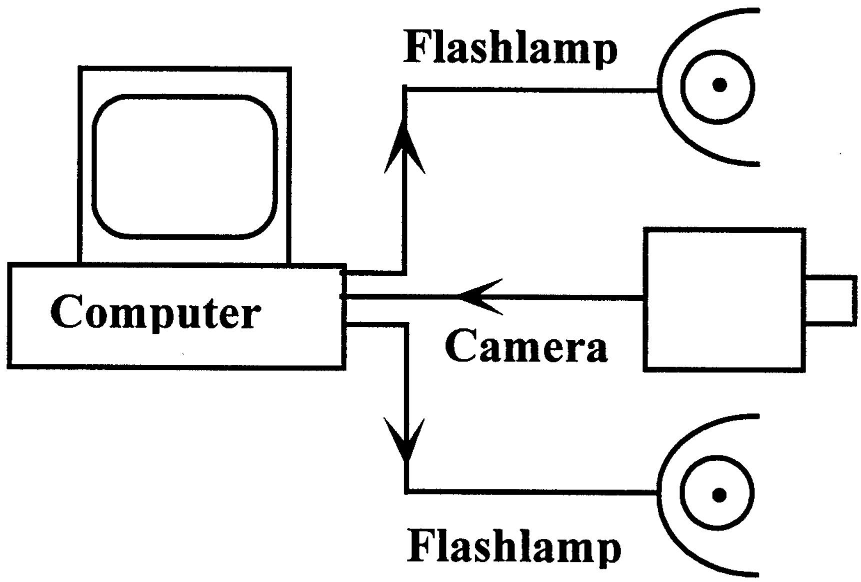
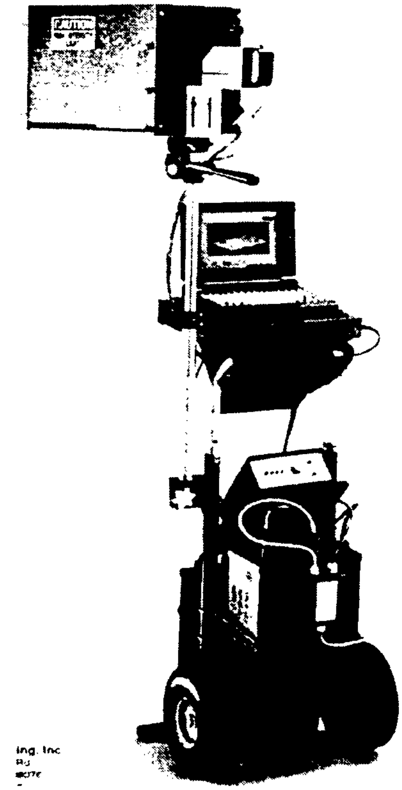


Figure 50: Schematic Diagram Of The Pulse-Echo Thermal Wave Infrared Imaging System

This temperature pulse propagates into the material as a thermal wave and gets reflected by any defects which may be present in the material. After a time delay determined by the depth of the defect, these thermal waves reflect and affect the temperature distribution on the aircraft surface. The resulting temperature distribution is then recorded by the IR camera and displayed on the computer monitor. In practice, the computer actually obtains several images at progressively later times after each flash. This method is particularly useful for imaging and determining the depths of disbonds and delaminations in Boron-Epoxy repair doublers on aircraft structures. A photograph of the Thermal Wave Imaging System being applied to an aircraft inspection is shown in Figure 51.



(a) Close-Up View of TWI Equipment

(b) Application of Thermography on 747 Aircraft

Figure 51: Thermal Wave Imaging System Inspecting an Aircraft

Results from Composite Doubler Inspections - Following are results obtained from Thermal Wave Imaging inspections on composite doubler installations which contain engineered flaws. Figure 17 shows a schematic of a composite doubler installed on an aluminum fatigue coupon. The schematic shows the disbond and crack flaws that were placed in the aluminum skin and composite doubler installation. The series of images produced at different times during the TWI inspection of this test specimen are shown in Figure 52.

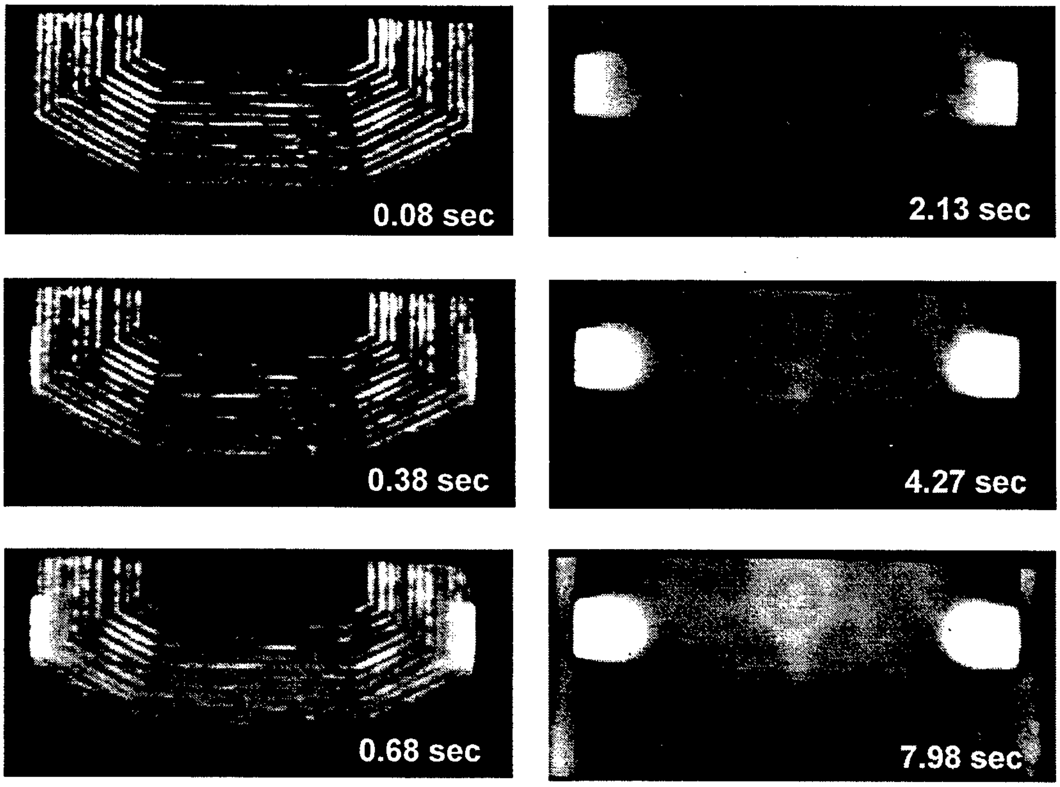


Figure 52: Sequence of Thermal Wave Images of Composite Doubler on Coupon BE-3

The early time images following the flash clearly resolve the ply drop-off at the edges of the 13 ply composite patch. Beginning at around 0.68 sec, intentionally placed disbonds between the patch and the aluminum at the left and right edges (where the patch is thinnest) begin to appear. As time progresses, these disbonds begin to show in thicker and thicker layers of the patch. Between 4 and 8 seconds it is possible to see the circular disbond which was implanted over the crack tip and a "tail" extending downward along the induced fatigue crack. The circular disbond is located 13 plies deep in the doubler installation. The disbond tail is also located between the 13 ply doubler and the aluminum skin and is associated with a cohesive fracture of the adhesive layer immediately adjacent to the crack growth.

TWI was applied to a Boron-Epoxy doubler which was installed on a DC-9 fuselage section in the AANC hangar. Figure 53 shows a schematic of the 10 ply doubler installation which identifies the size, shape, and location of the embedded flaws. The resultant sequence of images produced by a TWI inspection are shown in Figure 54.

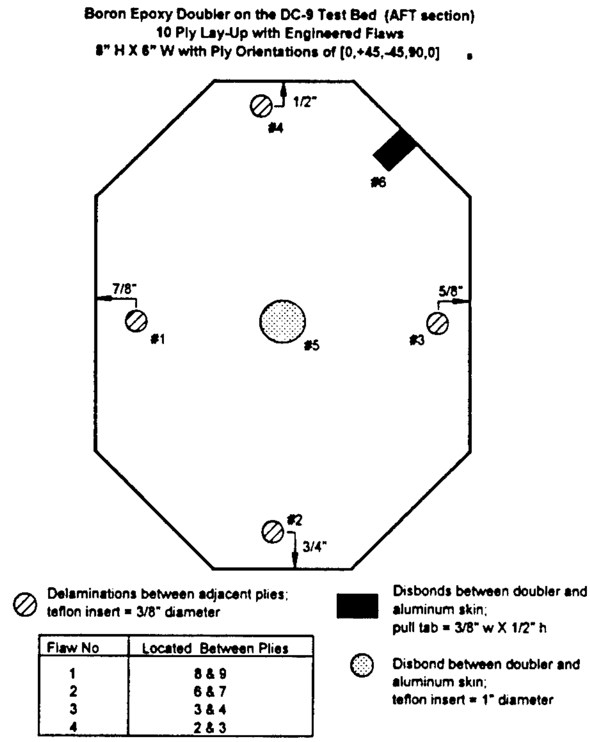
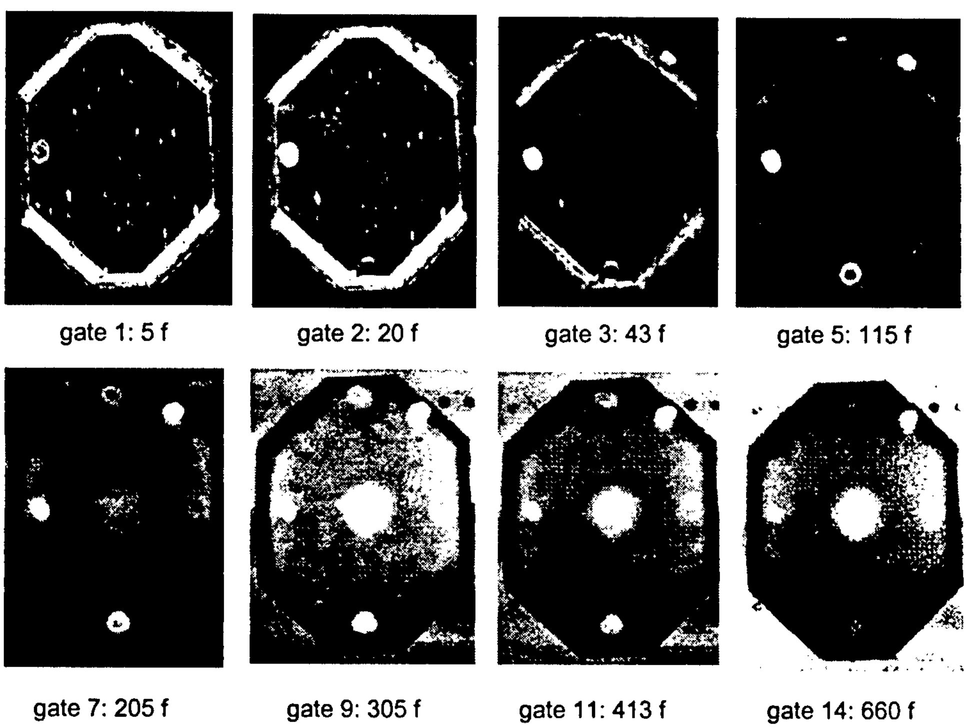


Figure 53: Composite Doubler Installation on DC-9 Testbed



frame time ("f") = 1/60 of a second

Figure 54: Sequence of Thermal Wave Images from DC-9 Composite Doubler Inspection

The features seen at early times are defects closest to the outside surface of the patch (note appearance of flaws #1 and #2 in the first few frames). The disbonds, located at the base of the 10 ply doubler, and the deeper delaminations appear in the later frames corresponding to their delayed effect on the thermal field. All six embedded flaws were identified in the TWI images and flaws smaller than 0.5" in diameter could be detected. Another item of note is that the flaws around the perimeter of the doubler, at its thinnest region, are clearly imaged and do not induce the imaging difficulties observed in the UT C-scan results.

Advantages of Thermography -

1. thermography can be performed without physical contact with the surface
2. single images can include relatively large areas (1-2 ft^2) allowing for rapid inspections of large surface areas
3. two-dimensional image of the inspected surface helps the operator visualize the location and extent of any defect
4. electronic recording of the image data allows for more thorough data analysis while other maintenance activities are being performed in the inspection area
5. coats of paint are not an obstacle, however, their presence must be taken into consideration
6. nonmetallic materials can be inspected more easily than metals because of a difference in thermal properties.

Disadvantages of Thermography -

1. it is often necessary to apply a high-emissivity coating during inspections to obtain an acceptable image; steps have been taken to minimize the labor time associated with this task
2. damage to layers deep within a structure is more difficult to detect than damage in surface layers because the larger mass of material tends to dissipate the applied heat energy; preliminary experiments have shown that TWI can inspect doublers up to 40 or 50 plies (0.25" to 0.30") thick
3. image interpretation requires an understanding of the physics of thermography and may require a high level of operator expertise; sophisticated data analysis and presentation software has minimized this dependency on in-depth expertise in thermography physics.

During the course of this composite doubler development effort, thermography was applied to over a dozen different doubler installations. The two examples above highlight the viability of thermography for inspecting bonded composite doublers. However, more comprehensive and structured tests need to be performed to better determine the sensitivity and resolution of thermography in detecting composite doubler disbonds, delaminations, and porosity. Furthermore, tests must be conducted to ascertain the effects of a host of inspection impediments (e.g. underlying structure, doubler protective coatings) on the overall probability of flaw detection. The Airworthiness

Assurance Center at Sandia National Labs is conducting tests of this nature to apply thermography inspections to aircraft maintained by Warner Robins Air Force Base [47].

3.0 Inspections for Cracks in Parent Material Beneath Composite Doublers

3.1 Challenges in Crack Monitoring

In addition to the normal difficulties associated with crack detection in aircraft structures, the added complexity of inspecting through a composite doubler to assess the aluminum structure beneath introduces new impediments. The two NDT inspection techniques commonly used for crack detection were assessed in this study: eddy current and X-ray.

Eddy Current (EC) - External surface inspections which may key off visible attributes such as rivet head locations (normal origin of fatigue cracks) must now be performed blind since the doubler covers the aluminum surface. Mylar maps of the doubler area, which include rivet and substructure element locations, can alleviate this difficulty and minimize false calls. Although the doubler does not interrupt an eddy current signal it does create a lift-off effect which reduces the signal strength. Lower frequency probes can be used to produce a greater depth of EC penetration, however, this is accompanied by a loss in sensitivity versus higher frequency probes. Thus, the thicker the doubler, the greater reduction in crack detection sensitivity. This problem is compounded in the case of subsurface crack detection where the surface aluminum layer and the doubler combine for even greater lift-off effects. Cover plies, especially those with conductive materials such as wire mesh lightning protection plies, may distort the EC signal and make the interpretation of output signals difficult. Finally, if a doubler edge runs in the same direction and occurs in the same vicinity of a crack it may corrupt the EC signal and make detection difficult. Composite doublers, however, do not normally have an edge along areas with the potential to develop cracks so this edge effect will rarely be encountered.

X-ray - The X-ray tests performed in this study determined that there are no additional impediments brought on by the presence of composite doublers. X-ray inspections were able to achieve high levels of resolution when inspecting through thick composite doublers and the films were very comparable with films acquired on similar structures without doublers. All difficulties associated with X-ray inspections - shadowing from substructure elements, accessibility, and safety issues - are the same as in structures without composite doublers.

3.2 Eddy Current Inspections

Eddy Current (EC) inspection uses the principles of electromagnetic induction to identify or differentiate structural conditions in conductive metals [39, 48]. In this study, 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.

When EC inspections are performed, an electrically conductive material is exposed to an alternating magnetic field that is generated by a coil of wire carrying an alternating current. As a result, eddy currents are induced on and below the surface of the material (see Figure 55). These eddy currents, in turn, generate their own magnetic field which opposes the magnetic field of the test coil. Cracks or thickness changes in the structure being inspected influence the flow of eddy currents and change the impedance of the test coil accordingly. EC instruments record these impedance changes and display them in impedance plane plots to aid the flaw detection process.

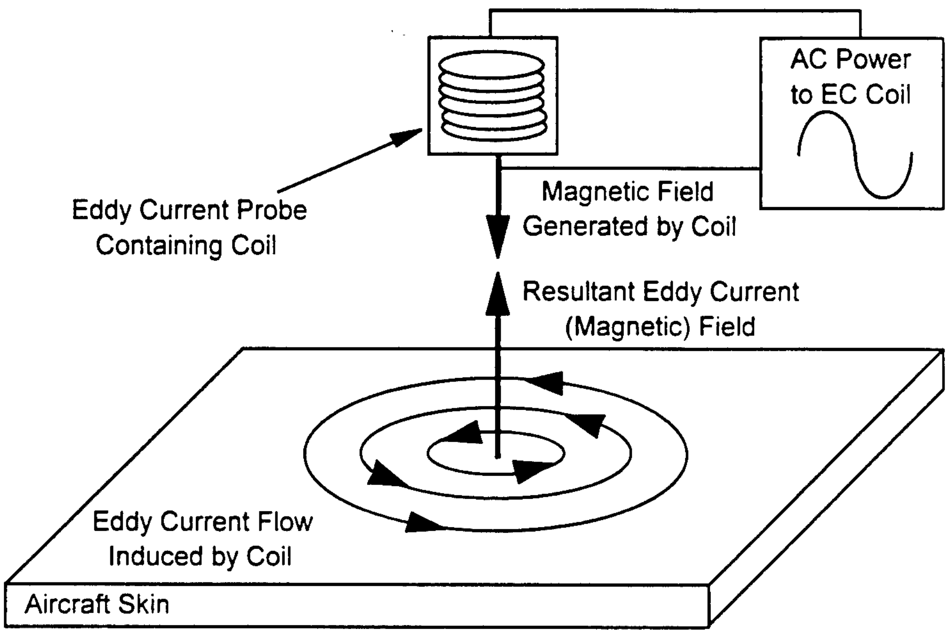


Figure 55: Induction of Eddy Currents in Conductive Materials

The depth of penetration of eddy currents is inversely proportional to the product of magnetic permeability, electrical conductivity, and frequency of the inducing currents. Therefore, eddy current tests are most sensitive to discontinuities on the surface next to the coil, which makes them very effective for detecting fatigue cracks in the near surface. High frequency eddy current (HFEC) is generally considered 100 kHz and above and is used to detect near-surface flaws. Low frequency eddy current (LFEC) is in the 100 Hz to 10 kHz range and is used to penetrate deeper to detect flaws in underlying structure. The thicker the structure to be penetrated, the lower the EC operating frequency that is required. However, the detectable flaw size usually becomes larger as the frequency is lowered. Eddy currents deeper in the material are weaker and lag in phase compared to the currents near the surface. By measuring the phase, it is possible to determine whether the defect is near the surface or at the inner wall. Figure 56 shows an example of an impedance plane display showing phase and amplitudes of EC signals generated by cracks of varying depths.

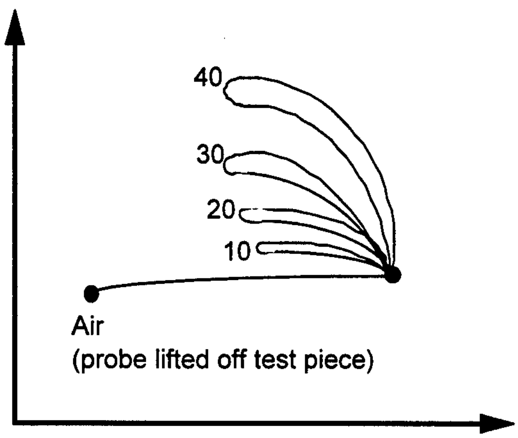


Figure 56: Impedance Plane Display Showing Signal Traces for Surface Cracks of 10, 20, 30, and 40 Mils in Depth

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. As noted above, these lower frequency inspections 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.

3.2.1 Sensitivity Assessment

As discussed earlier in this document, composite doublers are designed to reduce stress concentrations and mitigate crack growth. However, inspection techniques must evaluate the success of each composite doubler in achieving this goal. This ensures the continued structural integrity of the repaired structure. Reference [49] describes a successful demonstration of the viability of EC inspections to detect aluminum skin cracks through composite doublers made from GLARE material. The difficulties described above regarding EC inspections through composite doublers were encountered. However, LFEC inspections were able to detect cracks in the parent skin (7079-T6 material) and the EC indications were similar to the ones obtained before the doubler was installed.

In order to adequately address the damage tolerance needs, these EC viability demonstrations must be expanded into more focused testing to assess sensitivity and reliability issues. Structured EC testing was performed in this study in an attempt to quantify EC performance through composite doublers. Both sliding and surface (pencil) probes were used in this inspection series. The sliding probe is best suited for these type of inspections and have the lower frequencies needed to penetrate the doubler layer. Figure 57 shows the Staveley 19e2 eddy current device being applied to one of the composite doubler fatigue coupon specimens (see Fig. 17). A 30 kHz pencil probe was able to reliably detect the crack tip - which was changing during the course of the fatigue testing - through a 13 ply doubler. Eddy current and microscopic inspections on the back side of the specimen (non doubler side) confirmed the accuracy of the EC inspections through the doubler. The reference [50] eddy current inspection procedure was prepared to guide the application of EC to composite doublers. This procedure is also provided in Appendix C of this report.

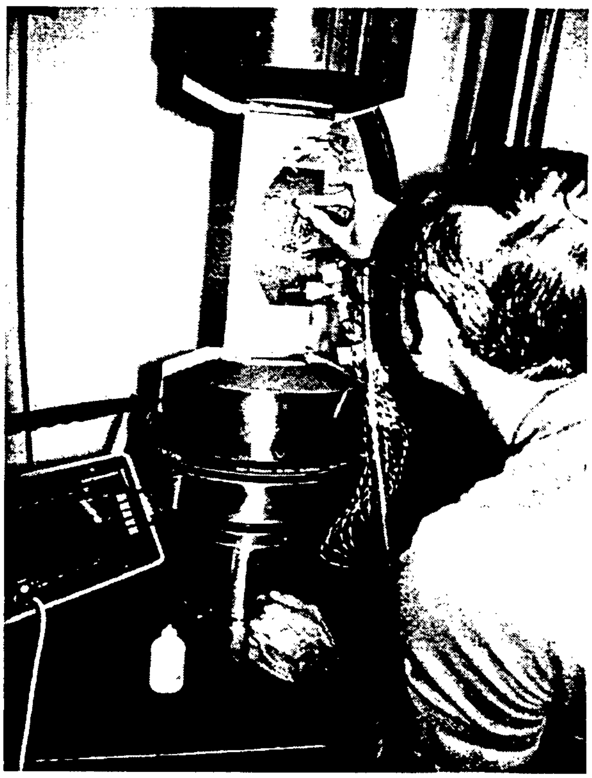


Figure 57: Application of Eddy Current Equipment to Detect Cracks Beneath Composite Doublers

Another test series utilized an array of 1st layer and 2nd layer crack specimens with both EDM notch and fatigue-induced cracks. Structural configurations included lap splices, butt splices, and finger doubler joints. A step wedge composite doubler was placed over each test specimen and EC inspections were performed through various thicknesses of the

Boron-Epoxy laminate (step thicknesses = 0.016", 0.031", 0.093", 0.143", 0.205", 0.251", 0.307", 0.361", and 0.470"). The laminate thickness were sequentially increased until the crack fell below the level of EC detectability.

Figure 58 shows representative EC signals from cracked structure located beneath Boron-Epoxy doublers. 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 composite doubler specimens with cracks in the parent aluminum skin established the following general 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 (2nd layer) crack can be detected through a 0.310" thick doubler and a 0.040" thick surface plate.

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. If the copper mesh is not present in the installation the results presented above indicate that acceptable crack detection can be obtained through doublers in excess of 40 plies thick (also see Section 3.2.2).

