Overview of Composite Projects at the FAA Airworthiness Assurance Validation Center

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Abstract
The Airworthiness Assurance NDI Validation Center (AANC) was established by the Federal Aviation Administration (FAA) William J. Hughes Technical Center at Sandia National Laboratories in 1991 to support nondestructive inspection (NDI) technology development and assessment. The evaluations are done using a variety of characterized test specimens and test beds including entire transport and commuter aircraft. Although the initial work at the Center concentrated on metallic structure, the FAA has more recently expanded the AANC's charter to include projects directed at composite repair and inspection. The three projects briefly described in this paper are: 1) the validation and technology transfer of a thermographic technique for composite inspection, 2) the development of generic composite laminate and honeycomb calibration reference standards, and 3) the certification of the use of a boron epoxy doubler on a Lockheed L-1011.

Background
The AANC was established by the Federal Aviation Administration FAA at Sandia National Laboratories to support nondestructive inspection (NDI) technology development and assessment. The major objective of the Center is to provide the developers, users, and regulators of aircraft needing NDI, maintenance, and repair information with comprehensive, independent, and quantitative evaluations of new and enhanced inspection, maintenance, and repair techniques.

The roles of the Validation Center are:

- To provide test specimens and procedures and do realistic assessments (technical and economic) of aircraft inspection, maintenance, and repair techniques,
- To provide quantitative reliability data on the field application of inspection and repair technologies,
- To serve as a catalyst for new technique development with subsequent technology transfer to industry.

Some examples of successful projects include: 1) The validation and transfer of a safer and more economical inspection technique for the Douglas DC-9 Tee Cap to industry use, 2) The development of an inspection technique for the Piper PA25 wing spar that became the basis for an airworthiness directive, 3) The development of an inspection procedure for United States Coast Guard HU25 window posts to look for cracks and the subsequent baselining of over 30 USCG aircraft.

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**Inspection Validation using Composites**

The expanded use of composite structures and the development of new composite repair techniques on United States Air Force (USAF) aircraft has created the need for improved portable, quantitative NDI methods and systems. Recent advancements in thermal imaging technologies could provide new inspection capabilities that can be used by field-level NDI personnel to reliably inspect aircraft composite structures and repairs. Under the sponsorship of the Warner Robins Air Logistics Center, Robins, Georgia, the AANC recently started a project to provide the USAF with a field-level thermal imaging NDI capability for inspection of bonded composite structures and repairs on USAF aircraft. This project targets two applications on Air Force aircraft: 1) bonded composite doublers on the C-141 wing plank, and 2) composite honeycomb structure on the F-15 rudder. The composite honeycomb structure is boron epoxy skin to aluminum honeycomb.

**Project Overview**

This project will produce new composite inspection capabilities ready for use on operational USAF aircraft. The work is divided into five phases:

**Phase I - System Evaluation:** Produce a list of candidate thermography systems for formal testing and evaluation,

**Phase II - Structured Validation Experiments:** Evaluate USAF selected thermography systems in a series of statistically valid, structured experiments to determine which system best meets the USAF inspection requirements,

**Phase III - Calibration Standards:** Develop and deliver composite calibration standards and manufacturing procedures for the standards,

**Phase IV - Field Evaluation:** Support field level evaluation of the USAF selected thermography system, and

**Phase V - Documentation:** Provide the final NDI procedures manual, calibration standards with manufacturing procedures, expanded training syllabus (including a practical hands-on section), and prototype commercial thermography inspection system.

**Project Status**

Candidate thermography systems have been selected for formal testing and evaluation. The experiment design and protocols are complete, the test specimens and calibration standards have been manufactured, and the data acquisition and grading methods have been developed. The structured experiments are underway and will continue throughout the summer of 1997. The on-
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aircraft field evaluations will be conducted during the first quarter of 1998, with the program completion scheduled for the third quarter of 1998.

The experiments primarily emphasize the detection and quantification of disbonds (e.g., honeycomb core to composite skin disbonds, structural element skin to repair disbonds), interlayer delaminations, and fluid ingress. The manufactured test specimens simulate an F-15 rudder, a C-141 weep hole reinforcement, and a composite repair on a C-141 fuselage. Although this project focuses on specific F-15 and C-141 inspection applications, it is expected that the implemented technology will be transferable to numerous USAF composite inspection requirements.

Composite Inspection Reference Standards

After developing a Composite Inspection Handbook, the Commercial Aircraft Composite Repair Committee (CACRC) Inspection Task Group identified a need for a set of "generic" composite reference standards for use by operators in setting up their inspection equipment. The reference standards would include typical composite flaw scenarios - delaminations, disbonds, and inclusions/porosity - and incorporate structural configurations of Boeing, Douglas, Airbus, and Fokker aircraft. The AANC's participation in this effort was solicited by CACRC personnel because it was felt that the AANC could develop and evaluate the standards in an independent manner and the results reflect the inspection needs of all aircraft designs.

