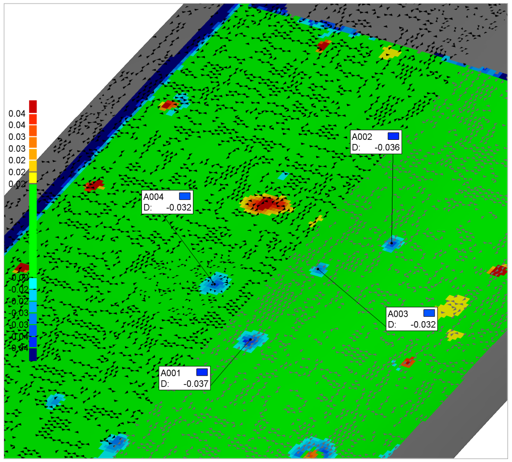
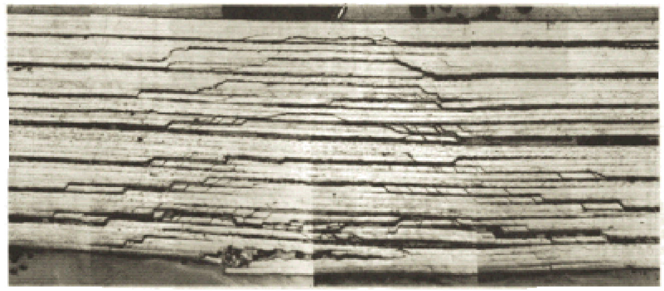
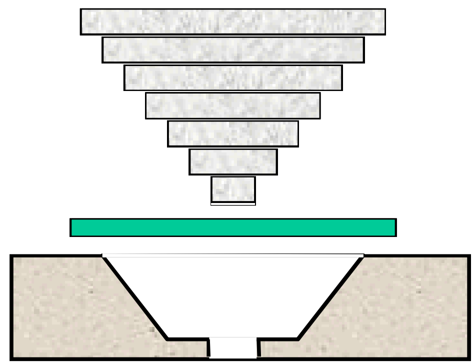
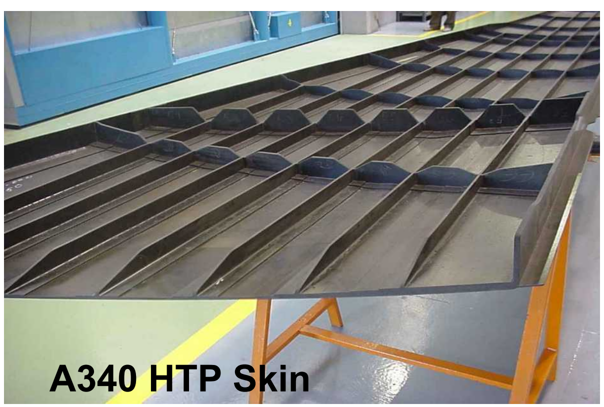
Probability of Detection Studies to Quantify Flaw Detection in Composite Laminate Structures

SAND2013-7868C









Dennis Roach & Tom Rice
Sandia National Labs
FAA Airworthiness Assurance Center

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Inspection Task Group Team Participants

CACRC Inspection Task Group Members:

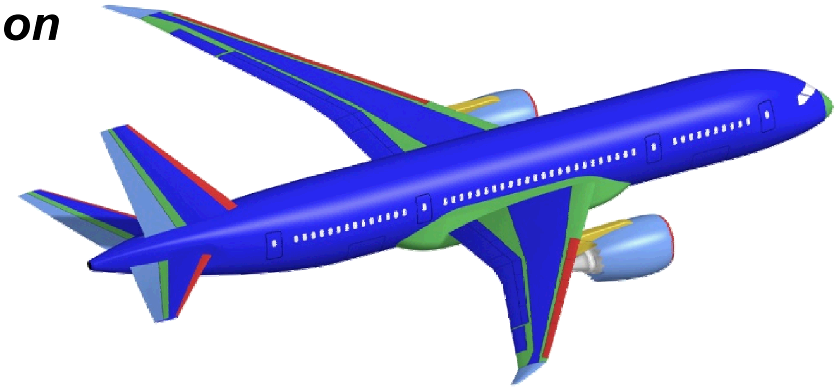
Wolfgang Bisle – Airbus
Chris Dragan – Polish Air Force Institute of Technology
Don Duncan – US Airways
Jim Hofer – Boeing
Quincy Howard – Boeing
Jeff Kollgaard – Boeing
Francois Landry – Bell Helicopter
Robert Luiten – KLM Airlines
Alex Melton – Delta Air Airlines
Eric Mitchell – American Airlines
Stephen Neidigk – Sandia Labs AANC
Keith Phillips – Airbus
Tom Rice – Sandia Labs AANC
Dennis Roach – Sandia Labs AANC (Chair)
Vilmar da Silva do Vale – Embraer
Dennis von Seelen - Lufthansa Technik
Darrell Thornton – UPS
Sam Tucker – United Airlines
Roy Wong – Bombardier