3.2.2 Probability of Crack Detection

The limits of crack detection listed above were not arrived at in a blind manner. That is, the operator knew the locations of the cracks and made a judgment call as to whether the variation in EC signal was sufficient to justify a flaw call. True flaw detection performance must be measured through blind experiments where the inspector must make flaw calls from an assortment of cracked and uncracked rivet sites. The specimen set must be statistically relevant and provide: 1) opportunities for flaw calls over the full range of applicable crack lengths, and 2) sufficient unflawed sites to assess the Probability of False Alarm (PoFA). In order to make a valid measurement of the flaw detection capabilities of EC inspections through composite doublers a structured Probability of Detection (PoD) study was performed.

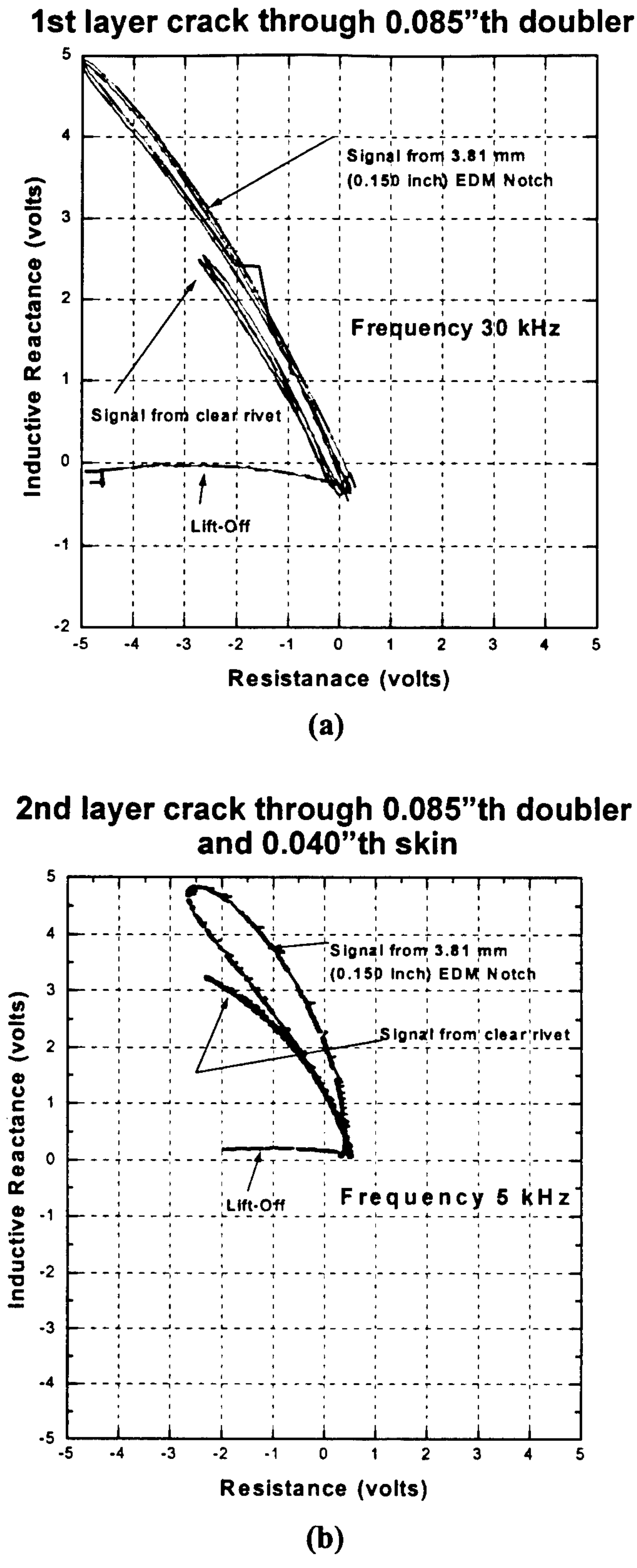


Figure 58: EC signal for a) 1st layer crack through 0.085" thick doubler and b) 2nd layer crack through 0.085" thick doubler and 0.040" thick skin

The PoD study utilized a series of surface crack and subsurface crack aircraft panels. These panels, which mimic a Boeing lap splice joint, contain an assortment of fatigue cracks with specific lengths which were carefully engineered in the upper or lower skins [51]. The primary use of these panels is in the quantitative evaluation of conventional and advanced NDI techniques (Probability of Detection studies). To determine the limits of crack detectability through composite doublers of various thicknesses, the composite laminate step wedge described above was superimposed over the lap splice crack panels as shown in Figure 59. In these specimens, the cracks were located in the upper rivet row of the outer skin (i.e. surface cracks).

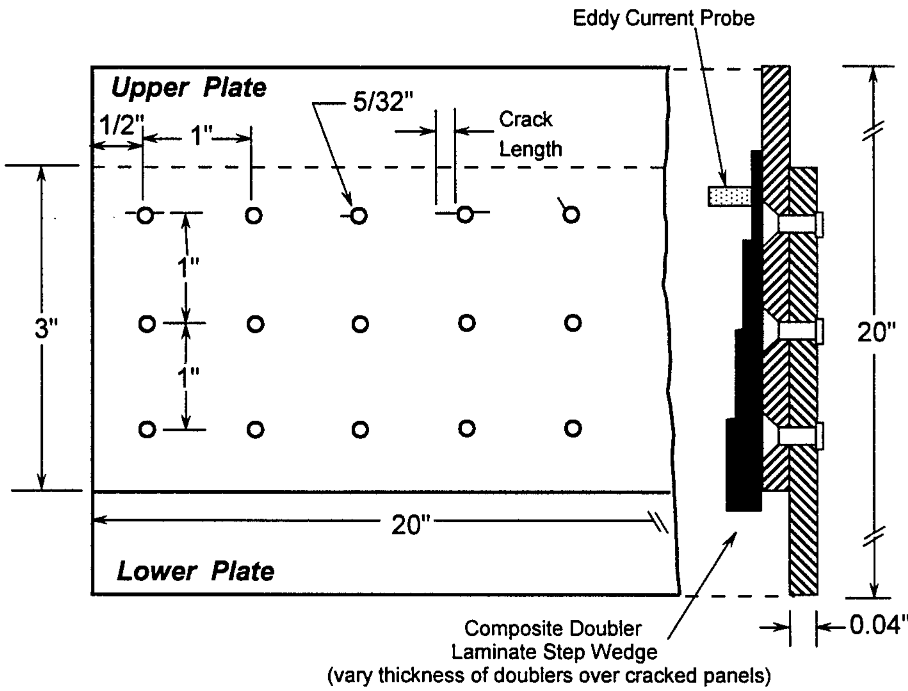


Figure 59: Test Set-Up for Detection of Surface Cracks Through Composite Doublers

Surface Crack PoD - The suite of 18 lap splice panels were inspected through the following four laminate thicknesses: 1) 0.031" th. (5 plies), 2) 0.085" th. (15 plies), 3) 0.143" th. (25 plies), and 4) 0.199" th. (35 plies). Figure 6 shows the resulting PoD curves which were generated from the inspections on surface crack panels. It can be seen that all cracks of 0.17" length and greater were found regardless of the thickness of the composite doubler. Also, the family of curves follow the trend presented in the Section 1.4 discussion on probability detection where the PoD performance diminishes with increasingly difficult circumstances (see Fig. 16). In this case, as the doubler becomes thicker the PoD drops off slightly. These results are quite good in light of the damage tolerance requirement to find fatigue cracks beneath doublers before they reach 1" in length. The EC detection capabilities corresponding to the standard 95% PoD goal are summarized in Table 2.

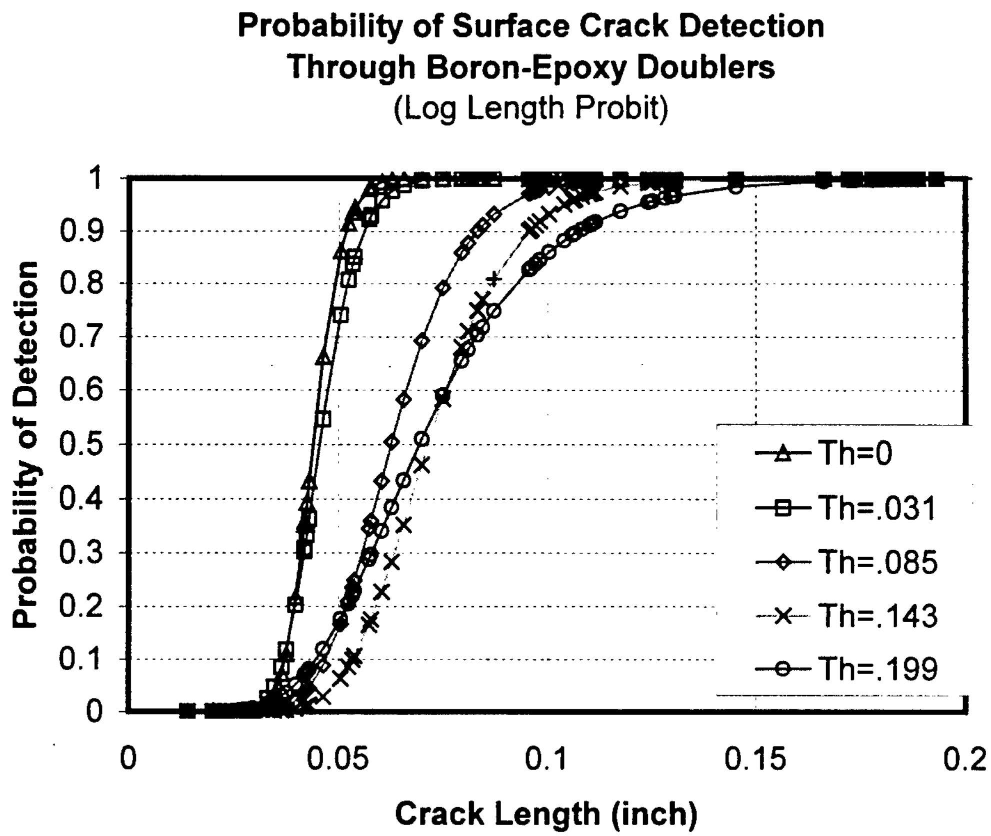


Figure 60: Probability of Detection Curves for Eddy Current Surface Crack Inspections Through Different Thicknesses of Composite Doublers

Composite Doubler Thickness (Number of Plies)	Surface Crack Length at 95% Probability of Detection Threshold
No Doubler (0 plies)	0.053"
0.031" (5)	0.059"
0.085" (15)	0.091"
0.143" (25)	0.103"
0.199" (35)	0.121"

Table 2: Eddy Current Surface Crack Detection Performance Through Bonded Composite Doublers

The surface crack probability of detection experiment used eighteen aircraft panels with a total of 360 rivet inspection sites (upper row of lap splice outer skin only). Since 81 of these inspection sites were cracked, there were 279 opportunities for false calls. Two false calls were made on the panels which were inspected without a composite doubler (0.7%) while no false calls were recorded during any of the inspections through the various composite doublers. Overall, it can be said that the false call rate for inspections through composite doublers in the 5 to 35 ply regime is less than 1%. It should be noted that the above results pertain to a single ASNT level II inspector's findings. While the quantitative results are certainly valid, additional inspections, performed by other aircraft certified inspectors, are needed to draw final PoD conclusions.

Interlayer (Third Layer) Crack PoD - A second PoD study was performed to assess eddy current crack detection of subsurface cracks through composite doublers. The subsurface crack test panels were also lap splice joints with two different skin thickness sets: 1) top plate, bonded doubler, and bottom plate were all 0.40" thick, and 2) top plate, bonded doubler, and bottom plate were all 0.36" thick. Figure 61 shows the lap spice configuration where the cracks are in the lower row of the inner skin (third layer). The major difference between these specimens and the surface crack panels shown in figure 59 is the presence of the bonded aluminum doubler between the upper and lower skins. Thus, this experiment challenged eddy current inspections to detect third layer cracks through either 0.80" thick material (2 layers of 0.40" thick each) or 0.72" thick material (2 layers of 0.36" thick each).

The suite of 17 lap splice panels were inspected without a doubler in place and then again after placing the 0.031" th. (5 plies) doubler over the cracked panels. Figure 62 shows the resulting PoD curves which were generated from the inspections on the interlayer crack panels. The interlayer crack detection is shifted to the right relative to the surface crack PoD curves because of the added depth of penetration required for the eddy current (and the associated loss in resolution). However, the curves do infer that cracks of 1" and greater can be detected in subsurface structures beneath composite doublers. It should be noted that the curves were generated by producing a fit through the data. There were insufficient crack detections to fully populate the curve and thus, portions of the curves are extrapolations using accepted PoD curve fitting algorithms. Therefore, a table of 95% PoD values, which would be primarily extrapolation numbers, is not presented for the interlayer PoD study.

The interlayer crack probability of detection experiment used seventeen aircraft panels with a total of 340 rivet inspection sites (lower row of lap splice inner skin only). Since 98 of these inspection sites were cracked, there were 242 opportunities for false calls. One false call was made on the panels which were inspected without a composite doubler (0.4%) and one false call was recorded during the inspections through the 0.031" th. composite doubler. The number of cracks detected in this experiment could be higher but the penalty may be a higher number of false calls. Once again, while the quantitative results are certainly valid, additional inspections, performed by other aircraft certified inspectors, are needed to draw final PoD conclusions. Additional tests would also help highlight the relationship between an inspector's age, experience, and false calls with probability of crack detection.

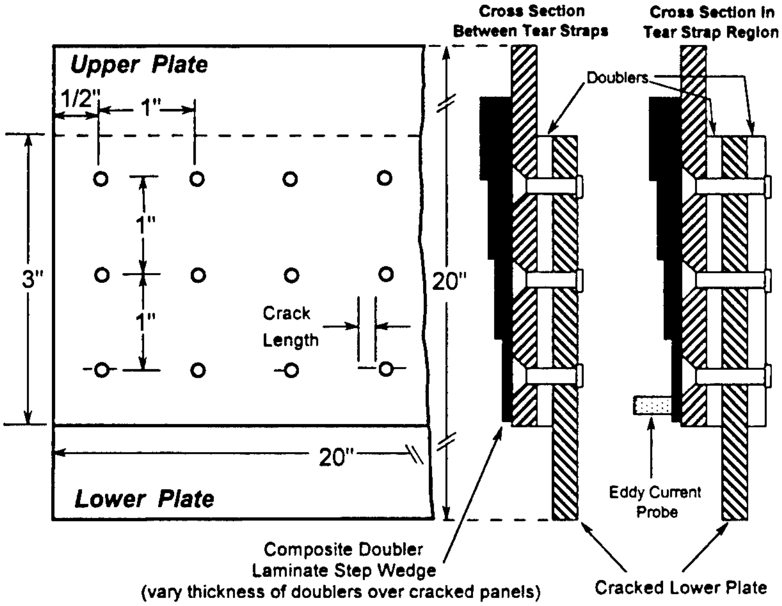


Figure 61: Test Set-Up for Detection of Subsurface Cracks Through Composite Doublers

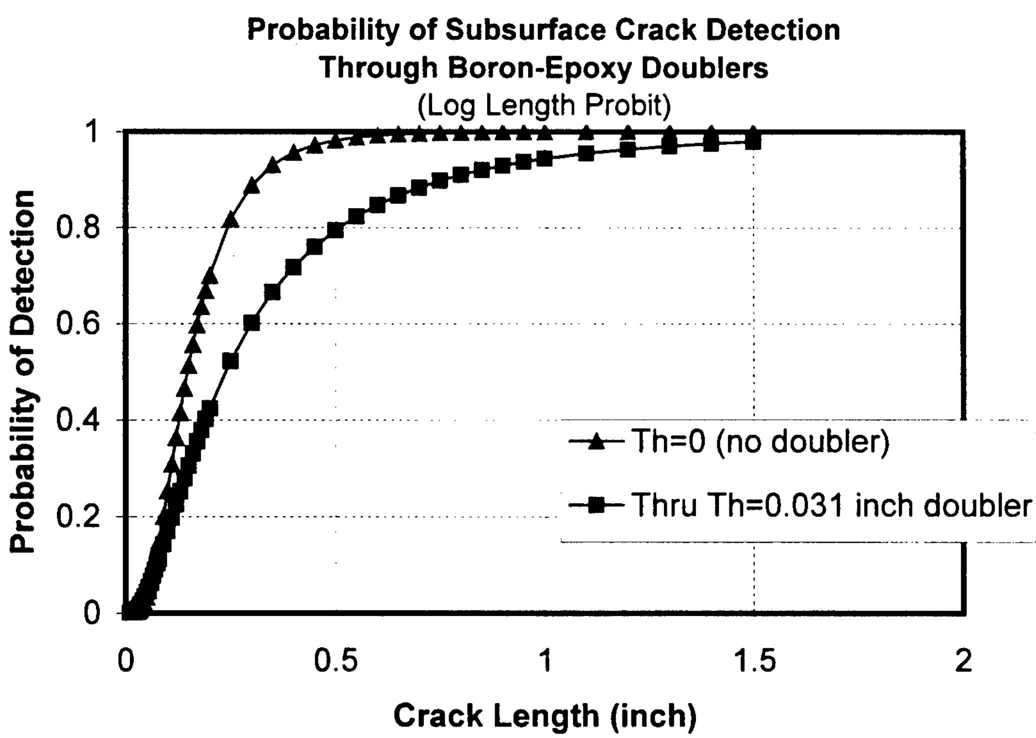


Figure 62: Probability of Detection Curves for Eddy Current Subsurface Crack Inspections Through Different Thicknesses of Composite Doublers

3.3 X-Ray Inspections

Radiographic inspection is a nondestructive method of inspecting materials for surface and subsurface discontinuities [39]. The method utilizes radiation in the form of either x-rays or gamma rays, which are electromagnetic waves of very short wavelength. The waves penetrate the material and are absorbed depending on the thickness or density of the material being examined. By recording the differences in absorption of the transmitted waves, variations in the material can be detected. Figure 63 shows an application of X-radiography in a hangar environment.

The most common way of measuring X-ray transmission is with film. After exposure and development, the film will become proportionally darker depending on the amount of radiation which reached the film. Areas that are thinner or lower density will allow more radiation to pass through the part. The greater the radiation transmitted through the part, the darker the film will be.

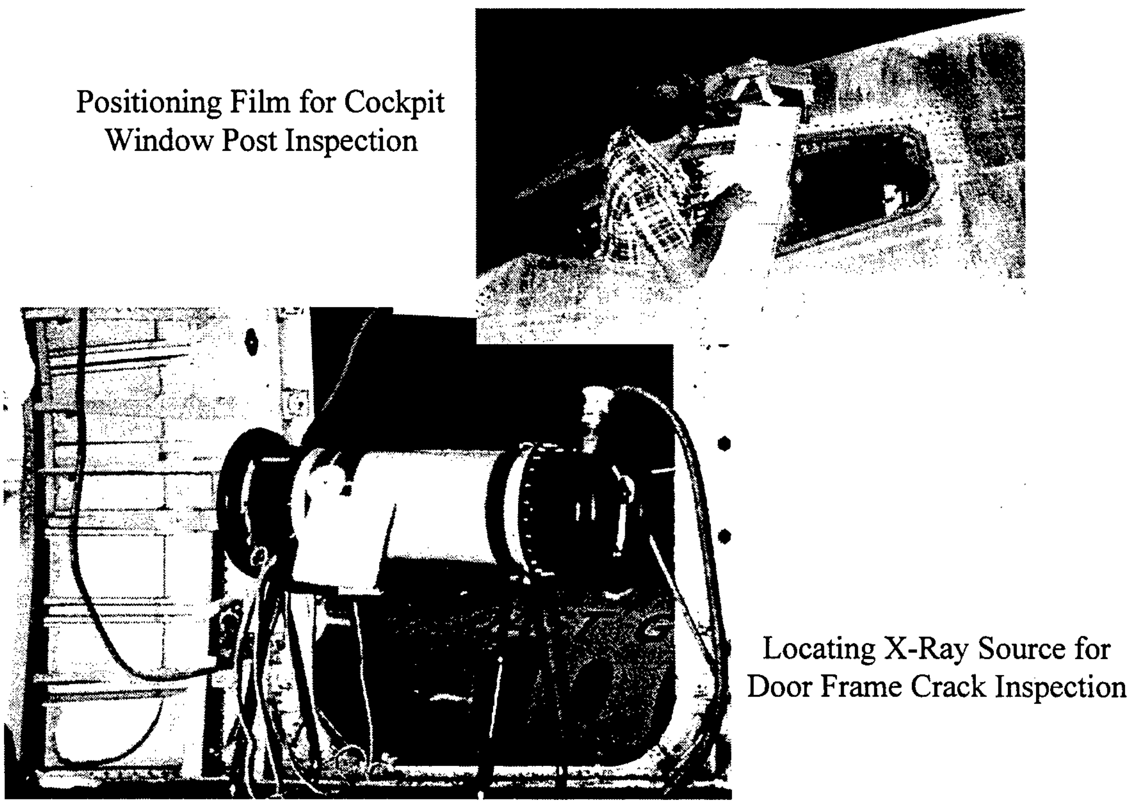


Figure 63: Aircraft Fuselage Inspection for Cracks Using X-Ray

Radiographic Sensitivity (Image Quality) - Radiographic sensitivity is a function of two factors. The ability to see a density variation in the film, which is "radiographic contrast" and the ability to detect the image outline which is "radiographic definition." Radiographic contrast is the difference in darkness of two areas of a radiograph. If contrast is high, small defects or density changes will be noticeable. Using lower power will result in higher subject contrast. However, lower power requires longer exposure times to obtain the adequate film density. Too low an energy level will not penetrate the part at all.

Radiographic Definition - This term is defined as the ability to resolve the defect image on the radiograph. It is affected by the geometric factors of the exposure: size of the radiation source (focal spot size), distance from the target/source to the film, and distance from the part to the film. All of these factors contribute to geometric unsharpness and as geometric unsharpness increases, the ability to see small defects decreases.

Image Quality Indicators - Image Quality Indicators (IQI) are used to measure the quality of the exposure and assure that proper sensitivity has been achieved. They measure the definition of the radiograph. By imaging IQI wires of various thicknesses and lengths it is possible to verify the resolution and sensitivity of a radiographic technique/set-up.

In the particular case of the L-1011 composite doubler, evaluating X-ray results through composite doublers was important. An X-ray inspection requirement was already called out to detect cracks in the door corner region [52]. If acceptable results could be obtained through the door corner doubler, then it was not necessary to modify any existing procedures or introduce any new inspection techniques. Delta Air Lines would merely perform the same X-ray inspection as before the doubler was installed and acceptable flaw detection would be achieved. Section 3.3.1 describes the effort to assure that composite doublers do not adversely effect X-ray inspections.

3.3.1 Resolution and Sensitivity - Image Production Through Composite Doublers

The discussion above provides some background on X-ray inspections and difficulties associated with its use. All of the issues described above exist regardless of whether or not the X-ray exposure takes place through a composite doubler. The primary question to be addressed in this study was: What is the overall effect of a composite doubler on X-ray inspections of structure beneath the doubler? To answer this question, the AANC conducted a study to: 1) demonstrate that composite doublers do not interfere with the ability to perform X-ray inspections for cracks in aluminum, and 2) identify proper exposure time and power settings to optimize the sensitivity of the X-ray technique when inspecting through thick doublers [24].

X-Ray Inspections of Fatigue Crack Specimens - Several fatigue crack specimens and the L-1011 fuselage test article were inspected through a 72 ply composite doubler. X-rays were obtained using the specimen matrix listed in Table 3 below. To form a basis of comparison, X-rays were also taken without the doubler placed over the cracked specimens. Details of the doubler are as follows: 72 ply, multi-axial lay-up with a fiberglass top coat (as per the Lockheed L-1011 doubler design drawing). A single screen lightning protection ply was placed on top of the doubler to assess any degradation in the X-ray caused by this copper mesh. The specimens placed beneath the doubler included 1st layer, 2nd layer, EDM notch and fatigue crack panels with crack lengths ranging from 0.05" to 1.0".