Project Overview

The purpose of this project is to develop a set of composite calibration standards (laminate and honeycomb) to be used in NDT equipment calibration for accomplishment of damage assessment and post-repair inspection of all commercial aircraft composites. The project includes a number of steps: 1) review composite structure designs of each Original Equipment Manufacturer (OEM) and discuss unique reference standard needs with them, 2) develop processes for producing the various engineered flaws in the specimens, 3) apply NDI techniques to the resultant test specimens and assess their applications and limitations, and 4) produce new or enhance existing composite NDI procedures through the use of the reference standards and possible application of improved NDI equipment. The project tasks described below address both solid laminate and honeycomb composite reference standards. The solid laminates and composite honeycomb are both carbon graphite and fiberglass materials. The composite is Nomex skin bonded to fiberglass honeycomb.

Solid Laminate Composite Reference Standards

Task Definition - Conduct a series of tests on existing OEM laminate composite standards in order to assess the variations in ultrasonic inspection results. Compare the NDI results (material properties) from different laminates which have been manufactured in accordance with Douglas, Boeing, and Airbus specifications. The NDI issues include signal attenuation and velocity through the laminate.
Test Plan - Use 5 MHz and 10 MHz broad band transducers and perform inspections in a UT immersion tank in order to eliminate the coupling variable. This will allow comparison of the material properties of the different laminates. The test results will be used to establish a single, existing reference standard (or new one with a generic material) and to determine a series of correction/conversion factors to accommodate inspections on other materials.

Deliverables - 1) a series of NDI output curves such as signal attenuation vs. laminate thickness, laminate material, and inspection frequency, and 2) recommendations for a single laminate composite standard and a table of conversion factors to accommodate composite laminate inspections on all transport aircraft (i.e., other materials).

Honeycomb Sandwich Composite Reference Standards

Task Definition - Apply multiple conventional NDI techniques to a series of composite honeycomb reference standards which have been constructed with different fabrication options and flaw scenarios. Items to be varied include core thickness, core weight, skin material, cell size, skin thickness, and core material. Develop processes to reliably produce specimens with engineered flaws. Identify the important variables which should be included in composite honeycomb reference standards. Produce a design plan which describes how the variables should be combined and a fabrication plan to reliably produce consistent standards. Assess the effects of each variable on NDI in order to provide justification for minimizing the number of calibration standards.

Test Plan - Apply multiple NDI techniques to the suite of test specimens. Experiments will be performed using: 1) thru-transmission ultrasonics, 2) tap test, 3) Staveley Bondmaster (pitch-catch, swept, and MIA), 4) Zetec Sondicators. The application of these NDI techniques will be carried out using a method to control the probe pressure.

Deliverables - 1) series of flawed composite honeycomb specimens which isolate individual composite fabrication variables, 2) a lab report describing the effect of each variable on different inspection techniques and procedures, and 3) a corresponding series of recommendations for a set of void detection (disbond/delamination) standards.

Project Status

The AANC has completed the design, fabrication, and evaluation of a trial honeycomb test specimen for the project. Figure 1 shows the specimen which was fabricated in the Northwest Airlines composite shop. The specimen contains the following features:
- numerous duplicate flaws were implanted get some statistics on how well each approach works
- the laminate was individually cured
- the laminate was joined to the honeycomb using a secondary bond
- disbonds were generated by machining recesses in the honeycomb material; this produced air gaps between the honeycomb and the composite laminate
delaminations were generated using the four methods shown in Figure 1: 1) teflon inserts, 2) "pillow" inserts, 3) teflon pull tabs, and 4) stainless steel pull tabs.

- the pillow inserts consisted of 3 layers of 1 mil thick paper enclosed by 2.5 mil, high temperature Kapton tape; the paper stack interrupts an NDT signal and simulates an air gap between adjacent plies
- the stainless steel pull tabs were treated with a chemical release agent to prevent any connection to the adhesive.

The trial test specimen from Fig. 1 was evaluated using four different nondestructive inspection techniques. The results below are very preliminary and a more comprehensive assessment will be performed on the full set of test specimens.

**Thru-Transmission Ultrasonics (TTU)** - Figure 2 shows a C-scan obtained using through-transmission ultrasonics. All of the flaws are visible although the 0.5" wide pull tabs are less obvious than the 0.5" diameter delamination inserts. This technique rates all flaw production methods as equally effective.

**Bondtester (resonance mode)** - The Staveley Sonic Bondmaster (165 KHz and 330 KHz probes) was able to detect all of the delamination flaws. Large signal deviations, which exceeded preset alarm levels, were obtained from both the 1" and 0.5" delaminations. The disbonds could not be detected.

**Bondtester (MIA mode)** - The Staveley Sonic Bondmaster (range of 2.5 to 12 KHz) produced unsatisfactory results in MIA mode. With the gain set to its maximum of 49.5 dB and an equipment-picked frequency of 5.9 KHz, it was possible to get small signal deviations over the flaws. The pull tab and insert delaminations produced signal movements of 3 divisions while the disbonds produced 1.5 divisions of signal movement (8 divisions is preferred to make a call). These results are considered inconclusive and further work is needed to determine the applicability of MIA to composite honeycomb inspections.