Rusty Jones, Larry Ilcewicz, Dave Galella, Paul Swindell – FAA

Program Motivation - Extensive/increasing use of composites on commercial aircraft and increasing use of NDI to inspect them

Composite Structures on Boeing 787 Aircraft

- Carbon laminate
- Carbon sandwich
- Fiberglass
- Aluminum
- Aluminum/steel/titanium pylons



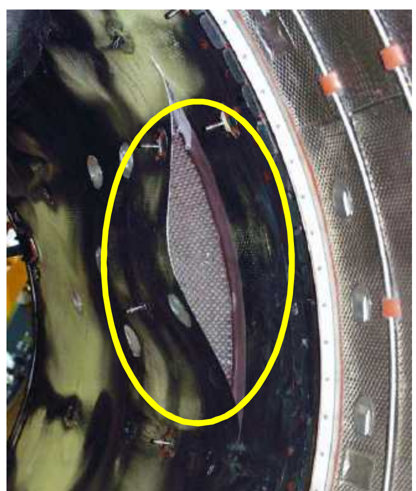
Program Goals: Assess & Improve Flaw Detection Performance in Composite Aircraft Structure

Sources of Damage in Composite Structure

One airline reports 8 composite damage events per aircraft (on avg.) with 87% from impact; cost = $200K/aircraft