X-Ray Number	Specimen Number	Description
Comp-1	AANC 141	Two-plate, riveted assembly with 3/4" EDM notches joining adjacent rivets
Comp-2	Nortec SPO-3952	Two-plate, riveted assembly with 1/4" - 1/2" cracks in second layer; EDM notches emanating from rivet sites
Comp-3	Foster-Miller 3B-12	Lap splice panel with array of fatigue cracks in the 1/4" to 3/4" range
(A)		doubler over rivets 4,5,6
(B)		doubler over rivets 6,7,8
Comp-4	L-1011 Door Surround Structure	Fuselage section with composite doubler installed

Table 3: Test Matrix for X-Ray Inspections Through Composite Doublers

X-Ray Inspections on L-1011 Fuselage Test Article - An X-ray inspection is currently carried out by Delta, as per the L-1011 NDT manual, during Heavy Maintenance Visits (HMV). All inspections were performed using the same set-up with respect to distances and angles as the one deployed by Delta in L-1011 X-ray inspections. This assures that the proper location (angle) for the source and target film will remain the same. The purpose of this investigation was to determine the equipment settings needed to obtain a suitable image resolution while maintaining a film density of between 2 and 3 (as required by L-1011 NDT Manual). The damage tolerance requirement for the L-1011 door corner is to detect a 1.0" long crack. Particular attention is paid to the crack reference locations around the door corner and door handle cut-out as shown in Figure 4. X-rays were obtained from the L-1011 door surround structure test article. The inspection procedure and the resultant X-ray resolution met the requirements set forth in the L-1011 NDT manual. For these inspections, portable field equipment was deployed in order to mimic inspections carried out in the hangar.

X-Ray Results - Radiography was found to be a very effective inspection method to interrogate the interior of the parent material covered by a composite doubler. This technique provides the advantage of a permanent film record. To increase the contrast on the film, the X-ray inspection was performed at low kilovoltage (80 kV).

The damage detection threshold for cracks under the doubler is 1.0" (for L-1011 application). Test results showed the ability to detect cracks less than 1" in length. The EDM notches (length range of 0.25" to 1.0") were readily apparent in the X-rays. Further, fatigue cracks on the order of 0.38" in length were found under 0.41" thick (72 ply) Boron-Epoxy doublers. A sample X-ray result of a crack imaged through a 72 ply composite doubler is shown in Figure 64. [Note that significant resolution is lost in translating the X-ray film to a black and white graphic.] Comparisons with X-rays taken without composite doublers revealed that while the doubler may darken the X-ray image slightly it does not impede the X-ray inspection. Power and exposure times were adjusted in order to restore the desired contract and maintain the specified film density of between 2 and 3. The initial set-up (80 kV, 12 mA, 6 inch source-to-film-distance and 30 second exposure time) on medium speed film produced a film density of 0.98. Increasing the exposure time to 90 seconds produced a film density of 2.64. Image Quality Indicators (IQI), inserted into the field of view, verified the resolution and sensitivity of the radiographic technique. IQI lines with widths of 0.010" and dots with diameters of 0.10" were clearly imaged on the X-ray film. These results showed that X-ray inspections are as effective as before a doubler is installed.

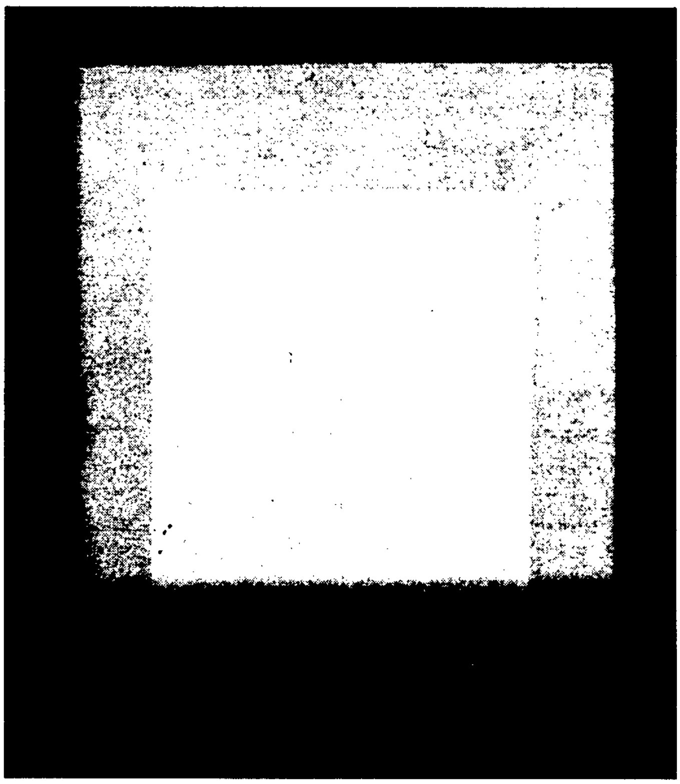


Figure 64: Sample X-Ray Image of a Cracked Aluminum Structure Beneath a 72 Ply Composite Doubler

4.0 Use of Realistic Calibration Standards

A critical element in the application of any piece of NDT equipment is the use of realistic calibration standards. The standards must have representative flaws which are engineered in a reliable manner and possess the appropriate structural configuration (e.g. doubler thickness and lay-up, skin thickness). Furthermore, all flaw detection challenges, with the exception of full scale accessibility and deployment issues, should be included in the calibration standard. Once the inspection equipment is set-up using feedback from the calibration standards, aircraft inspections can proceed with the knowledge that acceptable probability of detection numbers can be achieved. In the case of bonded composite doublers, the calibration or reference standards must include disbonds and delaminations in the doubler and cracks in the parent aluminum material. Disbond and delamination inspections can be accommodated with a single standard while another standard is used to support crack inspections.

4.1 Calibration Standards For Disbond and Delamination Inspections

A representative calibration standard containing artificial flaws of known size and depth should be used to ensure a repeatable inspection. The flaws must be engineered in the standards in a well-controlled manner and they must adequately represent the size, depth, and signal variation effects of actual disbond and delamination flaws. Amplifier gains and UT signal gates should be established during scans of the calibration standard. Depending on the physical size of the composite doubler and the degree of thickness variation, the inspector can determine the number of scans (unique set-ups) 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.

The initial reference standard developed for the 13 ply fatigue coupon inspections (see Section 1.4.2) did not possess a taper in the laminate. The inspection null point was created using an unflawed 13 ply thick area. In the case of the Bondmaster (resonance mode) inspection device this moved the dot to the center of the screen. The transducer was then placed on a 13 ply area with an engineered disbond. The instrument gain and rotation were used to position the dot three divisions away from the center of the screen and on the axis. Figure 1 shows how composite doublers are commonly tapered at the edge in order to produce a more gradual load transition. When the tapered sections of the fatigue samples were inspected - especially areas with only a few plies - low signal indications were found. The low signal levels provided a less than desirable detection reliability. To obtain better inspection results on the taper sections of the test specimens a new inspection standard was designed. Figure 65 shows this reference standard which can be used to support UT inspections in composite doublers up to 15 plies thick. This reference standard contains disbonds between the composite doubler and aluminum skin, delaminations between adjacent composite lamina, and nulling areas in both the full thickness and tapered/thin regions.

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.

This investigation determined that it is helpful to employ multiple calibration sites when inspecting composite doublers with thickness variations in excess of 10-12 plies. Specifically, it was found that a new set-up null point should be established after every 10-12 ply drop off in the tapered region (or change in thickness of 10 plies). In the case of the 13 ply fatigue coupons, a second calibration site for disbonds and delaminations is required. The reference standard shown in Figure 65 makes this provision by including disbonds, delaminations, and null areas in each of the important laminate thickness regions. This eliminates sporadic low signal flaw indications and improves flaw detection reliability.

Fabrication of Disbonds and Delaminations - The basic specimen flaws consist of disbonds between the laminate and the substructure (aluminum skin) and interply delaminations between adjacent composite plies. To create a disbond at an adhesive/substrate interface or an interply delamination, a contamination site that interferes with the wetting action of the adhesive is required. There are several methods which can be used to produce these types of controlled flaws in test specimens. The most successful techniques are: 1) inserting a Teflon or Stainless Steel pull tab on the bond line surface or between plies, 2) cutting a hole in the adhesive and adding a Teflon insert or other "pillow" insert which can interrupt an interrogating NDT signal, and 3) coating the disbond area with a silicone mold release (chemical agent which resists adhesion). The AANC has experimented with each of these approaches and has evaluated the flaw realism using assorted nondestructive inspection techniques.

1. Pull Tab - These inserts, which are removed after the adhesive curing process, produce a true "air gap" disbond or delamination in a specimen. A piece of stainless steel shim stock (0.003" to 0.004" thick) is placed between adjacent composite plies or between the base of a laminate and the mating aluminum structure. The stainless steel shims should be treated with a chemical release agent to prevent any permanent bond to the adhesive. Prior to their use, the coated pull tabs should be baked at a temperature which is greater than the doubler cure temperature. This will assure the performance of the release agent during the doubler installation.

2. Pillow Insert - Special inserts can be placed in the laminates during the lay-up operation to produce interply delaminations. The inserts will interrupt an inspection

signal and simulate an air gap between adjacent plies. Teflon, or a stacked assembly of sheet materials ("pillow"), can be used as inserts. Pillow inserts are composed of Kapton tape surrounding 3 layers of tissue paper. This pillow insert assembly can be fabricated with a total thickness of 0.008" - 0.009". This helps to minimize the amount of local deformation of the doubler in the area of the inserts. Teflon or pillow inserts can be fabricated with unusual or "random" shapes in order to model real life flaws.

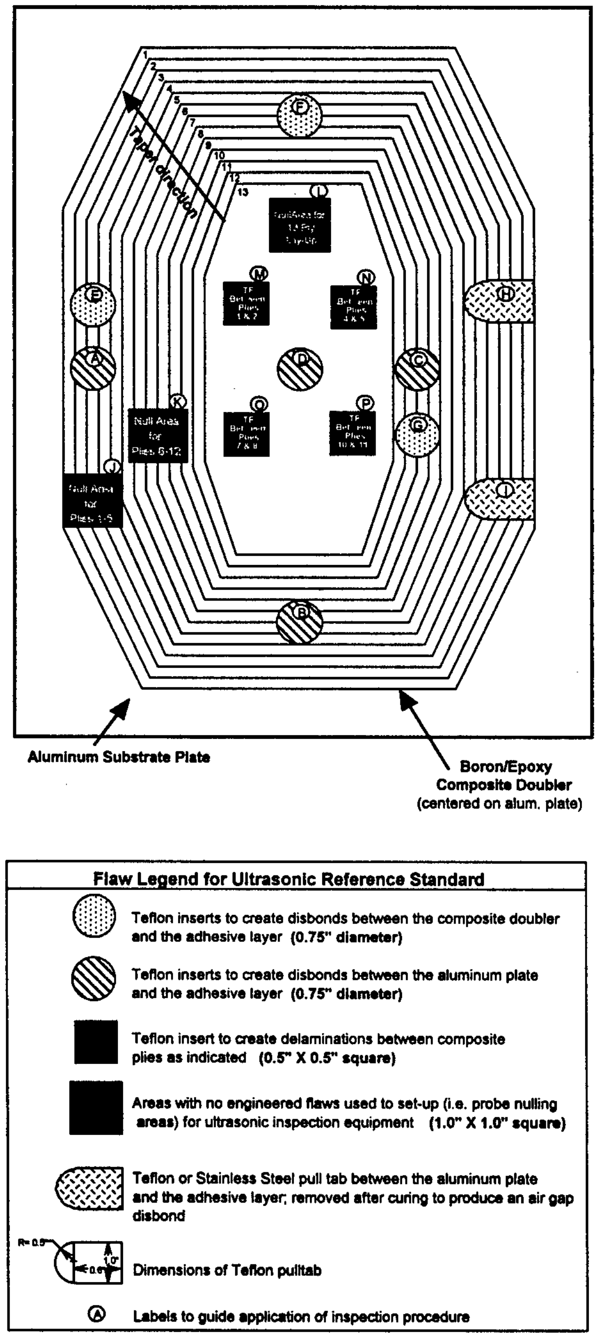


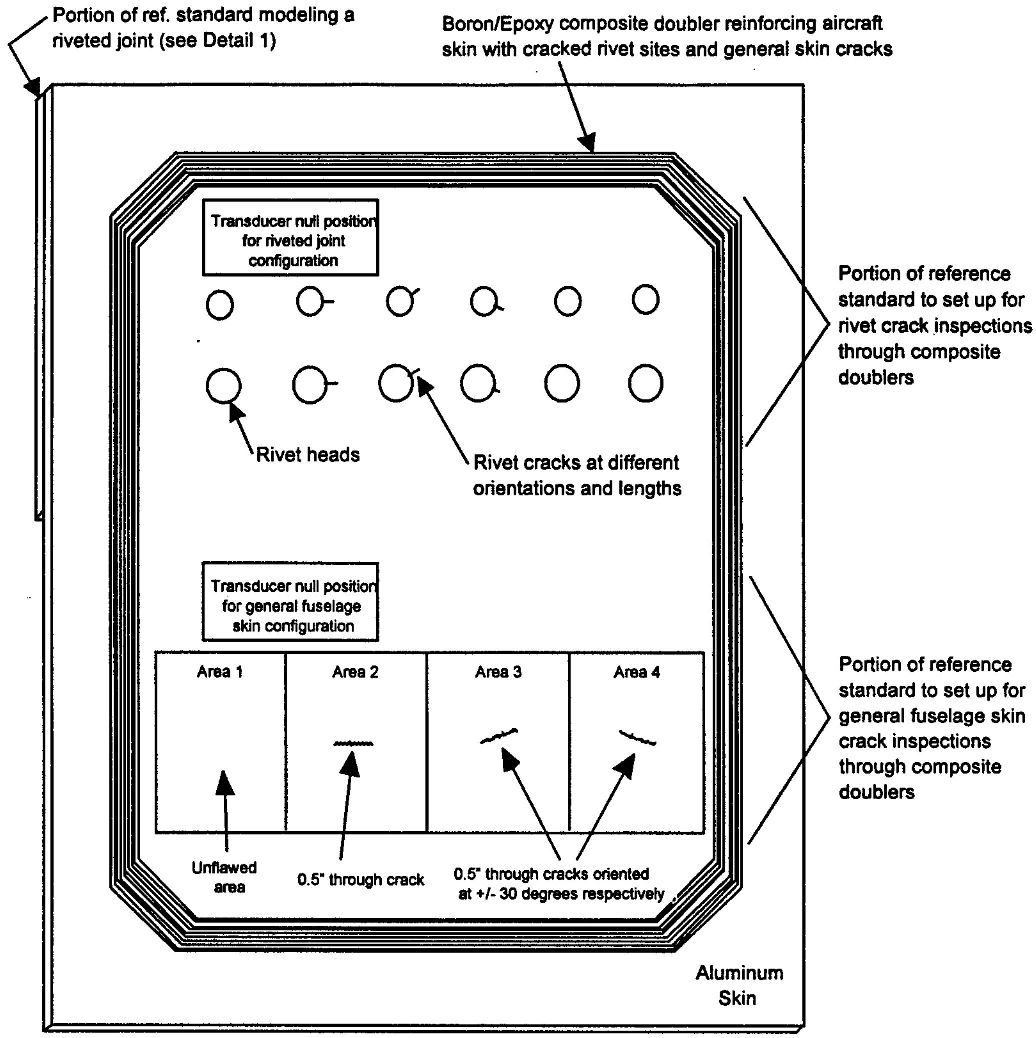
Figure 65: Configuration of Composite Doubler Reference Standard to Support Disbond and Delamination Inspections

3. Pin Hole - This flaw engineering method allows for the production of random shaped (and less controllable) disbonds between a Boron-Epoxy doublers and its parent aluminum structure [31]. In this process, small "pin holes" are drilled through the parent metallic material. This causes a vacuum leak path and results in adhesive being pulled away from the hole area during the cure process. The resulting disbonds have irregular shapes with small tentacles. This approach produces more realistic disbond flaws, however, the flaw shape is uncontrolled and the reliability is uncertain.

4.2 Calibration Standards For Crack Detection in Parent Material

Since these inspections pertain to the original aircraft structure, it is possible to utilize existing crack reference standards as called out in the aircraft manufacturer's NDT Manuals. Most commonly, the crack reference standards take the form of single or riveted plate assemblies with EDM notches. The notches are used to simulate cracks emanating from holes (rivet sites). In our testing, conventional crack standards were used to set-up the NDT equipment. As in normal deployment of eddy current equipment, the standards must match the structure of interest with regards to material type, material thickness, rivet type and/or hole size, crack depth (surface or subsurface), and crack length. To complete the standard for use with bonded doublers, a composite doubler laminate - cured without adherence to a parent metallic structure - is placed over the crack standard to simulate the aircraft doubler. The laminate should match the key characteristics of the aircraft composite doubler. The most critical characteristics to match are: 1) doubler thickness/number of plies, and 2) the presence of wire mesh lightning protection plies. Fiberglass environmental protection plies are less essential except for the additional lift-off effects they produce (this may be only 0.004"-0.008"). Ply orientation does not appear to have an effect on eddy current inspections so an exact match of the doubler lay-up is not necessary. Finally, it is essential that the doubler laminate conform properly to the crack standard. This will eliminate unintentional, and unrealistic, probe lift-off which will change the resolution of the inspection.

Thus, it is possible to simply superimpose a composite laminate over existing crack reference standards as called out in the manufacturer's NDT manuals. By adjusting the laminate overlay to match the repair of interest, it is possible to use the same crack standards to support many different repair inspections. Figure 66 shows a sample eddy current reference standard for use with bonded composite doublers. It has a number of similarities with the conventional eddy current standards which are called out in the Boeing NDT Manuals. The standard in figure 66 contains an array of rivet sizes with cracks of different lengths and orientations emanating from the fasteners. It includes riveted joints in case there are any effects of second layer skin on the detection of cracks in the surface skin. It also includes skin cracks which are not associated with fastener holes. This area can be used to set up equipment for inspections through composite doublers which are repairing skin dents or corrosion grind-outs.



NOTE: (1) Reference standard flaws lie in the aluminum underneath the boron/edpoxy composite doubler.
(2) All reference standard flaws lying underneath the composite doubler should be marked on the face of the doubler for easy location of the flaws.

Figure 66: Eddy Current Reference Standard Used to Support Inspections for Cracks in Aluminum Beneath Composite Doublers

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5.0 Conclusions

Air transportation is critical to the U.S. economy. Passengers want safe and reliable transportation at an economical price. The aviation industry and the FAA are continuously searching for ways to improve aircraft maintenance practices. Enhanced safety is the primary goal while cost reduction is necessary to our nation's competitiveness in the global air transportation market. Composite doubler repairs successfully address both of these concerns.

The unavoidable by-product of aircraft use is that crack and corrosion flaws develop throughout the aircraft's skin and substructure elements. Economic barriers to the purchase of new aircraft have created an aging aircraft fleet and placed even greater demands on efficient and safe repair methods. The composite doubler repair technique provides a safe and cost-effective solution to aircraft repair challenges. The engineering advantages associated with composite doubler use should accelerate their use in civil aviation repairs. Periodic field inspections of the composite is essential to assuring the successful operation of the doubler over time. 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.

NDI in Light of Damage Tolerance - By combining the ultimate strength, disbond growth, and the crack mitigation results obtained in this program, it is possible to truly assess the capabilities and damage tolerance of bonded Boron-Epoxy composite doublers. In this test series, relatively severe installation flaws were engineered into the test specimens in order to evaluate Boron-Epoxy doubler performance under worst case, off-design conditions. The engineered flaws were at least two times larger than those which can be detected by NDI. It was demonstrated that even in the presence of extensive damage in the original structure (cracks, material loss) and in spite of non-optimum installations (adhesive disbonds), the composite doubler allowed the structure to survive more than four design lifetimes of fatigue loading. Furthermore, the added impediments of impact - severe enough to deform the parent aluminum skin - and hot-wet exposure did not affect the doubler's performance. Since the tests were conducting using extreme combinations of flaw scenarios (sizes and collocation) and excessive fatigue load spectrums, the performance parameters were arrived at in a conservative manner. This damage tolerance assessment indicates that the current composite doubler inspection requirements are very conservative. Even in view of these encouraging doubler performance results, the cautious NDI approach is necessary in order to accumulate data on the operation of bonded doublers in actual flight environments. A strong history of success may allow the inspection intervals on these repairs to be lengthened or eliminated.

Disbonds and Delamination Flaws - 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 0.25" in diameter. Furthermore, the bond tester technique is also able to map out a changing flaw profile - a cohesive failure in the adhesive caused by the crack propagating through the aluminum - during fatigue testing of the composite doubler. Material nonuniformities inherent in composite laminates produce inconsistent signals when resonance ultrasonics is applied to laminates greater than 0.115" thick (20 plies). In this region, it is difficult 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 optimum method to achieve both field deployment and ease of signal interpretation involves the use of Pulse-Echo C-Scan ultrasonics. C-Scan views are area maps of the inspection surface. They provide the inspector with easier-to-use and more reliable data with which to recognize flaw patterns. 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.

Extensive testing has shown that the two-dimensional, color coded images produced by manual and automated scanners are able to reliably detect disbond and delamination flaws on the order of 0.50" 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.

During the course of this composite doubler development effort, thermography was applied to multiple doubler installations. Successful results demonstrated the viability of thermography for inspecting bonded composite doublers. Flaws smaller than 0.5" in diameter could be detected using thermography and their depth could be accurately determined. Furthermore, while ultrasonics has difficulty resolving flaws in the thin (1 to 3 ply) doubler region around the tapered perimeter, thermography does not appear to have difficulty with this configuration. More comprehensive and structured tests are underway to better determine the sensitivity and resolution of thermography in detecting composite doubler disbonds, delaminations, and porosity.

Inspections for Cracks - 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.

Testing conducted by the AANC on composite doubler specimens with cracks in the parent aluminum skin established the following general 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 (2nd layer) crack can be detected through a 0.310" thick doubler and a 0.040" thick aluminum surface plate. A blind, probability of crack detection study was performed using a statistically valid set of fatigue crack panels and composite doublers of various thicknesses. It was found that even through doublers as thick as 35 plies (0.199" th.), the probability of finding surface cracks of 0.2" in length exceeds 95%. The results were achieved with a false call rate of less than 1%. These results are quite good in light of the damage tolerance requirement to find fatigue cracks beneath doublers before they reach 1" in length.

The AANC completed a study to: 1) demonstrate that composite doublers do not interfere with the ability to perform X-ray inspections for cracks in aluminum, and 2) identify proper exposure time and power settings to optimize the sensitivity of X-ray technique when inspecting through extremely thick doublers (72 ply). Radiography was demonstrated to be a very effective inspection method to interrogate the interior of the parent material covered by the composite doubler. X-ray inspections are as effective as before the doubler was installed. The Boron-Epoxy material does not impede the X-ray inspections. Power and exposure times can be adjusted to accommodate the presence of the doubler and achieve the required film density and resolution. Again, the required damage detection threshold for cracks under the doubler is 1.0". X-ray images showed the ability to detect fatigue cracks on the order of 0.38" in length beneath 0.40" thick (72 ply) Boron-Epoxy doublers.

The entire aviation industry can receive the engineering and economic benefits provided by this new technology. Technical advantages include: 1) improved fatigue life, 2) increased strength, 3) decreased weight, 4) eliminates introduction of crack initiation sites (i.e. fastener holes), 5) does not corrode, and 6) improves aerodynamics. Economic benefits include: 1) cost savings through reduction in man-hours required to install a repair, and 2) reduced aircraft downtime.

Before the use of composite doublers could be accepted by the civil aviation industry, it was imperative that methods be developed which could quickly and reliably assess the integrity of the doubler. This report presented a series of tests which were conducted to evaluate both conventional and advanced NDI techniques for bonded composite doublers. Sensitivity studies showed that a team of NDI techniques can identify flaws well before they reach critical size.

The most visible end-result of this investigation into bonded composite doublers is that a doubler has been placed on a commercial aircraft in the U.S. fleet. The NDI testing described here addressed the concerns surrounding composite doubler technology: long-term survivability and the validation of appropriate inspection procedures. This study validated the inspection techniques and developed the procedures necessary to assure the continued safe operation of composite doublers. A follow-on study is attempting to streamline the design-to-installation process and develop a set of repairs which are pre-approved by the OEM to repair common fuselage damage.