**X-ray** - The insert delaminations were visible in X-rays, however, the smaller, 0.5" diameter delaminations were quite difficult to see. Slight shadowing could be discerned in the area of the pull tabs but this would only be detected if one knew where to look. The disbonds did not appear on the X-ray images.

Based on the results of the NDI experiments, a final test specimen configuration was designed and approved by the CACRC. The suite of test specimens, which isolate critical design and flaw variables, are currently being fabricated.

**Application of Boron-Epoxy Doublers to Commercial Aircraft**

The AANC is conducting a technology evaluation project on Boron-Epoxy doublers with Delta Air Lines, Lockheed Martin, Textron, and the FAA. The project focuses on applying a bonded, composite doubler in place of a riveted, metallic doubler. By focusing on a specific commercial aircraft application - reinforcement of the L-1011 door frame - and encompassing all "cradle-to-grave" tasks such as design, analysis, installation, and inspection, this program is designed to
objectively assess the capabilities of composite doublers. The final phase of this project includes the installation of a composite doubler on an L-1011 in Delta's fleet. This will represent the first (non-decal) bonded composite doubler on a U.S. commercial aircraft.

Repairs and reinforcing doublers using bonded composites have numerous advantages over mechanically fastened repairs. Adhesive bonding eliminates stress concentrations 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.

**Project Overview**

To demonstrate the capabilities of composite doubler reinforcement technology in an area of known fatigue cracking, this project included the following technical activities: 1) structural design of the doubler, 2) development of doubler installation procedures, 3) structural evaluation of the design, 4) inspection procedures, and 5) laboratory and flight tests of a composite doubler installed on an operating aircraft. The general issues addressed were:

A. Doubler design - strength, durability and reliability issues, flaw containment, optimum adhesive properties, and critical patch parameters.

B. Doubler installation - surface preparation, tooling, heat sinks, effect of underlying rivets, difficulties of field installation field work.

C. NDI techniques used to qualify and accept an initial installation and to perform periodic inspections. The NDI equipment will be required to inspect for flaws at three different structural levels: 1) in the parent material (crack or corrosion growth), 2) in the adhesive bond (debonds), and 3) in the composite doubler (delaminations).

The overall distribution of tasks among the team participants is listed below. These tasks, along with the flow of activities are summarized in Figure 3.

1. Composite Patch Design and Analysis (Lockheed)
2. Installation Process and Material Properties (Textron and Lockheed)
3. Structural Verification Testing, NDI Development, and Overall Project Management (Sandia Labs AANC)
5. Oversight and Certification (FAA Aircraft Certification Office)

**Project Results**

References [1-8] provide detailed results from the tasks described above. The data stemming from this study serves as a comprehensive evaluation of bonded composite doublers for general use. The associated documentation package, which is resident at the FAA Aircraft Certification Office, provides guidance regarding the design, analysis, installation, damage tolerance, and
nondestructive inspection of these doublers. Figure 4 illustrates the damage tolerance capabilities of bonded composite doublers. An AANC test series demonstrated that even in the presence of extensive damage in the original structure (cracks, material loss) and in spite of non-optimum installations (adhesive disbands), the composite doubler allowed the structure to survive more than 144,000 cycles 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 effect the doubler's performance [3, 5, 6, 8].

Multiple NDI techniques were assessed to inspect the doubler installation for disbonds and delaminations [1, 2, 7]. The optimum method to achieve both field deployment and ease of signal interpretation involves the use of Pulse-Echo C-Scan ultrasonics. Extensive testing has shown that the two-dimensional, color coded images produced by manual and automated scanners are able to reliably 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. Figure 5 shows a bonded doubler test article and the C-Scan image which was produced using the pulse-echo method and a scanning device. The AANC NDI study also showed that crack detection in the parent, aluminum material can be accomplished using conventional X-ray techniques. 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.

Summary

Although there are three separate projects described here, it should be noted that all benefit from the techniques and results of the others. For example, the test and calibration specimens for the USAF will be produced using the same techniques as the specimens for the composite reference specimens although some of the materials may be different. And the inspection techniques such as resonant bond test and ultrasonic thru-transmission developed for the boron epoxy doubler inspection will be used with the composite references.

The unique charter of the AANC allows the results from these and other experiments to be easily used by the community at large. Although the thermographic validation experiment and the boron epoxy doubler on the L-1011 are aimed at specific inspections, the results can be used as a basis for more widespread applications. Further the composite reference standards are designed to be widely applicable.

References


FIGURE 1: Trial Composite Reference Standard Specimen
FIGURE 2: Through Transmission Ultrasonic C-Scan of Composite Reference Standard Trial Specimen

FIGURE 3: Roles and Responsibilities of Participants in the Bonded Composite Doubler Validation Project
FIGURE 4: Fatigue Crack Growth in 2024-T3 Plates With and Without Reinforcing Composite Doublers

FIGURE 5: Pulse-Echo Ultrasonic C-Scan of Engineered Delamination Flaws in Bonded Composite Doubler Test Article