Lightning Strike on Thrust Reverser

Bird Strike

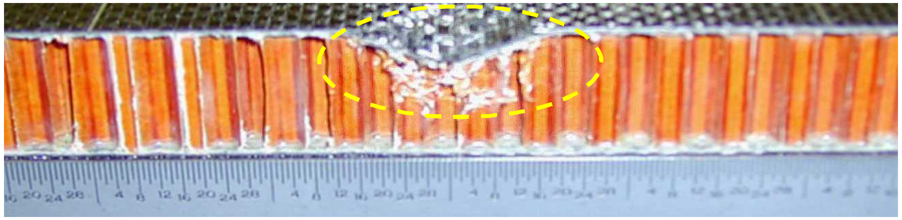


Disbonding at skin-to-honeycomb interface

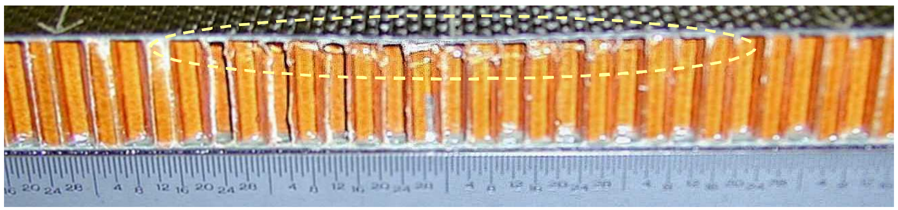
Towing Damage

Inspection Challenge – Hidden Impact Damage

Backside fiber failure from ice impact

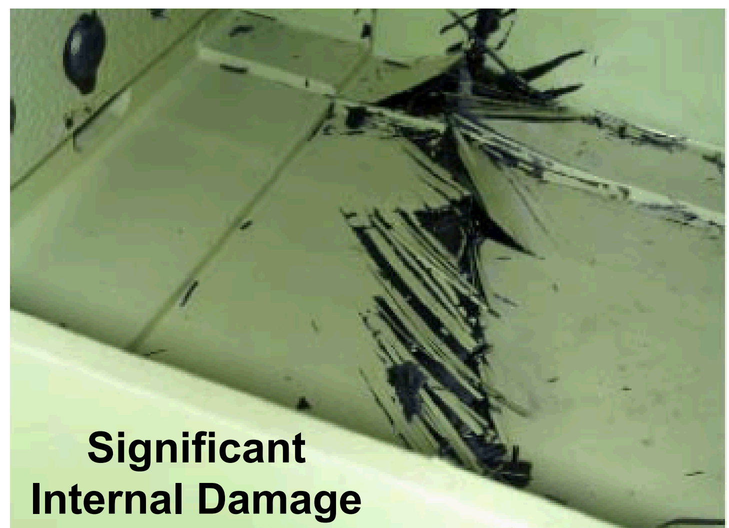


Visible Impact Damage – external skin fracture



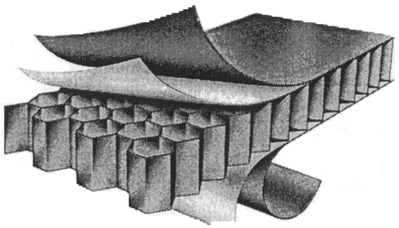
Backside Damage – internal skin fracture & core crush

Damage from ground vehicle



Source: Carlos Bloom (Lufthansa) & S. Waite (EASA)

Composite Honeycomb Flaw Detection Experiment

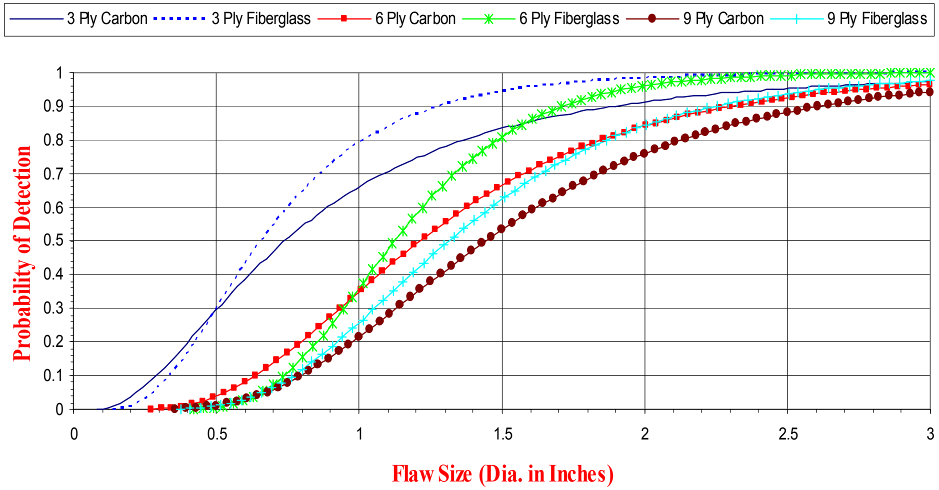


Composite Flaw Detection Experiment

Participation from over 25 airlines and maintenance depots

Industry-wide performance curves generated to quantify:

- **How well current inspection techniques are able to reliably find flaws in composite honeycomb structure**
- **The degree of improvements possible through integrating more advanced NDI techniques and procedures.**



Blind application of techniques to study hits, misses, false calls, and flaw sizing

Experiment to Assess Flaw Detection Performance

An Experiment to Assess Flaw Detection Performance in Composite Laminate Structures

Purpose

- Determine in-service flaw detection capabilities: 1) conventional NDT methods vs. 2) improvements through use of advanced NDT.
- Optimize laminate inspection procedures.
- Compare results from hand-held devices with results from scanning systems (focus on A-scan vs. C-scan and human factors issues in large area coverage).
- Provide additional information on laminate inspections for the "Composite Repair NDT/NDI Handbook" (ARP 5089).