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51. Spencer, F., Borgonovi, G. , Roach, D., Schurman, D. , Smith, R.; "Reliability Assessment at Airline Inspection Facilities, Volume II: Protocol for an Eddy Current Inspection Reliability Experiment"; Dept. of Transportation Report, DOT/FAA/CT-92/12-II, May 1993.
52. "L-1011 Nondestructive Testing Manual," Section 53-15-80, X-ray Inspection of Passenger, Galley, and Cargo Door Frame Corners," Lockheed California Co., Burbank, CA., Nov. 1979

Appendix A

Ultrasonic Inspection Procedure for Pulse-Echo Scanning Technique

Nondestructive Inspection Procedure for Bonded Boron-Epoxy Composite Doublers Using Ultrasonic Pulse-Echo C-Scan Technique

May 1998 - DRAFT

FAA Airworthiness Assurance NDI Validation Center
Sandia National Laboratories - Albuquerque, NM

Specification No. AANC-PEUT-Comp-5521/4-004

1.0 SCOPE

This procedure describes the criteria and procedure for ultrasonic (UT) inspection of bonded Boron-Epoxy Doublers on aluminum substrates. Flaws detected through the use of this procedure are disbonds, delaminations, and porosity.

2.0 REFERENCES

2.1 Operation Manual-Ultra Image International

3.0 REQUIREMENTS

3.1 Equipment

3.1.1 Ultra Image IV Automatic Scanner System Per Figure 1(A), 1(B) & 1(C)

3.1.2 Ultrasonic Probes (5 MHz and 7.5 MHz; 0.5 inch diameter)

3.1.3 Testech Weeper per Figure 2

3.1.4 Ultrasonic Calibration Standard per Figure 3

3.2 Materials

3.2.1 Ultrasonic Couplant - Distilled Water

3.3 Personnel

It is recommended that the inspector using this procedure be experienced and knowledgeable in the fundamentals of ultrasonic testing. Inspectors should fully possess the qualification of ultrasonic testing personnel as defined in <u>Recommended Practice No. ASNT-TC-1A, Personnel Qualification and</u>

Certification in Nondestructive Testing, available from ASNT (American Society for Nondestructive Testing), ATA 105 or other approved certification standard.

4.0 PROCEDURES

Refer to the referenced operation manuals for the location of the controls and a description of the instrument menu system. This procedure can be used with either a manual or automatic scanner system.

4.1 Instrument Set-Up

4.1.1 Connect the cables and hoses between the various components as shown in Figure 1. Place the probe into the WEEPER body and attach the WEEPER to the transducer holding fixture (ref. Figure 2). The WEEPER provides the water flow for ultrasonic coupling.

4.1.2 Place the scanner system over the UT Calibration Standard. The UT Calibration Standard for the composite doubler is shown in Figure 3. It consists of a composite doubler bonded to an aluminum plate. The doubler is a 72 ply [0,+45,-45, 90] lay-up. The aluminum plate is 2024-T3, 0.071" thick material. The UT Calibration Standard contains a series of engineered disbonds and delaminations in the various step regions and are labeled (1) through (20). These labeled locations are referenced in the following inspection procedure. They are used to set up the equipment and help interpret the inspection results.

4.1.3 Turn the scanner system power on. Depending on which ultrasonic scanner system is being setup (manual or automatic), select the appropriate software for scanning. Select Motorized v 9.0 software for the automatic scanner. The Upi 50 Scanmaster Imaging System v 9.1 software is now installed and operational. Select F4/SETUP from the menu. This allows the operator to select the F4/MOTION subroutine. The scanner can now be moved to X-HOME and Y-HOME to create the x-y scanner origin of (0,0). Select F3/DISPLAY and set the waveform to RF (radio-frequency). Then check that the MODE is pre-set to PE (Pulse-Echo).

4.1.4 Position the probe over the appropriate area of the UT Calibration Standard to accommodate the composite thickness range being inspected (e.g. for doubler areas in the 9-24 ply range use the 24 ply portion of the UT Calibration Standard). JOG the probe across the UT Calibration Standard to the unflawed area as shown in Figure 3 ("A", "B", "C", "D", or "E" as appropriate). Next EXTEND the probe until it is in contact with the surface and adjust the contact pressure so that the probe can move smoothly across the surface. Adjust the water flow into the WEEPER and clear out any air bubbles in the water column by adjusting the probe in the WEEPER. Select F3/UPR and choose F7/TIME

BASE. This places the data acquisition system in the "time mode" (microseconds).

Adjust the DELAY and RANGE to produce an A-trace on the display screen as seen in Figure 4. Figures 4(B) and 4(C) show expanded windows of the 4(A) signal. They are created by expanding the time base of select portions of the 4(A) waveform. The signal on the screen from left to right shows: A) the initial pulse, B) the echo from the WEEPER membrane, C) the front surface echo from the composite doubler, D) the echo from the composite doubler / bond / aluminum interface, E) the back wall echo of the aluminum, F) the first multiple signal in the aluminum, and G) the first multiple signal from the WEEPER membrane. Variations in these signals, especially at areas (C), (D) and (E), are used to detect disbonds and delaminations in the composite doubler.

4.1.5 Select F5/PULSER and adjust the DAMPING, GAIN, and waveform AMPLITUDE. Then select F6/RECEIVER and adjust GAIN and FREQUENCY. Adjust the amplitude of the echo from the composite/bond/aluminum interface ("D" in Fig. 4) until the maximum and minimum read at +90% and +10% Full Screen Height (FSH), respectively as shown in Figure 5. Both F5 and F6 should be adjusted to obtain the maximum signal response and highest resolution. These settings can vary from probe to probe and are somewhat dependent on operator preferences.

4.1.6 Before setting the GATES, select SURFACE FOLLOWER (S.F.) and set the surface follower threshold for +15%. This selection should give a consistent signal display with the A-trace screen display triggering at the front surface echo signal (C) as shown in Figure 6(A).

4.1.7 At this time, gates are set in order to control the acquisition of appropriate UT information. To inspect a composite doubler, a series of gates corresponding to specific thicknesses of the Boron-Epoxy doubler will be positioned in the data acquisition system. User specified depth gates allow only specific echo signals following the initial pulse, or interface echo, to be admitted to the receiver-amplifier circuit. The emphasized signals for this inspection: 1) fall within a limited range of delay times, and 2) exceed the specified gate amplitudes.

4.1.7.1 Now the operator is ready to select F4/GATES. The position and number of gates will determine the C-scan data recorded. The operator can select up to four separate gates consisting of either positive, negative, or both signal amplitudes. The gates can be positioned by selecting DELAY and RANGE from the F4/GATES menu (see ref. 2.1 "Operation Manual-Ultra Image International").

4.1.7.2 The operator should set a series of three gates (horizontal lines on the A-Scan screen) to collect: 1) any delamination signals in the composite doubler [between (C) and (D)], 2) the bond interface signal (D), and 3) the aluminum back surface echo (E) as shown in Figure 6(B). Thickness variations require the operator to track the front surface of the doubler and set the depth gates as appropriate. Set the initial gates above the noise levels, as shown in Fig. 6(B), such that the signals of interest (items (1), (2), and (3) described above) affect the gate thresholds as appropriate (see 4.1.7.3 and 4.1.7.4 below).

By employing a series of gates in one scan, it is possible to collect data over a range of depths (i.e. doubler thicknesses). However, to have complete coverage of thick composite doublers (in excess of 12 plies), it is necessary to use several different scans each containing their own unique set of gates which are appropriate for the laminate thickness being inspected. The gate locations are checked using the steps described in 4.1.7.3 and 4.1.7.4.

4.1.7.3 Move the probe to the disbond position on the UT Calibration Standard ("2", "6", "10", "14", or "18" as appropriate in Figure 3). This represents a disbond between the composite doubler and the aluminum. Note the A-trace display which shows the back wall echo of the composite doubler but no signal from the back wall of the aluminum (no "E" in Figure 7). The disbond eliminates the transmission of this latter, back wall signal. Variations and signal drop-outs (low amplitudes) in the areas of gates (2) and (3) create the disbond flaw maps (see Fig. 7).

4.1.7.4 Move the probe to the delamination position on the UT Calibration Standard ("3", "7", "11", "15", or "19" as appropriate in Figure 3). This represents a delamination between the plies in the composite doubler. The A-trace display shows an inter-ply echo signal between the front and back surface echo of the composite doubler (note the waveform between "C" and "D" in Figure 8). The existence of a large amplitude signal which exceeds gate (1) creates the delamination flaw map (see Fig. 8).

The location of the inter-ply echo signal will depend upon the depth of the delamination from the front surface. The location of the inter-ply delamination will also determine the number of multiple echo signals and their time displacement. The back wall echo signal of the composite doubler and the aluminum will completely disappear if the delamination is larger than the probe diameter (i.e. large enough to completely interrupt the UT signal).

4.2 Inspection Procedure

4.2.1 Place the UT scanner on the aircraft structure to be scanned. Set all the parameters for the area to be scanned using the set-up procedure in 4.1. Or, to recall a previously-stored set-up, select F3\UPR. This opens F\FILES so that the operator can P\PICK an existing file name to OPEN. By opening this file, all the old scanning parameters are called in.

4.2.2 The probe can now be JOGGED to the starting position. Set the A-trace display screen from large format to small. Select F7/QUICK and enter the scanning parameters:

Index Axis: Y	
Scan Axis: X	
X & Y Resolution	(EXAMPLE 0.05 inches)
Y-Scan Length	(EXAMPLE 12 inches)
X-Scan Length	(EXAMPLE 9 inches)
Y-Scan Speed	(EXAMPLE 2 inches/sec)
X-Scan Speed	(EXAMPLE 2 inches/sec)

The set-up information (scanning and UPR parameters) can be saved for future use (see ref. 2.1 "Operation Manual-Ultra Image International").

Select F5/SCAN, enter the output file name, then enter the documentation to identify the area scanned, probe and any set-up remarks. Set Acquire-Gate(s) Configuration to WRITE/PLOT the data during the scanning process. Finally, check over all the Scan Setup Parameters and, if satisfied, start the scan by clicking on the "Start" command. At the end of the scan, the operator can EXIT/SAVE the data. The probe will automatically return to the starting position.

4.2.2.1 Figures 9 and 10 show C-scan images of bonded composite doubler installations. The engineered flaws are clearly visible when viewed side-by-side with adjacent, unflawed material.

4.2.3 To RESCAN the same area with the same parameters GOTO 4.2.2 and call in the old set-up file name.

4.2.4 To RESCAN the same area after changing the parameters GOTO 4.1.5 and repeat the setup. Depending on the type of parameter adjustments, the calibration standard may or may not be needed.

4.2.5 To SCAN a new area of similar thickness to the last scan GOTO 4.2.2.

4.2.6 To SCAN a new area of a different thickness range GOTO 4.1.4.

5.0 EVALUATION

5.1 Detected flaws shall be identified in terms of their depth as correlated to the calibration standard.

6.0 INSPECTION RESULTS

6.1 In the 2.0 inch band around the perimeter of the doubler, report all delaminations and disbonds greater than 0.50 inches in diameter to the appropriate engineering personnel on site for further evaluation / action.

6.2 In the remaining interior region of the doubler, report all delaminations and disbonds greater than 2.0 inches in diameter to the appropriate engineering personnel on site for further evaluation / action.

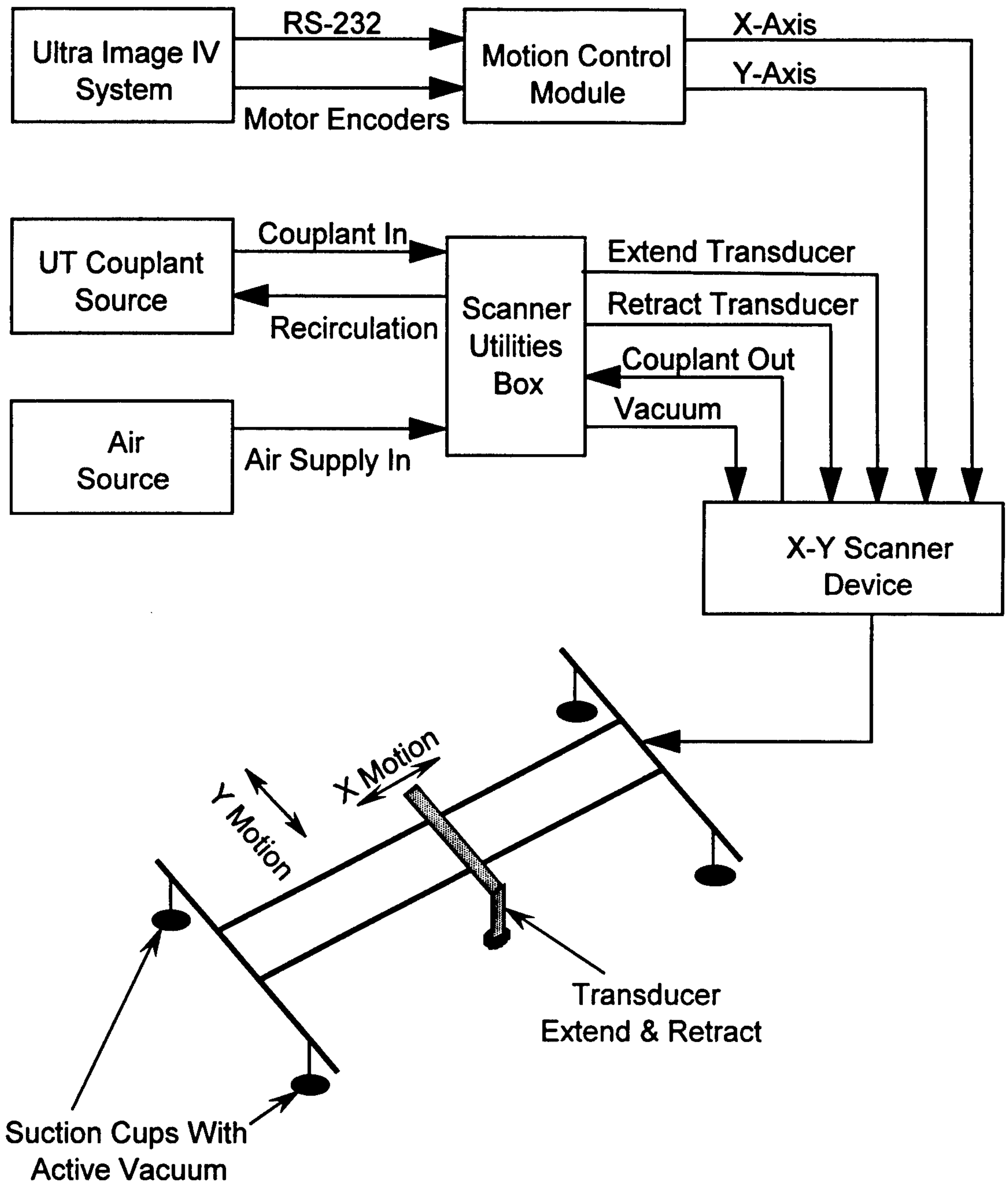


Figure A-1(a): Automatic Scanner System Interconnection Diagram

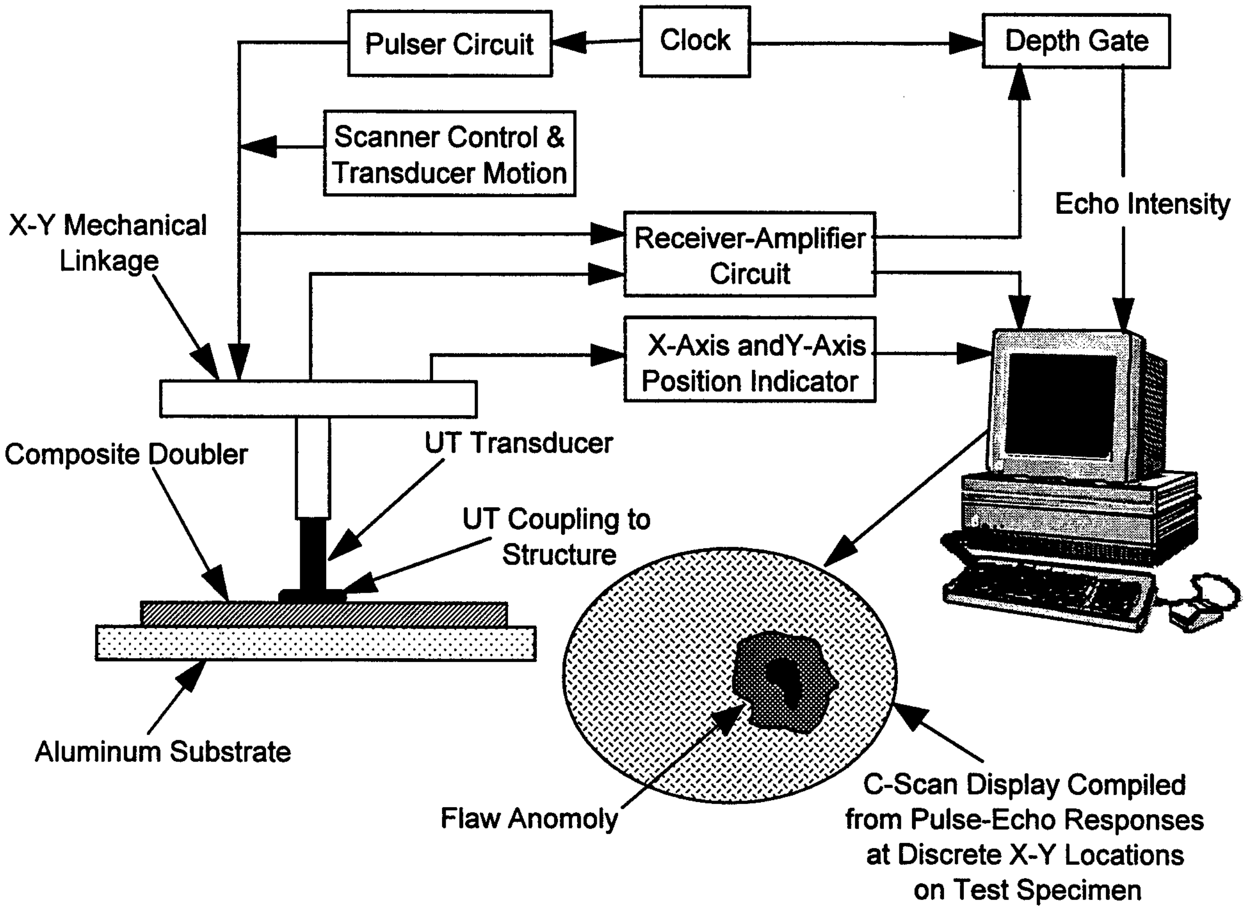


Figure A-1(b): Schematic of C-Scan Setup for Pulse-Echo Ultrasonic Inspection

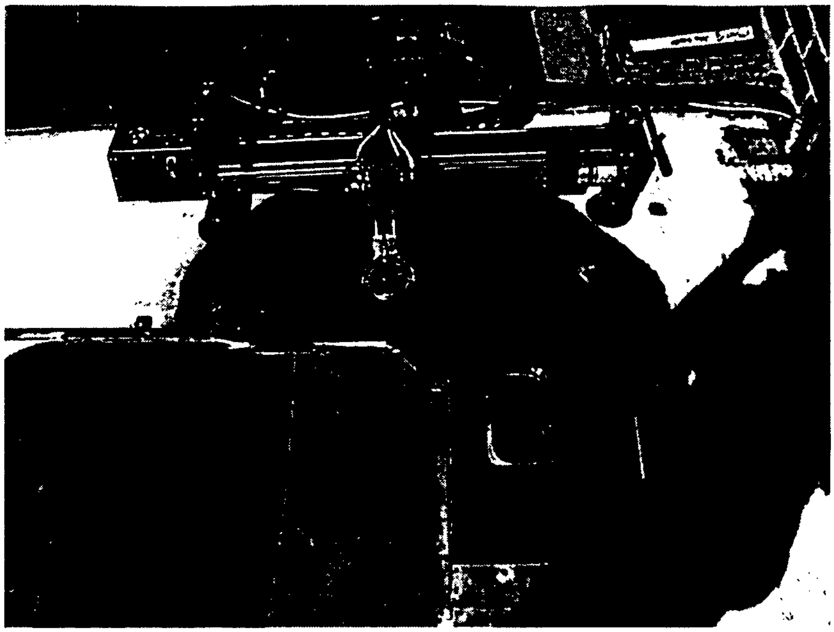


Figure A-1(c): Photograph of Automated Ultrasonic Scanner Inspecting a Composite Doubler on an L-1011 Fuselage

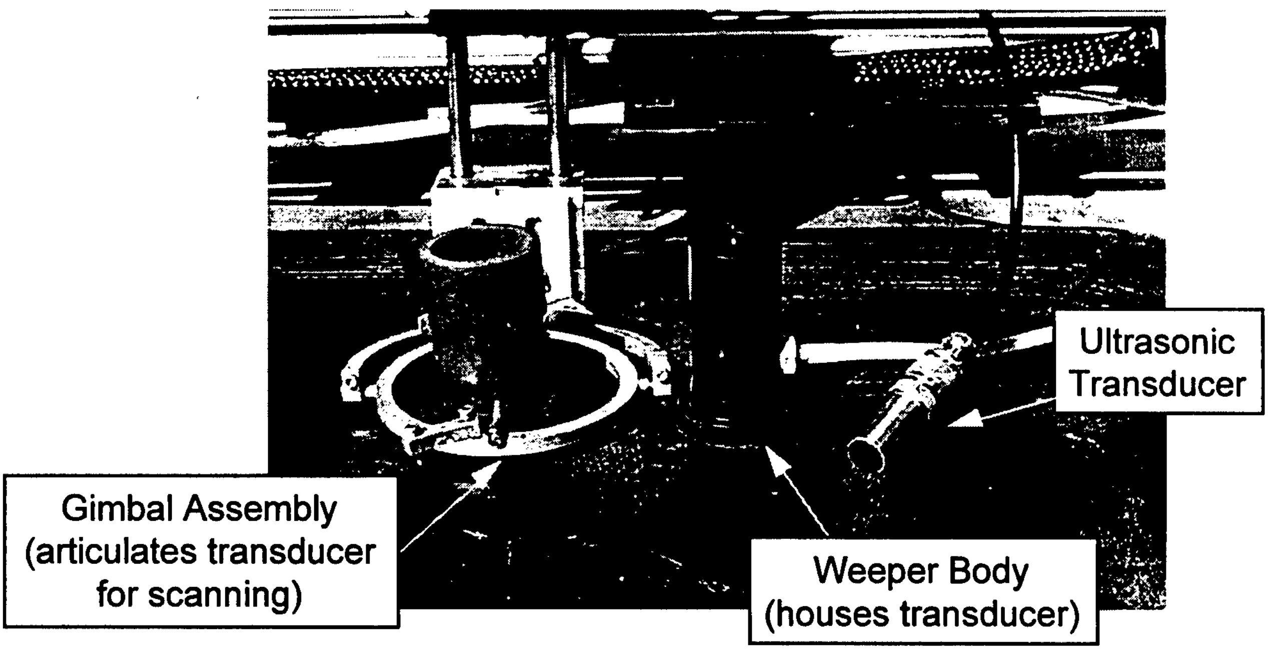


Figure A-2: Photograph of Transducer Assembly for Scanning (transducer fits inside the weeper body which is mounted in the gimbal assembly)

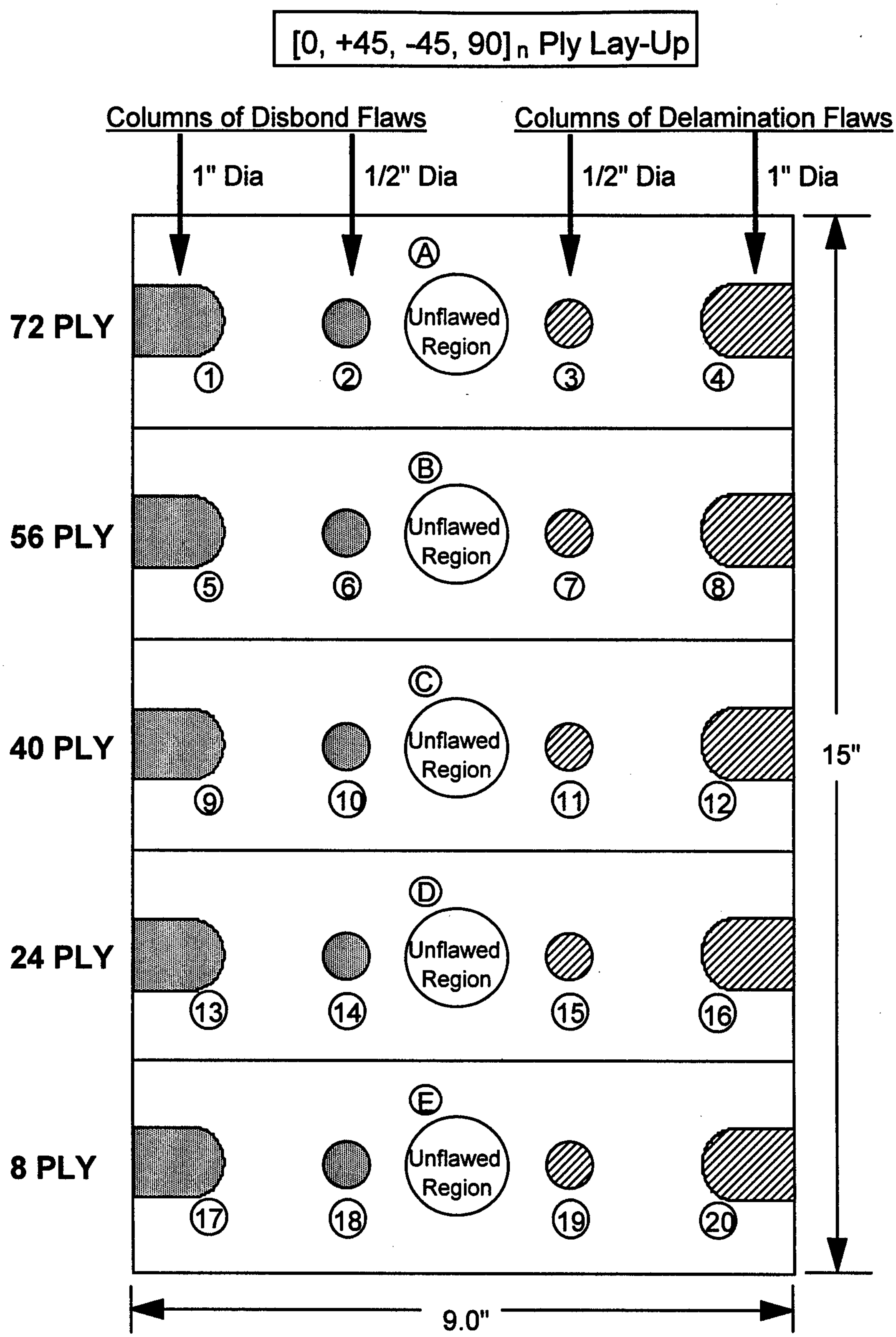


Figure A-3(a): Composite Doubler Calibration Standard for Ultrasonic Inspections

Table A-1: Implanted Disbonds and Delaminations

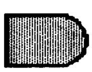
Legend
PT = stainless steel pull tab (removed to produce air gap disbond or delamination)
TF = Teflon insert (2 plies of 0.005" thick Teflon)

Implanted Delamination Depths

No. of Plies	Flaw Number	Depth (between plies x-y)
72	3	48 - 49
72	4	12 - 13
56	7	38 - 39
56	8	12 - 13
40	11	28 - 29
40	12	12 - 13
24	15	18 - 19
24	16	12 - 13
8	19	4 - 5
8	20	2 - 3


Teflon Insert (**Delamination**) at Depths Listed in Table 1 - 0.5" diameter


Teflon Insert (**Disbond**) at Bond Line Between Composite and Aluminum - 0.5" diameter


Pull Tab at Bond Line to Create **Disbonds** - 1.0" wide X 1.5" long with end diameter of 1.0"


Pull Tab Between Plies to Create **Delaminations** (see Table 1 for delamination depths) - 1.0" wide X 1.5" long with end diameter of 1.0"

Figure A-3(b): Flaw Legend for Ultrasonic Composite Doubler Calibration Standard

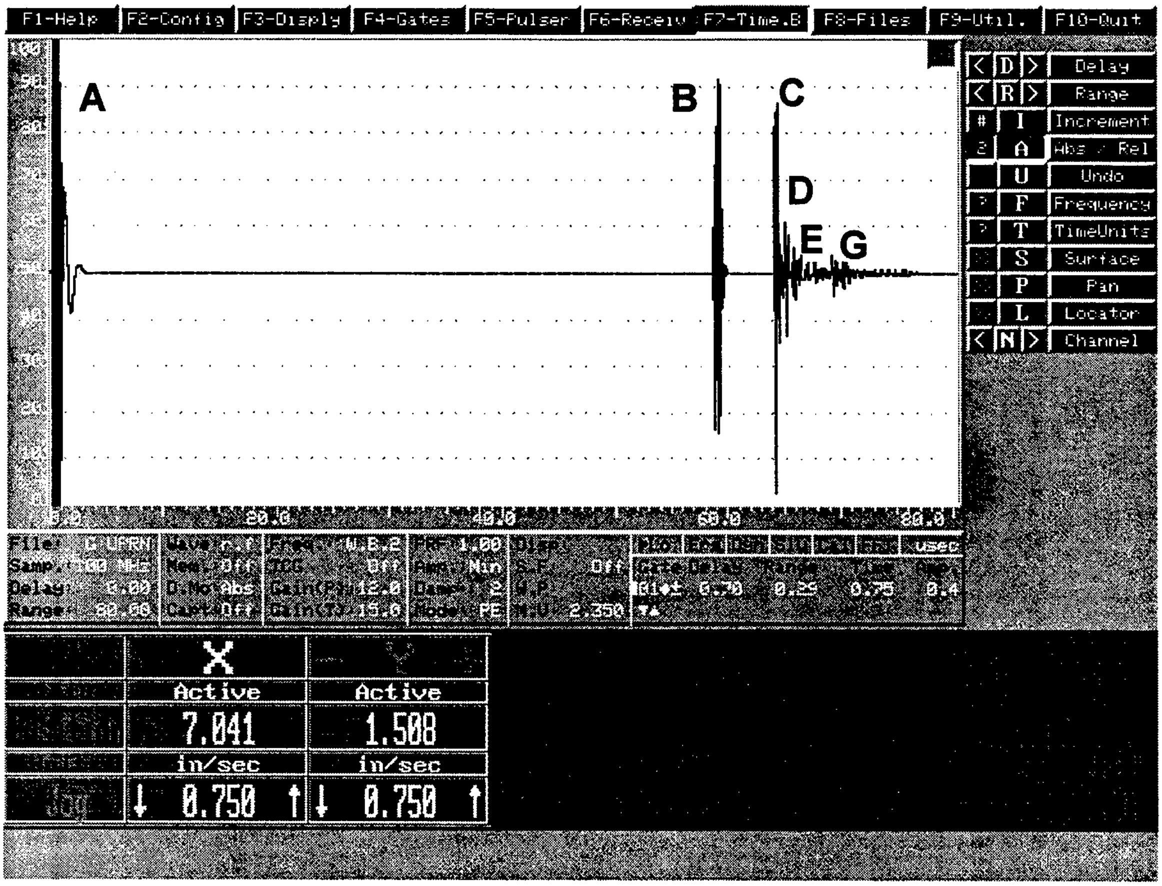


Figure A-4(a): A-Scan Trace on Display Screen with: A) initial pulse, B) echo from WEEPER membrane, C) FS echo from composite doubler, D) echo from composite/bond/aluminum, E) BS echo of aluminum, and G) first multiple echo from WEEPER membrane

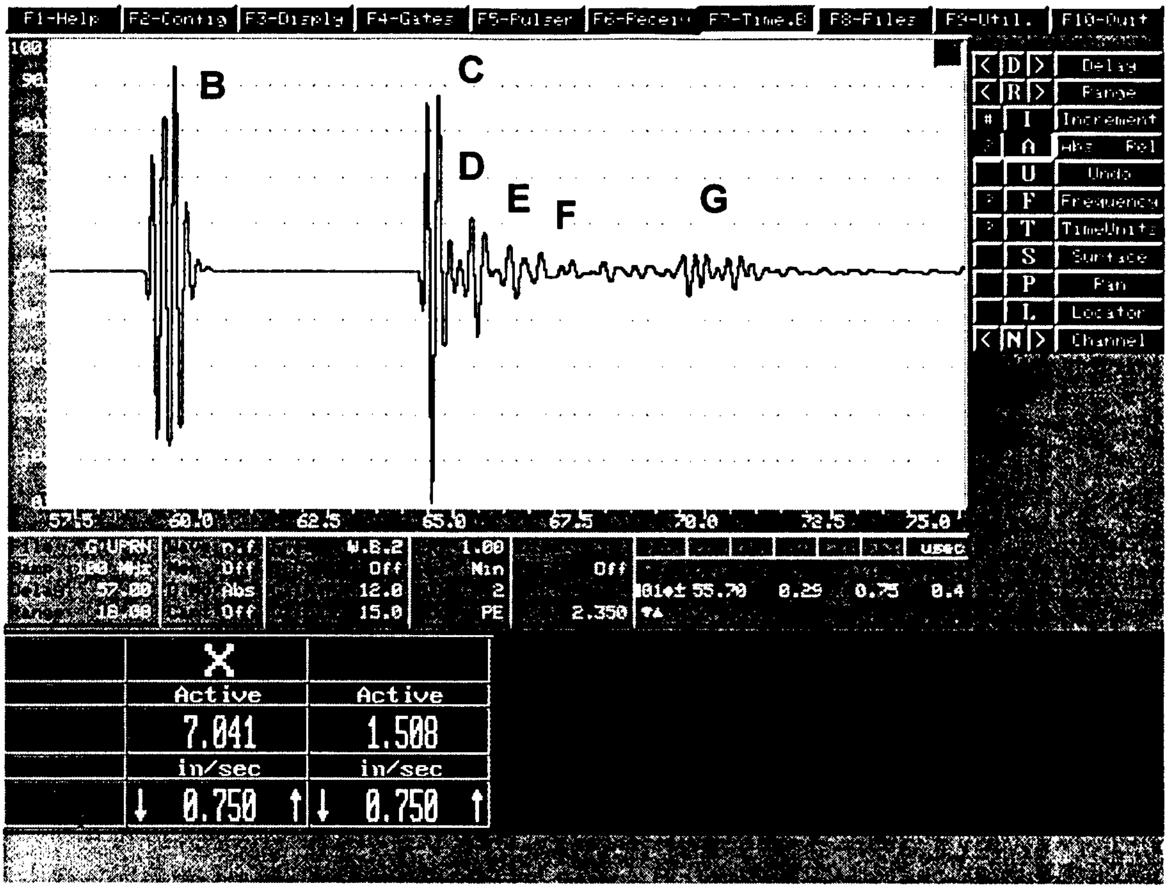


Figure A-4(b): A-Scan Trace on Display Screen with: B) echo from WEEPER membrane, C) FS echo from composite doubler, D) echo from composite/bond/aluminum, E) BS echo of aluminum, F) first multiple echo in aluminum, and G) first multiple echo from WEEPER membrane

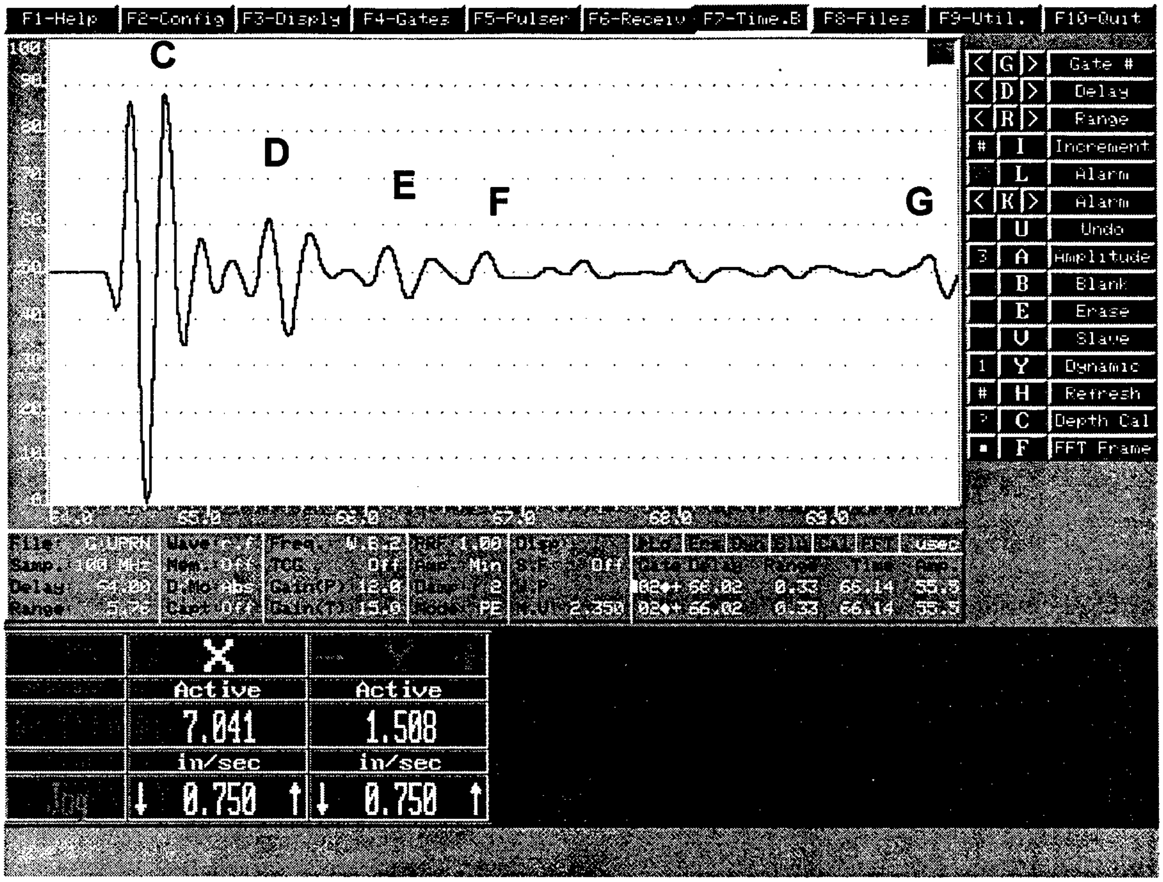


Figure A-4(c): A-Scan Trace on Display Screen with: C) FS echo from composite doubler, D) echo from composite/bond/aluminum, E) BS echo of aluminum, F) first multiple echo in aluminum, and G) first multiple echo from WEEPER membrane

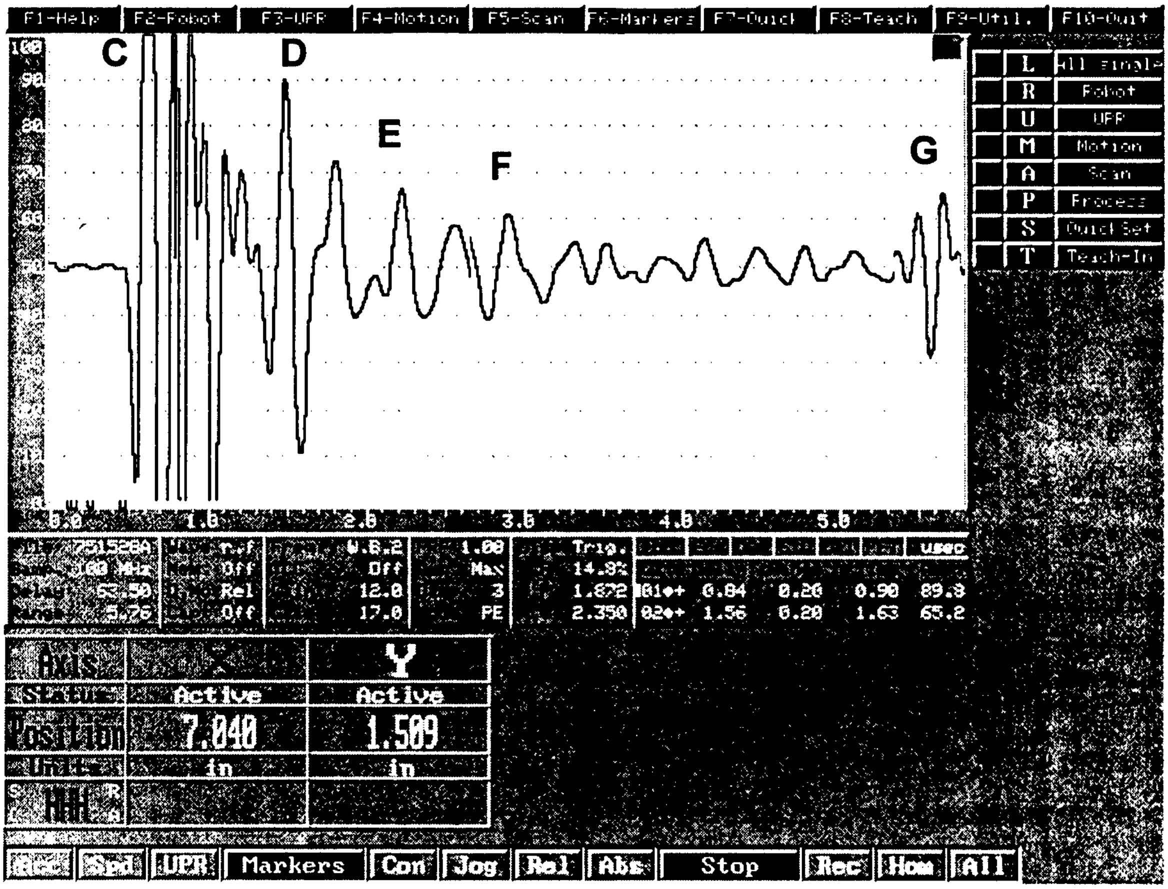


Figure A-5: A-Scan Trace on Display Screen with: D) echo from composite/bond/aluminum set for +90% to 10% FSH

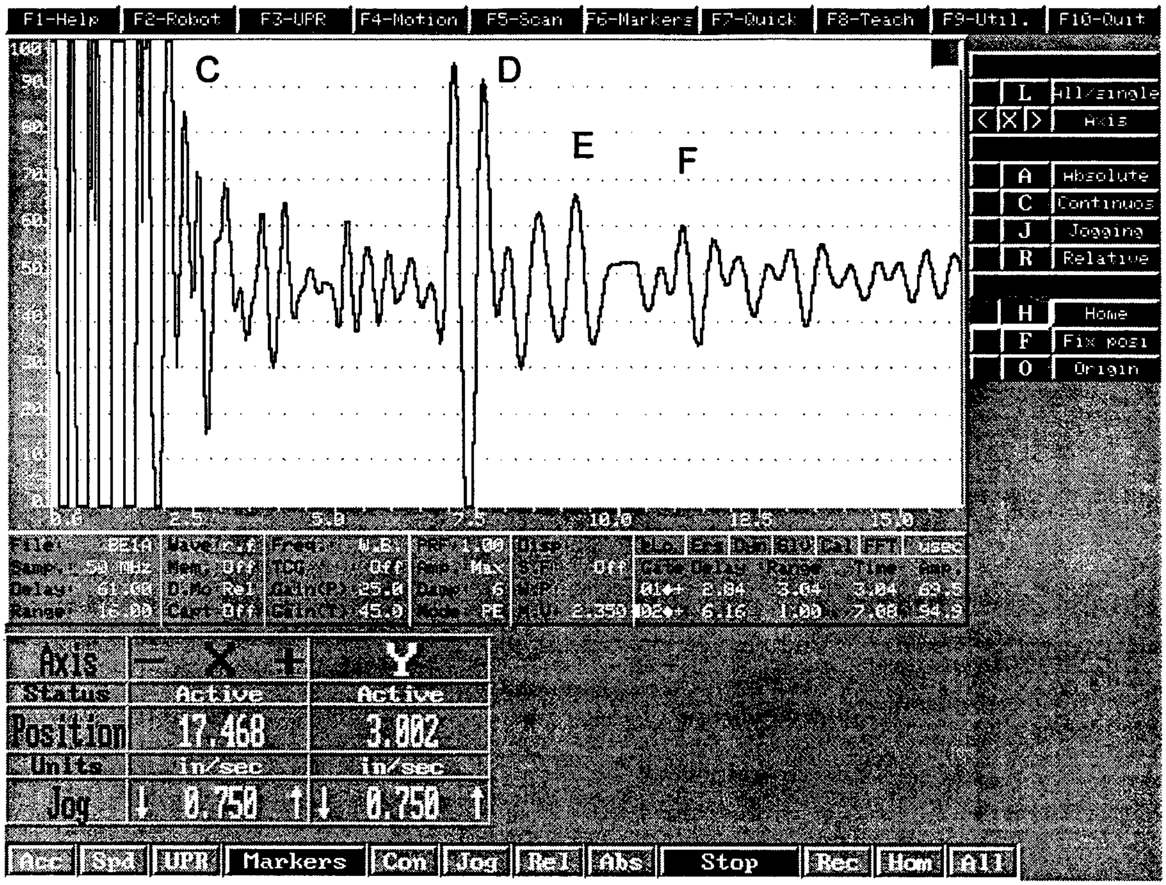


Figure A-6(a): A-Scan Trace on Display Screen with: Surface Follower (S.F.) threshold set for +15% on (C) waveform

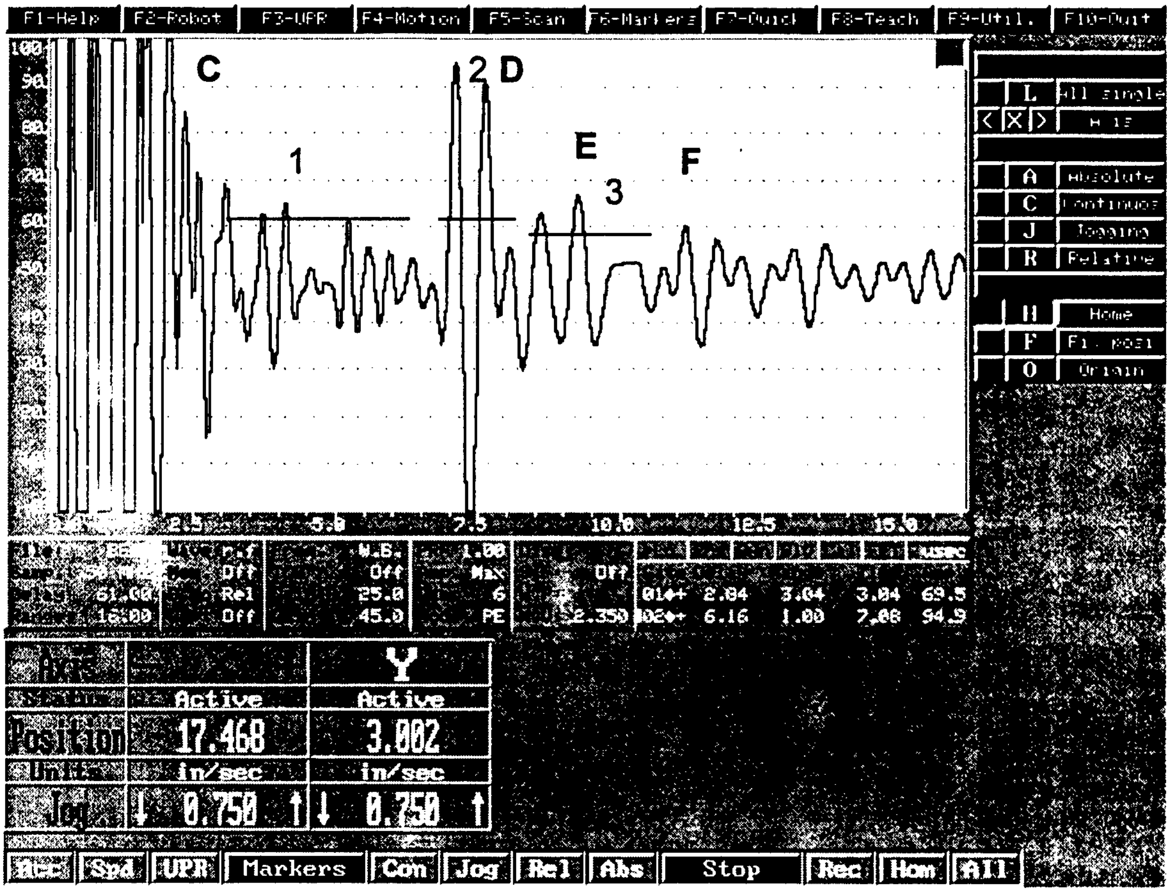


Figure A-6(b): A-Scan Trace on Display Screen with Series of Three Gates Set to Collect: 1) any delamination signals in the composite doubler, 2) bond interface signal, and 3) backwall echo of the aluminum

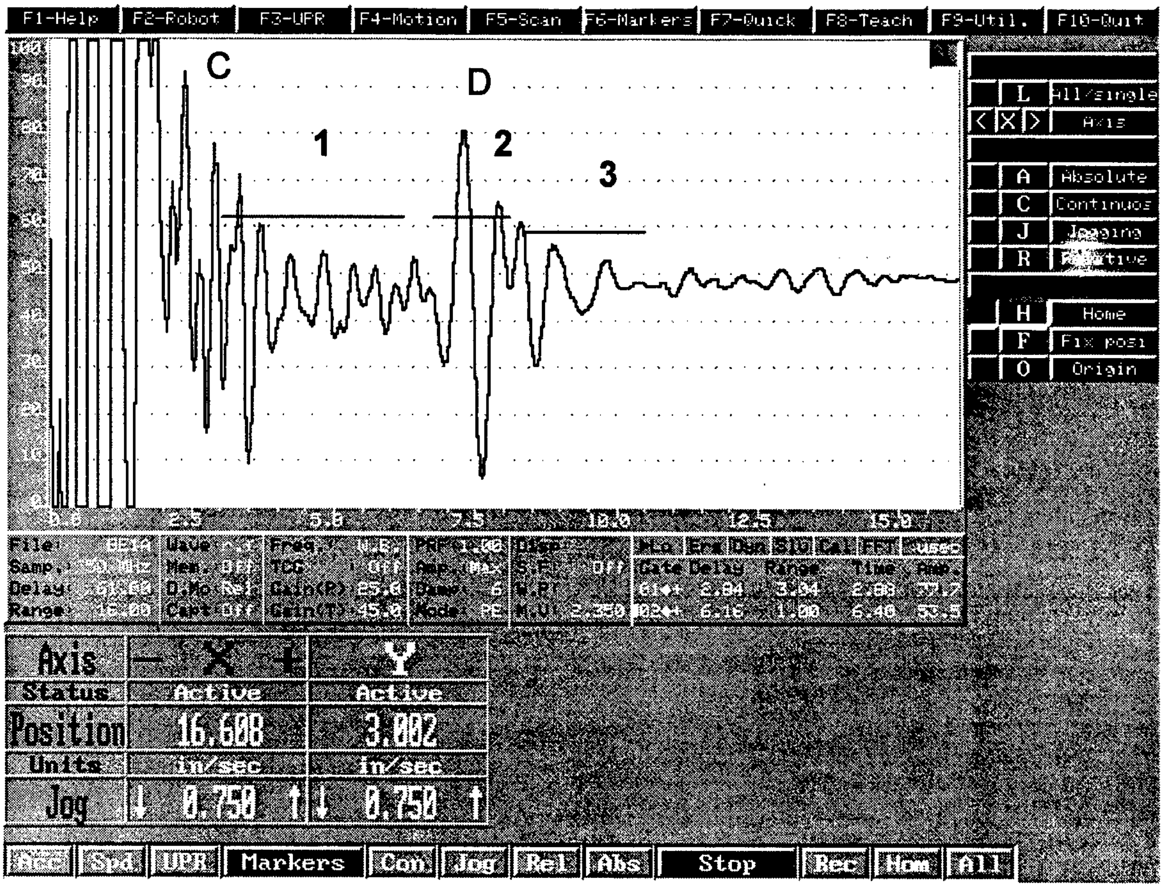


Figure A-7: A-Scan Trace on Display Screen with: 2) bond interface signal, and 3) no backwall signal from the aluminum

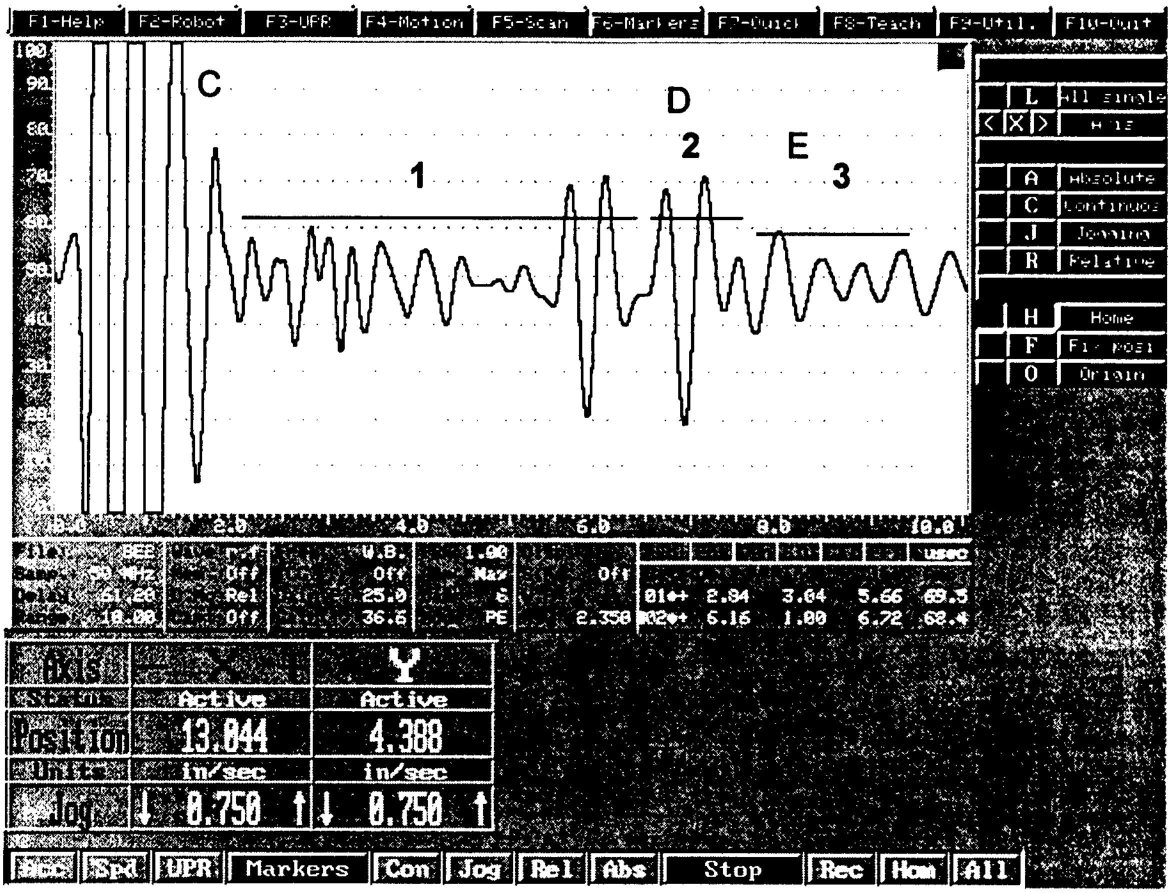


Figure A-8: A-Scan Trace on Display Screen with: 1) delamination signal in gate 1

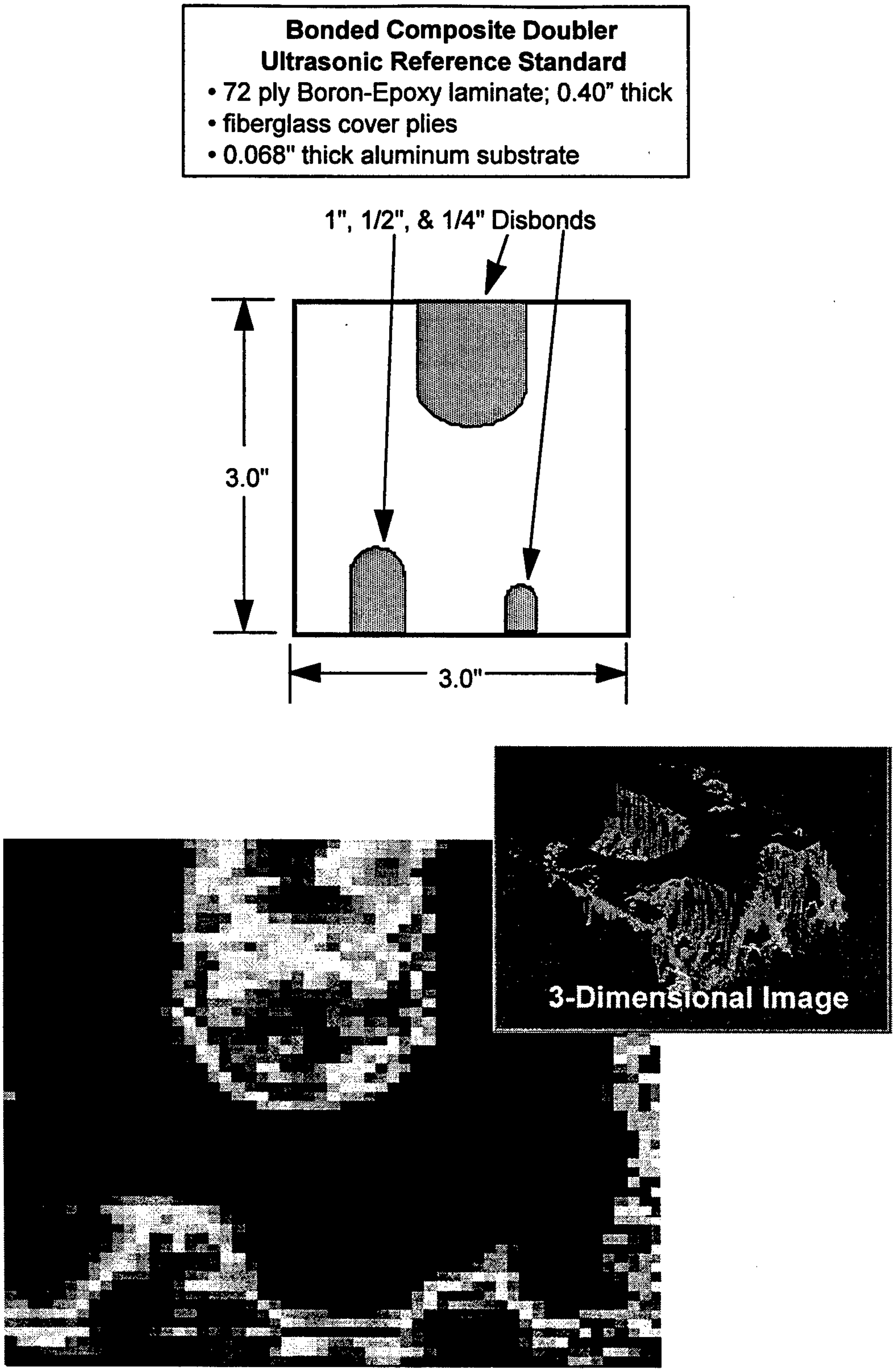


Figure A-9: Pulse-Echo Ultrasonic C-Scan of 72 Ply Bonded Composite Doubler Reference Standard with Engineered Flaws

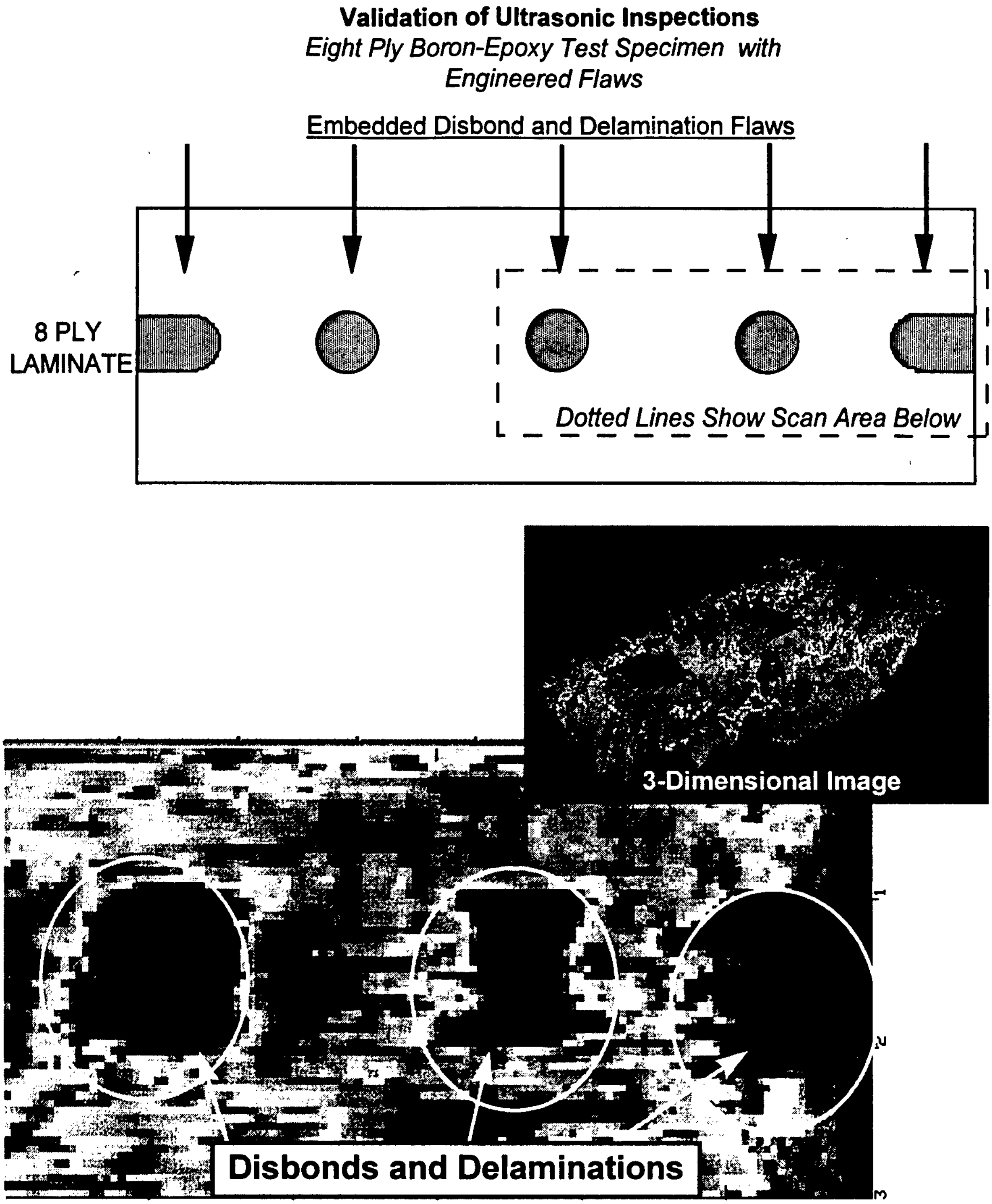


Figure A-10: Pulse-Echo Ultrasonic C-Scan of 8 Ply Bonded Composite Doubler Reference Standard with Engineered Flaws

Appendix B

Ultrasonic Inspection Procedure for Resonance Test Technique

Nondestructive Inspection Procedure for Bonded Boron/Epoxy Composite Doublers Using Ultrasonic Resonance Mode Technique

May 1998 - DRAFT

FAA Airworthiness Assurance NDI Validation Center
Sandia National Laboratories - Albuquerque, NM

Specification No. AANC-UT-Comp-5521/4-002

1.0 SCOPE

This procedure describes the criteria and procedure for ultrasonic (UT) inspection of bonded Boron Epoxy Doublers on aluminum substrates. Flaws detected through the use of this procedure are disbonds, delaminations, and porosity.

2.0 REFERENCES

2.1 Operation Manual - Staveley Sonic Bondmaster

3.0 REQUIREMENTS

3.1 Equipment

3.1.1 Sonic Bondmaster - (Staveley Instruments)

3.1.2 Resonant Ultrasonic Probe - 330 kHz Center frequency (Staveley Instruments)

3.1.3 Ultrasonic Reference Standard - Per Figure 1

3.2 Materials

3.2.1 Ultrasonic Couplant - Mixture of 50% water and 50% glycerin

3.3 Personnel

Personnel shall be certified to Level II minimum in the ultrasonic method per ATA 105 or other approved certification standard.

4.0 PROCEDURES

Refer to the operation manual for the location of the controls and a description of the instrument menu system.

4.1 Instrument Set-Up:

4.1.1 Attach the test probe to the instrument. The suggested probe is Staveley Instrument's S-PR-6, 330 kHz. If AC line current is to be used, attach the power cord and plug it into the appropriate power supply. Protect the probe by placing a covering of Mylar tape over the resonant crystal head. Care should be taken to assure that the tape covering the crystal is wrinkle free. Turn on the instrument.

4.1.2 Adjust the probe frequency to the desired setting of 330 kHz. This is done by pressing the 'set' button and adjusting the probe frequency by turning the control knob.

4.1.3 Use of UT Reference Standard - The UT Reference is shown in Figure 1. It consists of a composite doubler bonded to an aluminum plate. The doubler is a 13 ply $\{[0, +45, -45, 90]_3, 0\}$ lay-up and is bonded to the aluminum plate using the installation process called out in the Figure 1 notes. The aluminum plate is 2024-T3, 0.071" thick material. The UT reference standard contains a series of disbond, delamination, and probe nulling points (unflawed regions) which are used to carry out the inspection and interpret the inspection results. These points, labeled "A" - "O," are clearly marked on the UT Reference Standard and are referenced in the following inspection procedure.

4.1.4 <u>Setting Up Equipment for Inspection of the Maximum Ply Area (13 Plies) with Uniform Thickness</u>

4.1.4.1 Identify the area on the UT Reference Standard which corresponds to the maximum ply thickness of the doubler to be inspected. Using suitable ultrasonic couplant, couple the test probe to the unflawed, maximum ply nulling area of the UT Reference Standard (area "L" in Figure 1). Null the instrument using the null button; the dot on the active display should move to the center of the display.

4.1.4.2 Remove the probe from the standard. The display dot will move to an arbitrary location on the display. If the dot does not move from the null position, repeat steps 4.1.1 through 4.1.2 and 4.1.4.1 again to be sure the instrument is connected correctly.

4.1.4.3 Couple the probe to the location of the simulated disbond in the maximum ply region (area "D" in Figure 1). The display dot will move to an arbitrary location. Rotate the dot so it is located <u>on</u> the lower vertical axis (the negative y-axis). This is done by pressing the rotation button and using the control knob to adjust the rotation angle.

4.1.4.4 Couple the probe to the range of simulated interply delaminations that are located on the standard in the maximum ply region (areas "M", "N", "O", and "P" in Figure 1). Note each location of the display dot for each disbond and delamination reference. With these locations noted, couple the probe to the least sensitive disbond or delamination in the maximum 13-ply area. The least sensitive area corresponds to the disbond or delamination with the weakest signal. Adjust the gain so that there is at least a three division vertical separation from the null position to the display dot represented by the weakest signal. (NOTE: From the null position, the dot should travel downward when coupled to a disbond or delamination.)

4.1.4.5 With the proper gain set, once again couple the probe to each simulated disbond and delamination. At each location, use the 'store dot' button to store the representative dot for each disbond and delamination. The stored dots will appear on the 'stored' display on the right side of the screen. Note each location on the stored display.

4.1.4.6 Remove the probe from the standard. Store the 'lift-off' dot using the 'store dot' button. Note the location of the 'lift-off' dot on the stored display.

4.1.4.7 Set the alarm gate by pressing the 'alarm' button and then choosing the 'limits' button. Set the gate to encompass the lowest 2 vertical divisions of the display. The horizontal setting should include the total horizontal range of the display. Press the 'run' button when setting is complete.

4.1.5 Setting Up Equipment for Inspection of the Tapered Region (Plies 6-12) where the Doubler Thickness Changes in the X and Y Direction

4.1.5.1 Identify the area on the UT Reference Standard which corresponds to the tapered region to be inspected on the doubler (plies 6-12). Using suitable ultrasonic couplant, couple the test probe to the unflawed, 6-12 ply nulling area of the UT Reference Standard (area "K" in Figure 1). Null the instrument using the null button; the dot on the active display should move to the center of the display.

4.1.5.2 Remove the probe from the standard. The display dot will move to an arbitrary location on the display. If the dot does not move from the null position, repeat steps 4.1.1 through 4.1.2 and 4.1.5.1 again to be sure the instrument is connected correctly.

4.1.5.3 Couple the probe to the location of the simulated disbond in the 6-12 ply tapered region to be inspected on the doubler (area "C" in Figure 1). The display dot will move to an arbitrary location. Rotate the dot so it is located on the lower vertical axis (the negative y-axis). This is done by pressing the rotation button and using the control knob to adjust the rotation angle.

4.1.5.4 Couple the probe to the range of simulated disbonds in the 6-12 ply tapered region to be inspected on the doubler (areas "B", "C", "F", and "G" in Figure 1). Note each location of the display dot for each disbond reference area.

With these locations noted, couple the probe to the least sensitive disbond or delamination in the 6-12 ply tapered region to be inspected on the doubler. The least sensitive area corresponds to the disbond or delamination with the weakest signal. Adjust the gain so that there is at least a three division vertical separation from the null position to the display dot represented by the weakest signal. (NOTE: From the null position, the dot should travel downward when coupled to a disbond or delamination.)

4.1.5.5 With the proper gain set, once again couple the probe to each simulated disbond. At each location, use the 'store dot' button to store the representative dot for each disbond and delamination. The stored dots will appear on the 'stored' display on the right side of the screen. Note each location on the stored display.

4.1.5.6 Remove the probe from the standard. Store the 'lift-off' dot using the 'store dot' button. Note the location of the 'lift-off' dot on the stored display.

4.1.5.7 Set the alarm gate by pressing the 'alarm' button and then choosing the 'limits' button. Set the gate to encompass the lowest 2 vertical divisions of the display. The horizontal setting should include the total horizontal range of the display. Press the 'run' button when setting is complete.

4.1.6 Setting Up Equipment for Inspection of the Tapered Region (Plies 1-5) where the Doubler Thickness Changes in the X and Y Direction

4.1.6.1 Identify the area on the UT Reference Standard which corresponds to the tapered region to be inspected on the doubler (plies 1-5). Using suitable ultrasonic couplant, couple the test probe to the unflawed, 1-5 ply nulling area of the UT Reference Standard (area "J" in Figure 1). Null the instrument using the null button; the dot on the active display should move to the center of the display.

4.1.6.2 Remove the probe from the standard. The display dot will move to an arbitrary location on the display. If the dot does not move from the null position, repeat steps 4.1.1 through 4.1.2 and 4.1.6.1 again to be sure the instrument is connected correctly.

4.1.6.3 Couple the probe to the location of the simulated disbond in the 1-5 ply tapered region to be inspected on the doubler (area "A" in Figure 1). The display dot will move to an arbitrary location. Rotate the dot so it is located on the lower vertical axis (the negative y-axis). This is done by pressing the rotation button and using the control knob to adjust the rotation angle.

4.1.6.4 Couple the probe to the range of simulated disbonds in the 1-5 ply tapered region to be inspected on the doubler (areas "A", "E", "H", and "I" in Figure 1). Note each location of the display dot for each disbond reference area.

With these locations noted, couple the probe to the least sensitive disbond or delamination in the 1-5 ply tapered region to be inspected on the doubler. The least sensitive area corresponds to the disbond or delamination with the weakest signal. Adjust the gain so that there is at least a three division vertical separation from the null position to the display dot represented by the weakest signal. (NOTE: From the null position, the dot should travel downward when coupled to a disbond or delamination.)

4.1.6.5 With the proper gain set, once again couple the probe to each simulated disbond. At each location, use the 'store dot' button to store the representative dot for each disbond and delamination. The stored dots will appear on the 'stored' display on the right side of the screen. Note each location on the stored display.

4.1.6.6 Remove the probe from the standard. Store the 'lift-off' dot using the 'store dot' button. Note the location of the 'lift-off' dot on the stored display.

4.1.6.7 Set the alarm gate by pressing the 'alarm' button and then choosing the 'limits' button. Set the gate to encompass the lowest 2 vertical divisions of the display. The horizontal setting should include the total horizontal range of the display. Press the 'run' button when setting is complete.

4.2 Inspection Procedure:

4.2.1 Inspection of the Maximum Ply Area (13 Plies) with Uniform Thickness

4.2.1.1 Set up the equipment (obtain a null point and corresponding response dots for disbonds and delaminations) using the procedure described in 4.1.4.

4.2.1.2 Using sufficient couplant, scan the 13 ply inspection surface of the composite doubler with the probe, using a 20% overlap of probe passes. Observe the display to assure adequate contact is maintained. NOTE: It is important that the probe stays in the vicinity of the surface that the probe was calibrated for (13 ply thickness). If the probe is calibrated for the uniform 13 plies, it should stay near the specified uniform section. Likewise, if the probe is calibrated for a particular taper region, the probe should remain near that tapered section of the doubler (see section 4.2.2). If, however, the probe strays from the optimum calibrated surface, there is some leeway in disbond detection. This UT method is able to locate disbonds over a ply thickness range of +/- 5 lamina. Any excessive deviation from this range, without an appropriate re-nulling operation, will make classification of disbonds difficult.

4.2.1.3 Observe the display for flaw indications. Minor movement of the display dot (within 1.5 divisions) is expected due to normal variations in composite and bond line thicknesses. A flaw indication is one in which the display dot moves to, or beyond, the threshold of the equipment's alarm setting (three or more divisions in the negative y-direction from the null position). The display dot should move toward a location that has been stored as a flaw indication. Indications where the display dot moves to a location other than a stored flaw location and is in excess of two divisions from the null point should be brought to the attention of the appropriate NDT engineer.

4.2.1.3.1 When the display dot moves to a location that is near the stored lift-off dot setting, the indication should be verified as follows: Place the probe on the questionable area and hold it in a stationary position assuring that there is adequate couplant. If the display returns to the null position, the area indication was caused by lift-off. If the indication maintains it's position at the stored flaw location, it may be a flaw indication.

4.2.1.4 Detected flaws should be identified in terms of their depth (as correlated to the UT Reference Standard by using the stored flaw indications) and mapped per the following procedure:

4.2.1.4.1 Place the probe in the center of the identified indication. Move the probe in any direction while observing the display.

4.2.1.4.2 When the display dot returns to the vicinity of the null position, place a mark on the doubler at the edge of the probe on the opposite side of probe movement. Move the probe along the same line in the reverse direction traversing the flaw. When the display dot returns to the center null position, place another mark on the doubler at the edge of the probe on the opposite side of probe movement. The two marks indicate the outer edges of the flaw.

4.2.1.4.3 Repeat steps 4.2.1.4.1 and 4.2.1.4.2 until the flaw perimeter is completely mapped.

4.2.1.4.4 If the display returns to the center position upon any movement of the probe, then the flaw is equal to, or slightly smaller than, the probe diameter. In this case, exact dimensioning of the flaw contours is difficult.

4.2.2 <u>Inspection of the Tapered Region (Plies 6-12) where the Doubler Thickness Changes in the X and Y Direction</u>

4.2.1.1 Set up the equipment (obtain a null point and corresponding response dots for disbonds and delaminations) using the procedure described in 4.1.5.

4.2.2.2 Scanning the 6-12 Ply Inspection Surface - use the same procedure as 4.2.1.2.

4.2.2.3 Interpreting Flaw Indications - use the same procedure as 4.2.1.3.

4.2.2.4 Mapping Out Flaw Boundaries - use the same procedure as 4.2.1.4.

4.2.3 Inspection of the Tapered Region (Plies 1-5) where the Doubler Thickness Changes in the X and Y Direction

4.2.3.1 Set up the equipment (obtain a null point and corresponding response dots for disbonds and delaminations) using the procedure described in 4.1.6.

Note: Testing of UT probes on Boron-Epoxy doublers has shown that when the probe is used on the first three plies of the doubler, the probe response is close to the response when placed solely on the bare aluminum. The three composite lamina are nearly 'invisible' to the probe. Two steps are included here to alleviate this inspection difficulty and produce acceptable flaw detection levels. They are:

4.2.3.1.1 Null the probe on the appropriate tapered portion of the UT Reference Standard (area "J" in Figure 1) as per section 4.1.6.1.

4.2.3.1.2 Use a lower gain setting on the equipment. Repeat the calibration set-up procedure in section 4.1.6, however, go through the steps using a lower gain setting for the probe signal.

4.2.3.2 Scanning the 1-5 Ply Inspection Surface - use the same procedure as 4.2.1.2.

4.2.3.3 Interpreting Flaw Indications - use the same procedure as 4.2.1.3.

4.2.3.3.1 Note: Inspection of this thinnest portion of the composite doubler requires special attention in order to adequately interpret the resulting probe signals. To inspect the final five outer plies of the doubler taper area, multiple passes should be performed. For each pass, note all alarmed signals and locations. Multiple passes are necessary to note any inconsistent alarmed signals. After several passes, if the alarmed signals are inconsistent with one another, then the alarm could be due to the thin amount of composite that is between the probe and the aluminum skin. Assign disbond locations based on the consistency of an alarm over several repeat inspections of the same area.

4.2.3.4 Mapping Out Flaw Boundaries - use the same procedure as 4.2.1.4.

5.0 ACCEPTANCE / DISPOSITION

Report any flaw indications to appropriate engineering personnel on site for further evaluation and action.

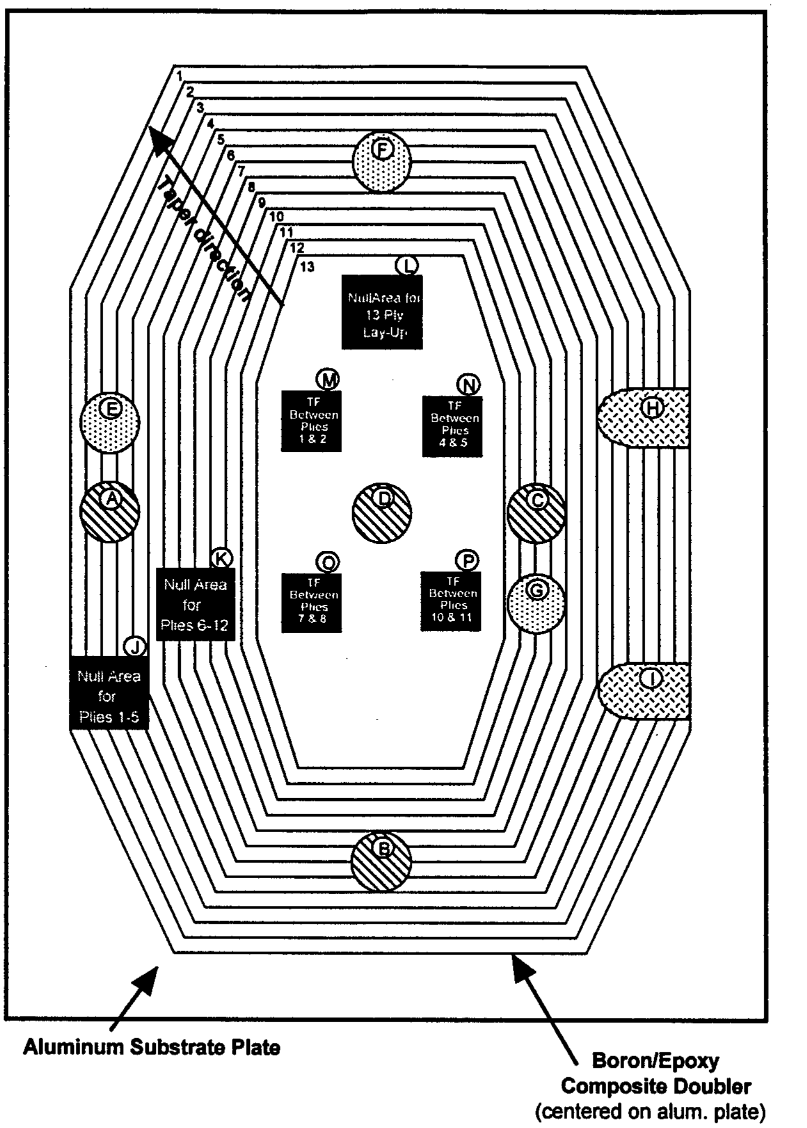


Figure B-1: Configuration of Boron-Epoxy Composite Doubler Reference Standard to Support Ultrasonic Inspections

Flaw Legend for Ultrasonic Reference Standard

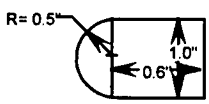
Teflon inserts to create disbonds between the composite doubler and the adhesive layer **(0.75" diameter)**

Teflon inserts to create disbonds between the aluminum plate and the adhesive layer **(0.75" diameter)**

Teflon insert to create delaminations between composite plies as indicated **(0.5" X 0.5" square)**

Areas with no engineered flaws used to set-up (i.e. probe nulling areas) for ultrasonic inspection equipment **(1.0" X 1.0" square)**

Teflon or Stainless Steel pull tab between the aluminum plate and the adhesive layer; removed after curing to produce an air gap disbond



Dimensions of Teflon pulltab

Ⓐ Labels to guide application of inspection procedure

Figure B-1 (continued): Flaw Legend for Reference Standard

Appendix C

Eddy Current Inspection Procedure for Detecting Cracks in Aluminum Structure Beneath Composite Doublers

Nondestructive Inspection Procedure for Aluminum Beneath Boron Epoxy Composite Doublers Using the Eddy Current Sliding Probe Technique

May 1998 - DRAFT

FAA Airworthiness Assurance NDI Validation Center
Sandia National Laboratories - Albuquerque, NM

Specification No. AANC-EC-Comp-5521/4-003

1.0 SCOPE

1.1 This procedure is used to find cracks on the fuselage skin underneath Boron Epoxy composite doublers.

1.2 This procedure is used to find cracks which emanate from the shank of the fastener in fuselage skins that are covered by a Boron Epoxy composite doubler. This procedure is also used to identify cracks that propagate in the skin from some other stress riser (i.e. without the help of a fastener shank).

1.3 The minimum detectable crack length depends on the thickness of the composite doubler as well as other doubler lay-up materials such as fiberglass (UV protection) and conductive coatings (lightning protection). Damage tolerance analyses will be used to determine minimum crack detection requirements.

1.4 Nominally, the procedure will be used to find a 0.5 inch (1.25 cm) long crack. Recent damage tolerance assessments have established adequate safety factors associated with the requirement to detect cracks which are 1.0" (2.5 cm) in length.

NOTE: This sliding probe procedure is sensitive to fastener diameter and crack orientation. It is intended to find cracks that extend parallel (+/- 30 degrees) to the axial centerline of the sliding probe. (This is in accordance with the sliding probes which have sensitivity characteristics like that of Staveley Instrument's SPO-3806 probe).

2.0 REFERENCES

2.1 Operation Manual - Supplied by each equipment manufacturer. (i.e. Staveley Nortec 19e " Eddyscope" or other eddy current device)

2.2 Boeing Nondestructive Test Manual - Part 6, 53-30-27

2.3 Lockheed Nondestructive Test Manual

3.0 REQUIREMENTS

3.1 Equipment

3.1.1 Instrument - An eddy-current impedance plane display instrument with a variable vertical and horizontal sensitivity control is required for this procedure. The instrument must have reflection probe capability and be able to operate between a frequency of 500 Hz and 30 kHz. The following instruments are candidates for use in this procedure and are included in Ref. [2.2] and Ref. [2.3].

(1) NDT 18, Nortec

(2) NDT 19, Nortec

(3) AV100, Hocking

(4) MIZ 20A, Zetec

Other instruments can be used if the probe and instrument combination can satisfy the requirements of this procedure.

3.1.2 Probe - Reflection probe that can find 0.50 inch (1.25 cm) long crack that starts at the base of a countersunk 5/32" and 3/16" diameter fasteners. The probe must be able to find cracks oriented parallel to the probe's axial centerline (+/- 30 degrees) when the probe is swept over a known rivet. The frequencies of the probes used for this inspection should have an operating frequency range of 500 Hz to 30 kHz. The following probes satisfy these requirements and were used to develop this procedure.

P/N	Frequency	Mfg.
SPO-3806	10 kHz - 30 kHz	Staveley Instruments (Nortec Div.)
S/300Hz-10kHz/.62	300 Hz - 5 kHz	Staveley Instruments (Nortec Div.)

3.1.3 Reference Standard - The composite doubler reference standard consists of a combination of the existing OEM crack reference standard (metallic) - for the area incorporated by the doubler footprint - and a composite laminate lay-up which is representative of the doubler designed for the particular application. This lay-up should include all geometry and materials which are present in the actual on-aircraft installation. These features include, but are not limited to, total number of plies with proper orientation, lightning protection layers, UV protection layers, metal clips or brackets, and composite ply tapers. The composite laminate lay-up is placed over the crack reference standard and all inspections are performed through the lay-up. Figure 1 shows an example of a composite doubler lay-up superimposed over a lap splice reference standard from Ref. [2.2].

A reference standard that best represents each area of inspection must be used. The structural configuration (skin, fastener, substructure elements, etc.) underneath the composite must be known prior to inspection. This is necessary for the proper calibration of the eddy current instrument for the structure being inspected. For example, when inspecting a lap joint underneath a doubler, a lap joint reference standard must be used with known manufactured flaws; see Detail 1 from Figure 1.

NOTE: It may be necessary to modify the OEM crack reference standard since the EDM notch cracks (e.g. 0.10" long for surface cracks and 0.20" long for second layer cracks) are shorter than the crack lengths needed for a composite-reinforced structure. Figure 1 also includes an example of a composite doubler superimposed over a cracked aluminum standard which has longer cracks (both 0^{o} and off-angle cracks). The Douglas crack reference standard (DR8354560) shown in Detail 2 would work for this scenario. In this case, the cracks emanating from the rivet holes are up to 0.60 inch long and are more representative of the crack detection goals for composite doubler reinforced structures

4.0 PREPARATION FOR INSPECTION

4.1 Make sure the inspection area is clean.

4.2 Make sure the probe and the power cords are plugged into the correct locations.

5.0 INSTRUMENT CALIBRATION

5.1 Turn the instrument on and perform the normal start-up procedures as specified by the instrument's operation manual. See also Ref. [2.2] and [2.3] for additional information on all of the steps described below.

5.2 Place the probe over an unflawed portion of the reference standard. Press the null button to obtain the location of the signal trace at the null position. Adjust the signal trace to the lower right-hand quadrant. The trace should be positioned two divisions up from the bottom and two divisions from the right side of the display as shown in Figure 2.

5.3 Set the frequency depending on the desired depth of flaw detection as driven by the thickness of the aluminum and composite doubler assembly. As a starting point, a setting of 30 kHz is suggested for doublers with thicknesses around 0.15" (25 plies).

5.4 Place the probe over a location on the reference standard that represents the doubler-skin configuration that is going to be inspected on the fuselage (i.e. if a row of rivets are to be inspected on multi-layered joint, then it is necessary to null on the portion of the reference standard that simulates an unflawed portion of the joint; see Figure 1). Null the instrument to calibrate the probe.

5.5 Rock the probe from side-to-side and adjust the lift-off response to move from right to left as shown in Figure 2.

5.6 Place the probe over a location on the reference standard that represents the known configuration of the inspection area (in this example, the lap splice portion). Begin to scan the first rivet that is marked (No. 1) on the composite doubler reference standard (see Figure 3a). To scan the rivet, slowly slide the probe perpendicular to the probe's axial centerline. While doing this, move the probe in the direction of the axial centerline (see Figure 3b). The signal trace should register a 'curve envelope' as shown in Figure 2.

5.7 Monitor the instrument signal pattern and adjust the instrument controls to get a signal with the same shape as shown in Figure 2. Different probes can give patterns which differ slightly from the shape from shown.

5.8 Scan the next fastener, No. 2 in Figure 3a, with the same procedure as described in step 5.6. (NOTE: It may be necessary to erase the signal trace on the instrument display. This should eliminate any ambiguity in the signal's shape for each inspection area.) The instrument signal pattern must be similar to the reference notch signal shown in Figure 4.

5.9 Adjust the gain controls so that there is a two vertical and/or horizontal division separation between the unflawed and flawed signal representations. NOTE: It will be necessary to rescan Nos. 1 and 2 after changing the gains. This <u>must</u> be done to assure a two division separation.

5.10 Scan the probe over fasteners No. 3 and 4 in Figure 3a while monitoring the instrument signal pattern. (NOTE: The instrument display may need to be recorded and cleared after scanning each fastener. This will allow the scanned signal for each fastener to be clearly identified). The instrument signal should be similar to Figure 5. There must be at least one vertical and/or horizontal division separation between the non-defect signal and the off-angle reference notch signals. If a one division separation is not found, adjust the gain controls to produce the desired separation. (NOTE: These two signals are considered the worst case inspection situations. All other flaw signals should have, at a minimum, a one division separation).

5.11 If the instrument has an alarm, set the alarm so that it will operate when the probe is moved over the reference notches at fasteners 2, 3, and 4 on the reference standard (see Figure 3a).

5.12 To set up the instrument to inspect the fuselage skin, away from a lap splice joint, continue with the following procedure:

5.12.1 Place the probe on an unflawed portion of the reference standard which represents the area having the same skin-doubler configuration as the actual inspection area on the aircraft (see lower portion of Figure 1 reference standard labeled "Normal Fuselage Skin Configuration"). Null the probe.

5.12.2 Begin to scan the first area (area 1, Figure 1) that is marked on the composite doubler reference standard. To scan this area, slowly slide the probe perpendicular to the probe's axial centerline. While doing this, move the probe in the direction of the axial centerline, scanning the whole area. The signal trace should <u>not</u> register a curve for this area. This represents an unflawed portion of the fuselage.

5.12.3 Scan the next area (area 2 in Figure 1) with the same procedure as described in step 5.12.1. The instrument signal pattern must be similar to the reference crack signal shown in Figure 6. Adjust the instrument's phase angle, frequency, and gain control so the instrument's signal pattern is similar to that of Figure 6.

5.12.4 Scan the probe over areas marked 3 and 4 in Figure 1 while monitoring the instrument signal pattern. (NOTE: The instrument display may need to be cleared after scanning each area. This should eliminate any ambiguity in the signal's shape for each inspection area.) The signal trace should map out a signal curve. (NOTE: When inspecting the uniform fuselage skin for a stray crack, any signal curve that is traced out is an indication of a skin flaw. This, however, does not hold true for the inspection of a fastened joint since, in these cases, crack signals must be differentiated from signal curves generated by the rivets under the composite doubler.)

6.0 INSPECTION PROCEDURE

6.1 Calibrate the instrument per Section 5.0. The instrument should use the gain, frequency, and phase angle settings that were noted in Section 5.0 for each skin-doubler configuration being inspected.

6.2 Place the probe on an unflawed area of the composite doubler reference standard that contains the configuration of the aircraft fuselage to be inspected. Null the instrument.

6.3 Make sure the lift off response is similar to that established in par. 5.5.

6.4 Inspect each area of the fuselage for which the instrument was calibrated. The sliding probe movement should be performed as explained in par. 5.6 (Figure 3). (NOTE: In order to assure a thorough inspection, the entire area of the specified skin configuration must be covered by the sliding probe.)

6.4.1 If a riveted lap joint is being inspected, begin scanning until the first rivet signal is found. (NOTE: Knowledge of the fuselage configuration underneath the doubler is very helpful when performing this step. With this knowledge, it is easier to pinpoint where each rivet fastener is located. Thus, it is possible to differentiate between signals stemming from rivet holes and signals stemming from cracks in the aluminum. It is recommended that a Mylar map of the repair area be made prior to the installation of the composite doubler. This map, which shows the location of all rivets and substructure elements, can then be placed over the doubler during subsequent eddy current inspections.)

6.4.2 For each rivet that is found when scanning over the composite doubler, a full scan of the rivet should be performed. A full scan requires the inspection of each rivet using three orientations of the sliding probe. The orientations are 0, 60, and 120 degrees as shown in Figure 7. Since the sensitivity of the probe is +/- 30 degrees, these three orientations are necessary to inspect all 360 degrees of the rivet fastener. Once this full scan is performed, the signal 'envelope' can be compared with those signals that were found during the calibration process. If there is a vertical or horizontal shift of one division or more, compared to a normal rivet signal, a flaw is present. (NOTE: If it is known that cracks are propagating in a specific direction, it is only necessary to inspect the configuration with the probe's axial centerline lined up in that given direction.)

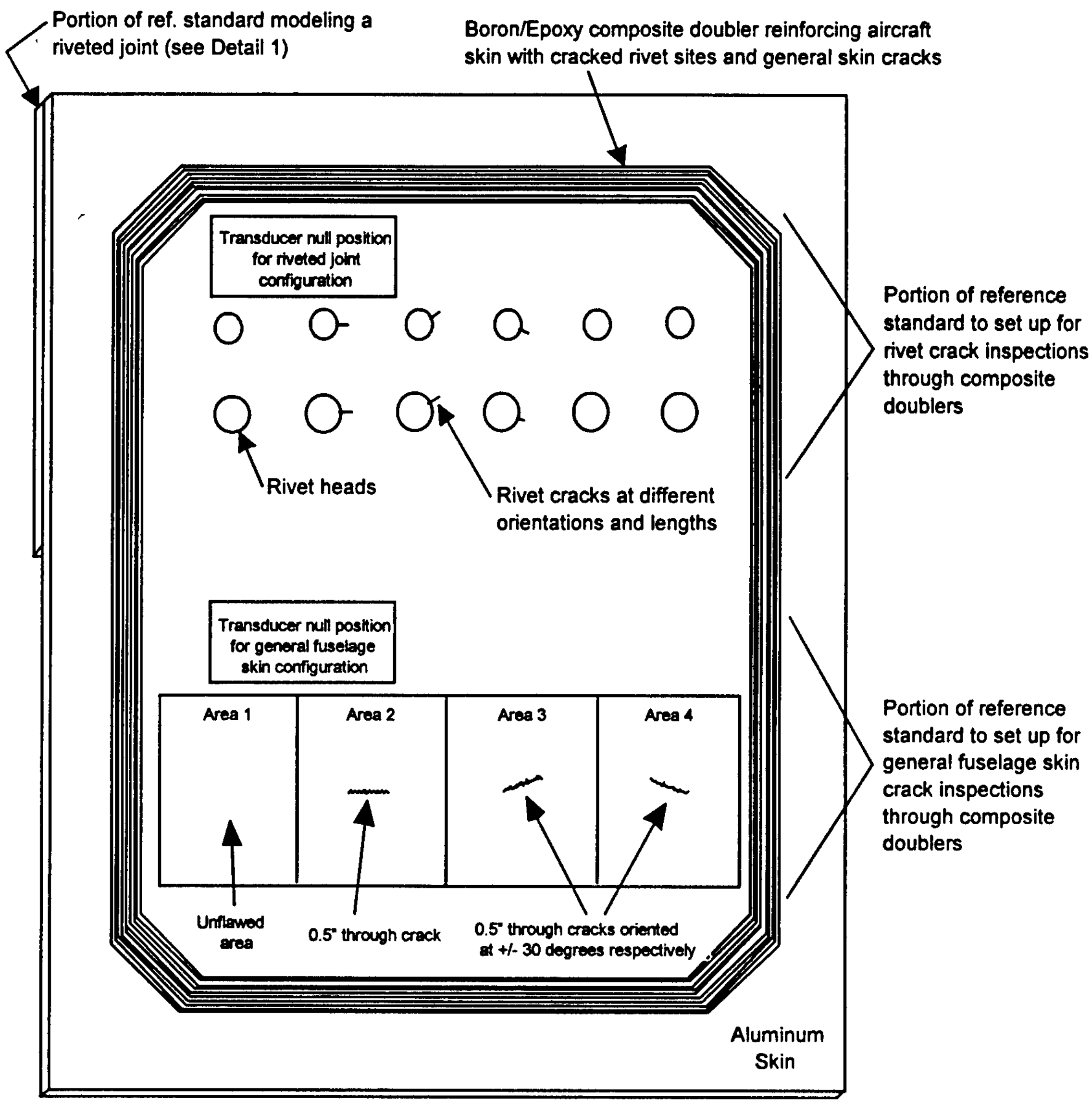
6.4.3 Continue inspecting each rivet fastener until each known fastener is inspected and compared with calibration signals.

6.5 Inspect all other known configurations of the fuselage that do not contain rivets. It is necessary to have the instrument's gain, frequency, and phase angle set to the calibrated settings for each given configuration. Note all signals that deviate the signal trace from the null position. If a fastener or any other outstanding skin characteristic is not known to exist in this location, the signal may be characterized as a fuselage flaw.

7.0 INSPECTION RESULTS

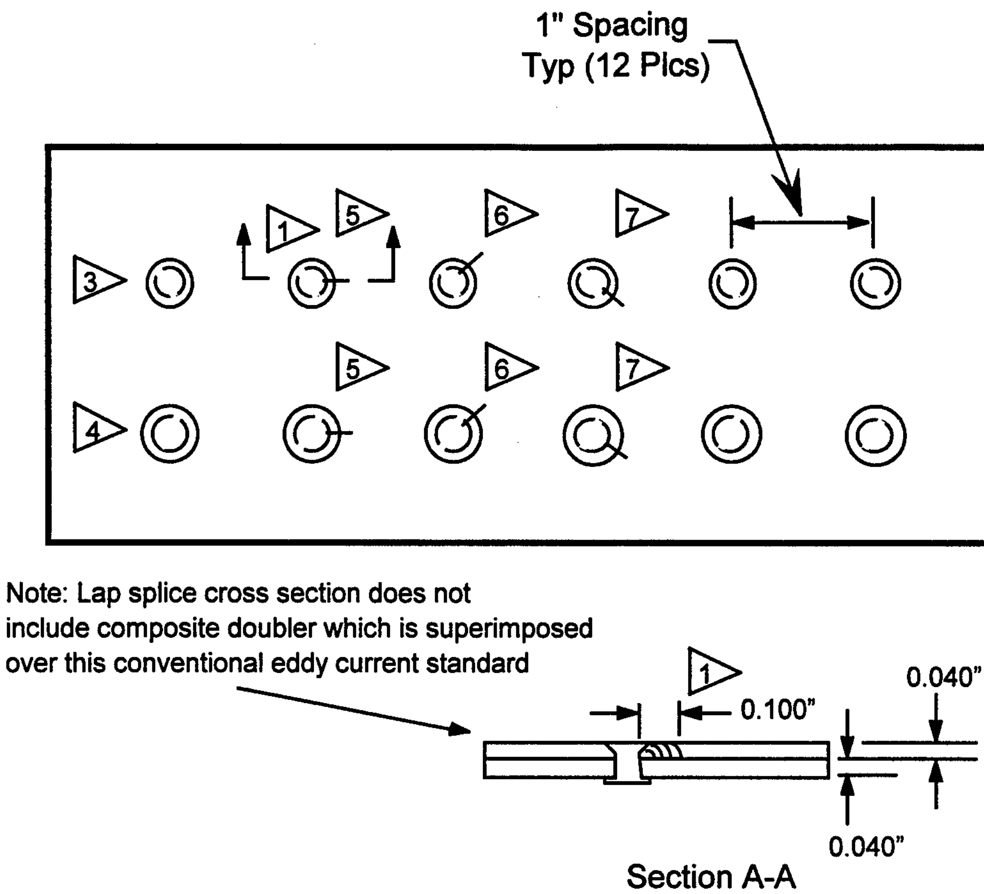
7.1 All vertical and/or horizontal shifts of one division or more indicate a crack and must be examined further. These shifts are relative to the calibrated, unflawed signals obtained from the reference standard.

7.2 Rivets that are not BACR15CE*D* rivets will give a different signal than the reference standard signal (Boeing NDT Manual, Part 6, 53-30-27). The calibration and subsequent inspections must be adjusted accordingly.



NOTE: (1) Reference standard flaws lie in the aluminum underneath the boron/edpoxy composite doubler.
(2) All reference standard flaws lying underneath the composite doubler should be marked on the face of the doubler for easy location of the flaws.

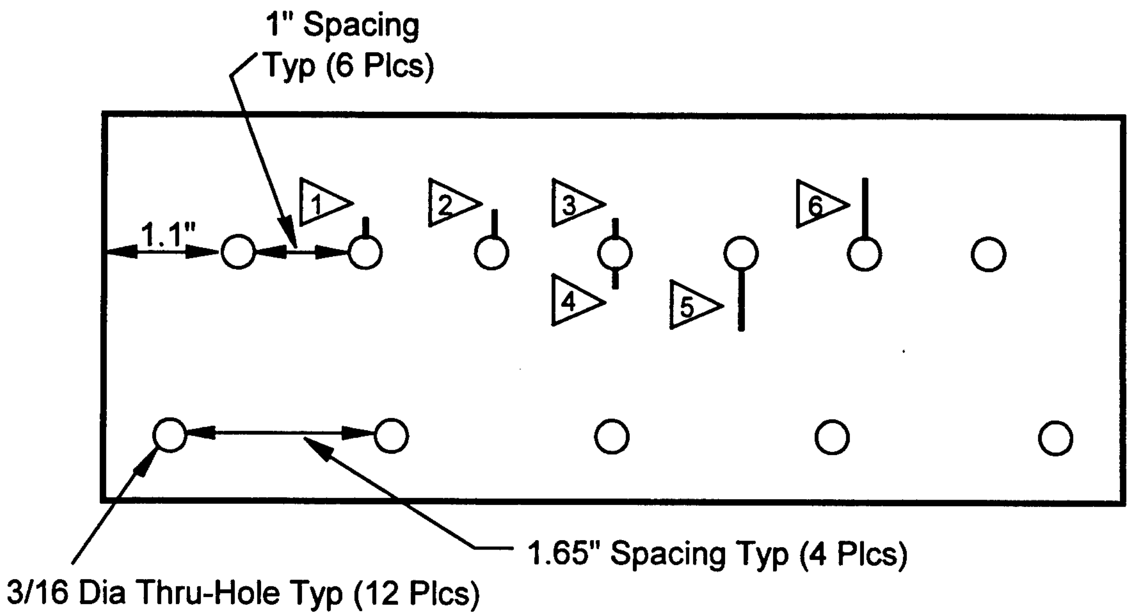
Figure C-1: Configuration of Composite Doubler Reference Standard to Support Eddy Current Inspections



Material: 2024-T3 or T4 Clad

- 1 EDM Notch, Max 0.007" Wide (6 Places)
- 3 5/32 Inch Fastener (6 Places)
- 4 3/16 Inch Fastener (6 Places)
- 5 Notch Orientation 90 Degrees
- 6 Notch Orientation 60 Degrees
- 7 Notch Orientation 120 Degrees

Figure C-1 (Detail 1): Configuration of Riveted Joint Portion of EC Reference Standard



Material: 2024-T3 or T4 Clad

1. 0.15" Long EDM Notch, Orientation 90°, Max 0.007" Wide
2. 0.25" Long EDM Notch, Orientation 90°, Max 0.007" Wide
3. 0.15" Long EDM Notch, Orientation 90°, Max 0.007" Wide
4. 0.125" Long EDM Notch, Orientation 90°, Max 0.007" Wide
5. 0.50" Long EDM Notch, Orientation 90°, Max 0.007" Wide
6. 0.50" Long EDM Notch, Orientation 90°, Max 0.007" Wide

Figure C-1 (Detail 2): Configuration of General Skin Crack Portion of EC Reference Standard

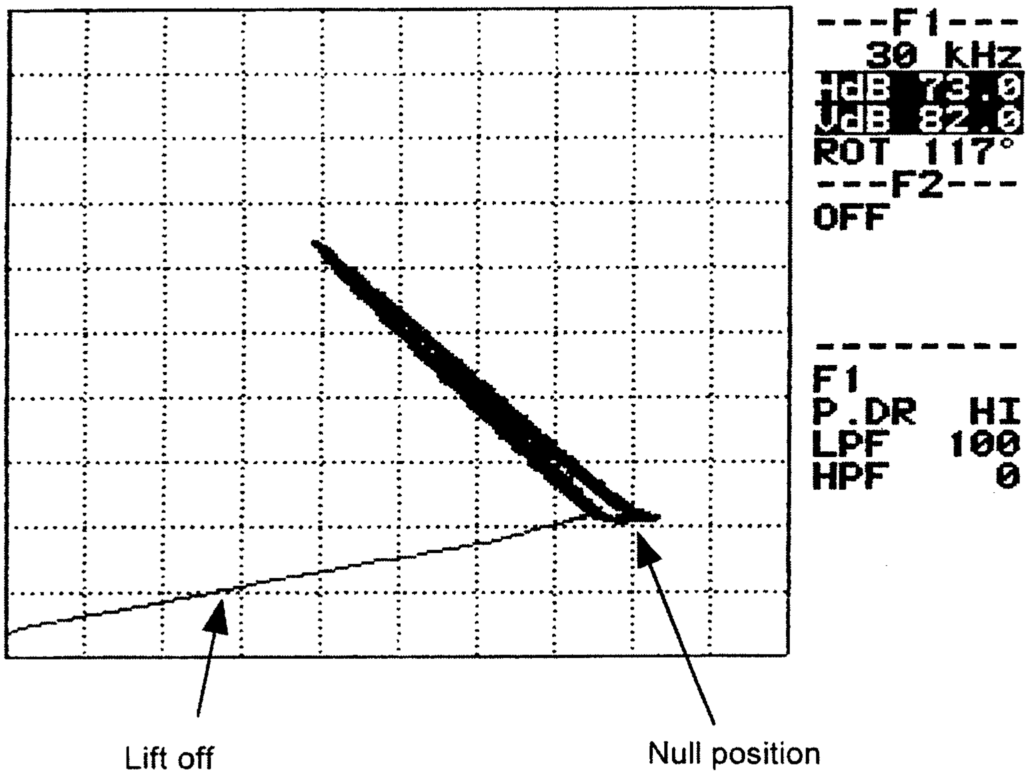
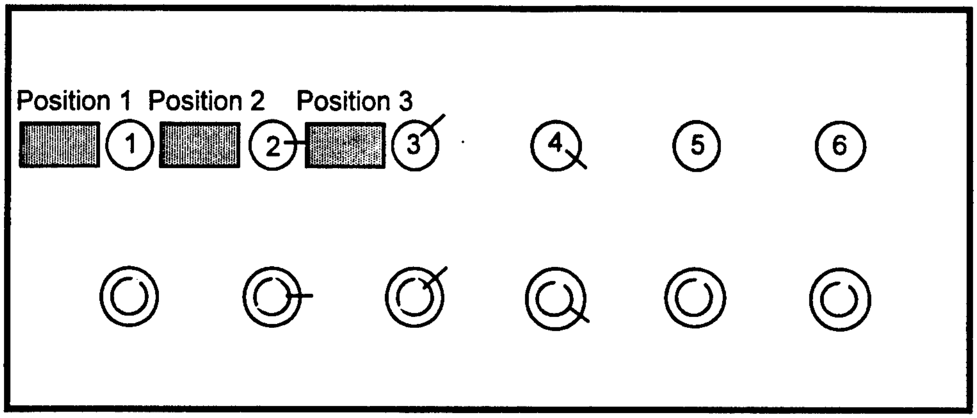
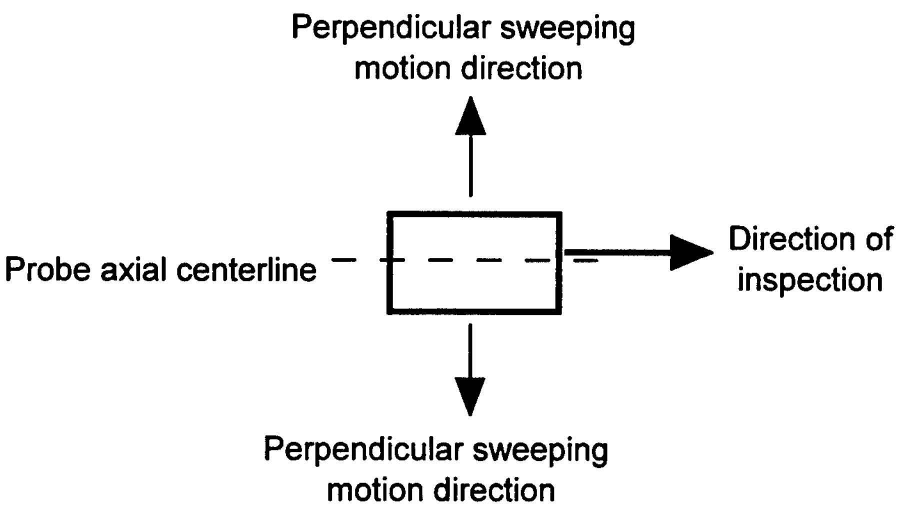


Figure C-2: Signal Trace of an Unflawed Rivet Site



(a) Lap joint reference flaw configuration originating from the shank of each fastener



(b) Top view of eddy current sliding probe.

Figure C-3: Motion of Sliding Probe Over Fasteners

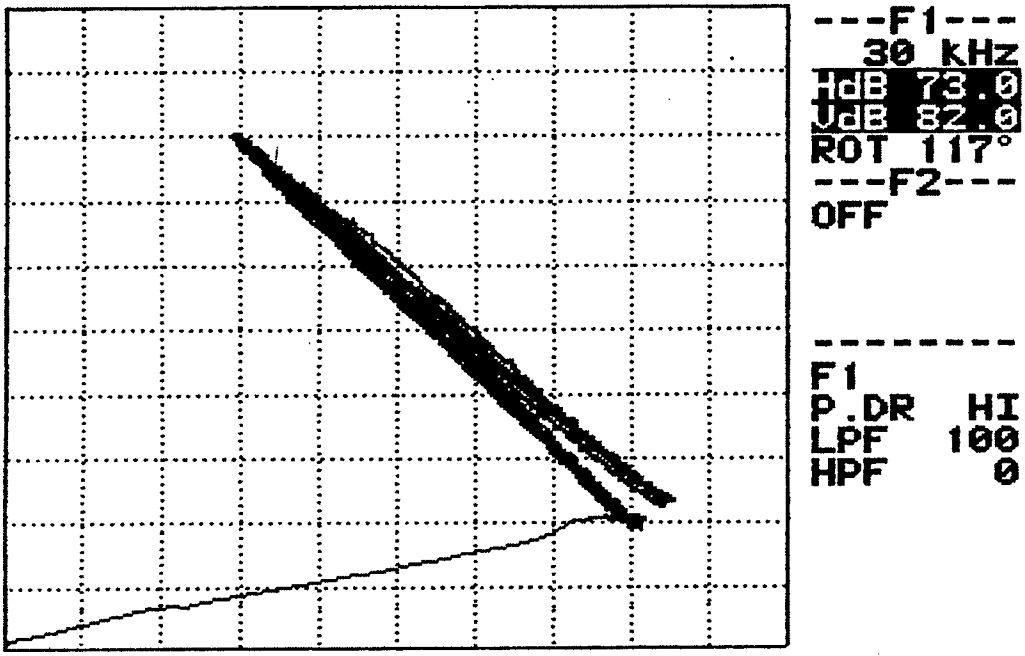


Figure C-4: Signal Trace of a 0.100" Long Crack Originating from a Rivet Shank at 0 Degrees

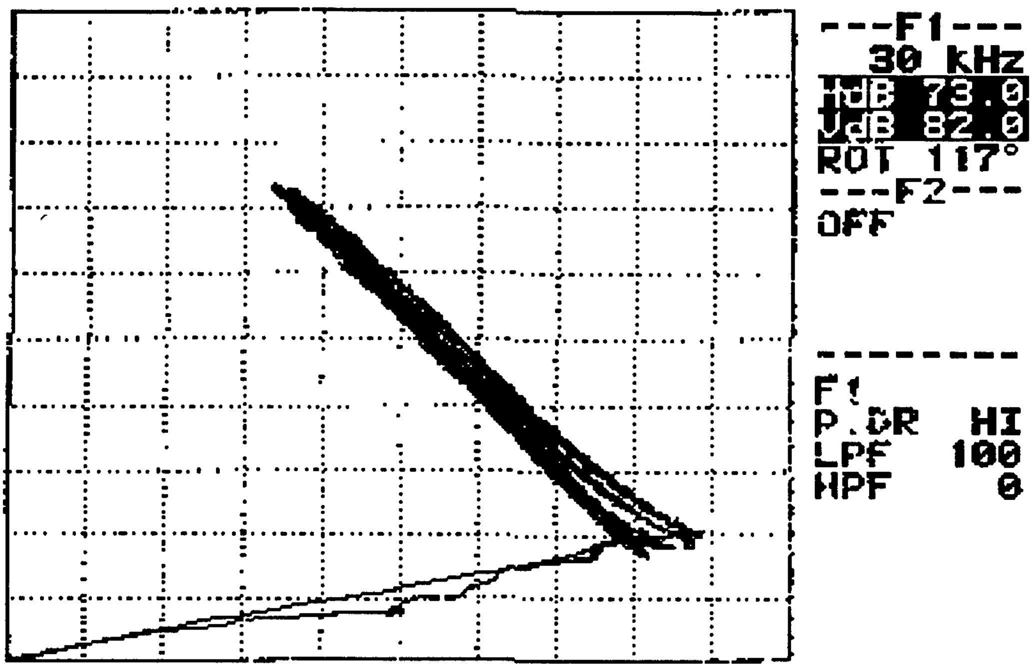


Figure C-5: Signal Trace of a 0.100" Long Crack Originating from a Rivet Shank at 30 Degrees

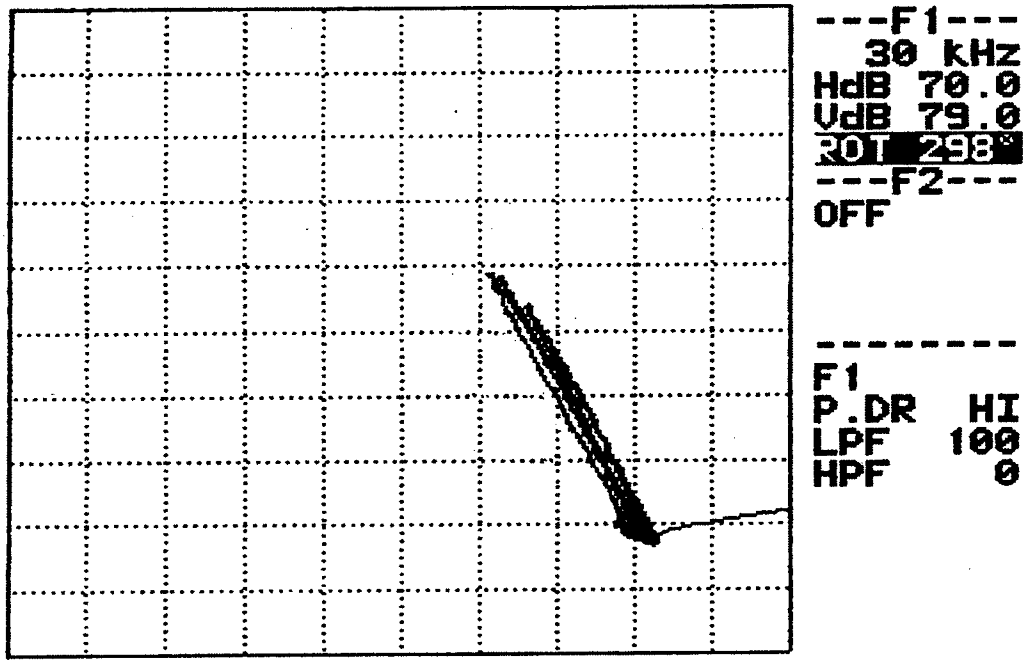
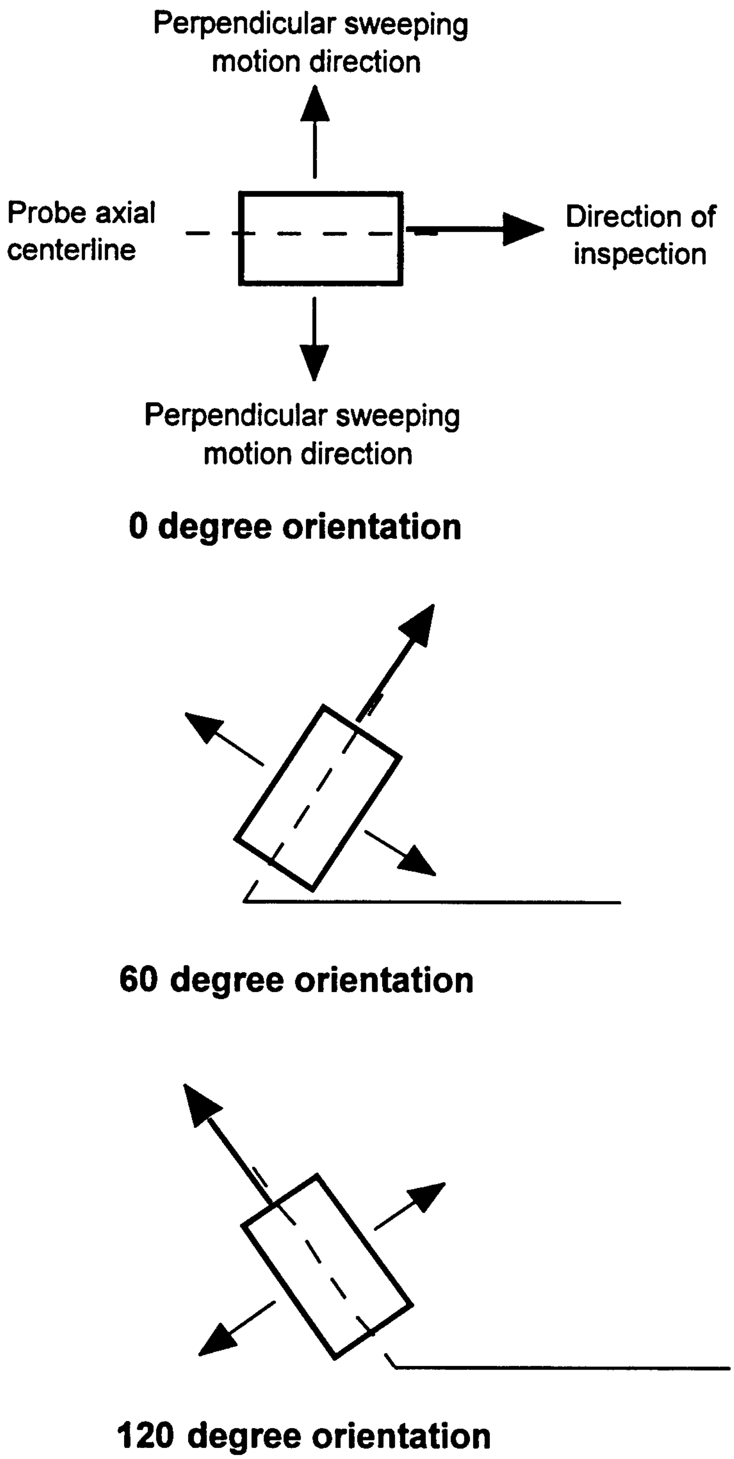


Figure C-6: Signal Trace of a 0.500" Long Crack Running Through a Portion of Uniform Fuselage Skin [Note: this crack does not emanate from a rivet shank]



NOTE: All three orientations are necessary for the sliding probe to be sensitive to all angles of cracks in the fuselage skin.

Figure C-7: Sliding Probe Orientations for the Inspection of Cracks Beneath Composite Doublers

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