A380 Fuselage Section 19

737 Composite Horiz. Stabilizer

Flaw Detection in Solid Laminate Composites

Approach

- Statistical design of flaws and other variables affecting NDI - range of types, sizes & depths of flaws
- Study factors influencing inspections including composite materials, flaw profiles, substructures, complex shapes, fasteners, secondary bonds, and environmental conditions
- POD and signal-to-noise data gathering
- NDI Ref. Stds. prepared to aid experiment

Expected Results - evaluate performance attributes

1) accuracy & sensitivity (hits, misses, false calls, sizing)
2) versatility, portability, complexity, inspection time (human factors)
3) produce guideline documents to improve inspections
4) introduce advanced NDI where warranted

Specimen Design - Flaw Detection in Solid Laminate Composites

<u>Specimen Types</u> – Solid laminate carbon (12 to 64 plies)

- Contoured and tapered surfaces
- Substructures – stringers, ribs, spars; honeycomb impediment
- Bonded & sealed joints; fasteners
- Large enough to warrant scanners; complex geometry to challenge scanners
- Carbon, uniaxial tape

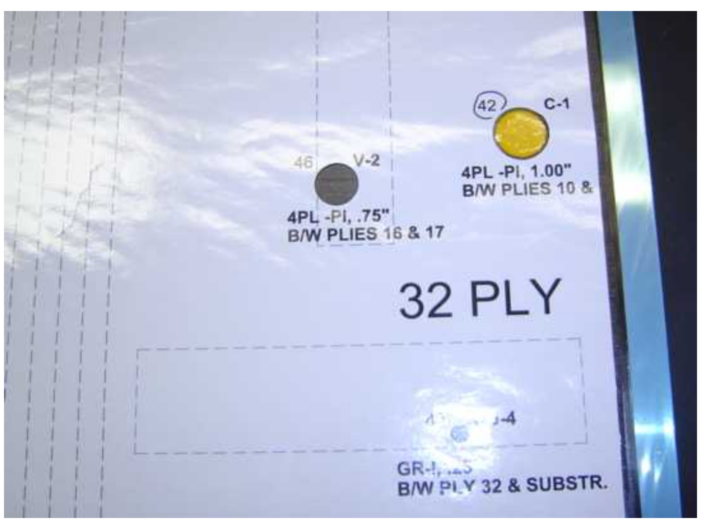
<u>Flaw Types</u> - statistically relevant flaw distribution with range of sizes & depths (near front & back surfaces; in taper regions)

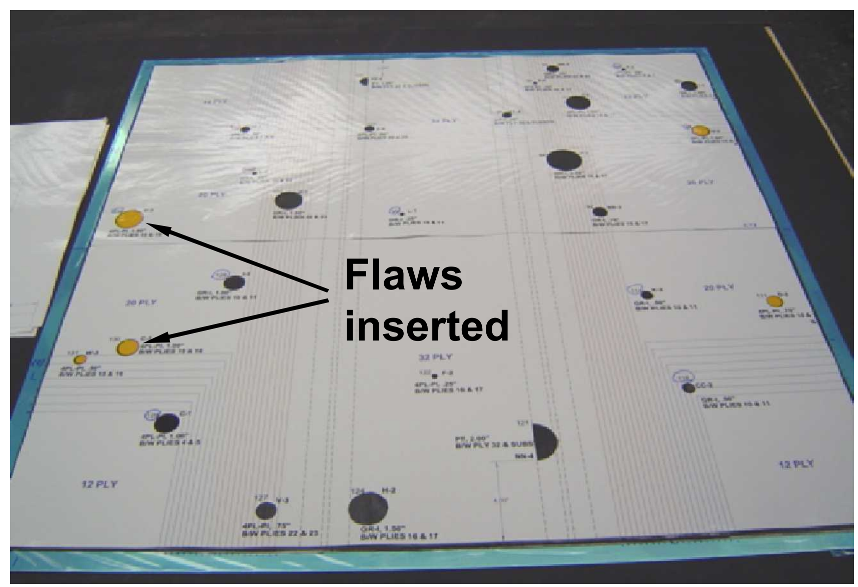
1) interply delaminations ("kissing" and air gap)
2) substructure damage
3) skin-to-stiffener disbonds
4) simulated impact damage

Low Energy Impact

Thick Laminate With Complex Taper - Fabrication

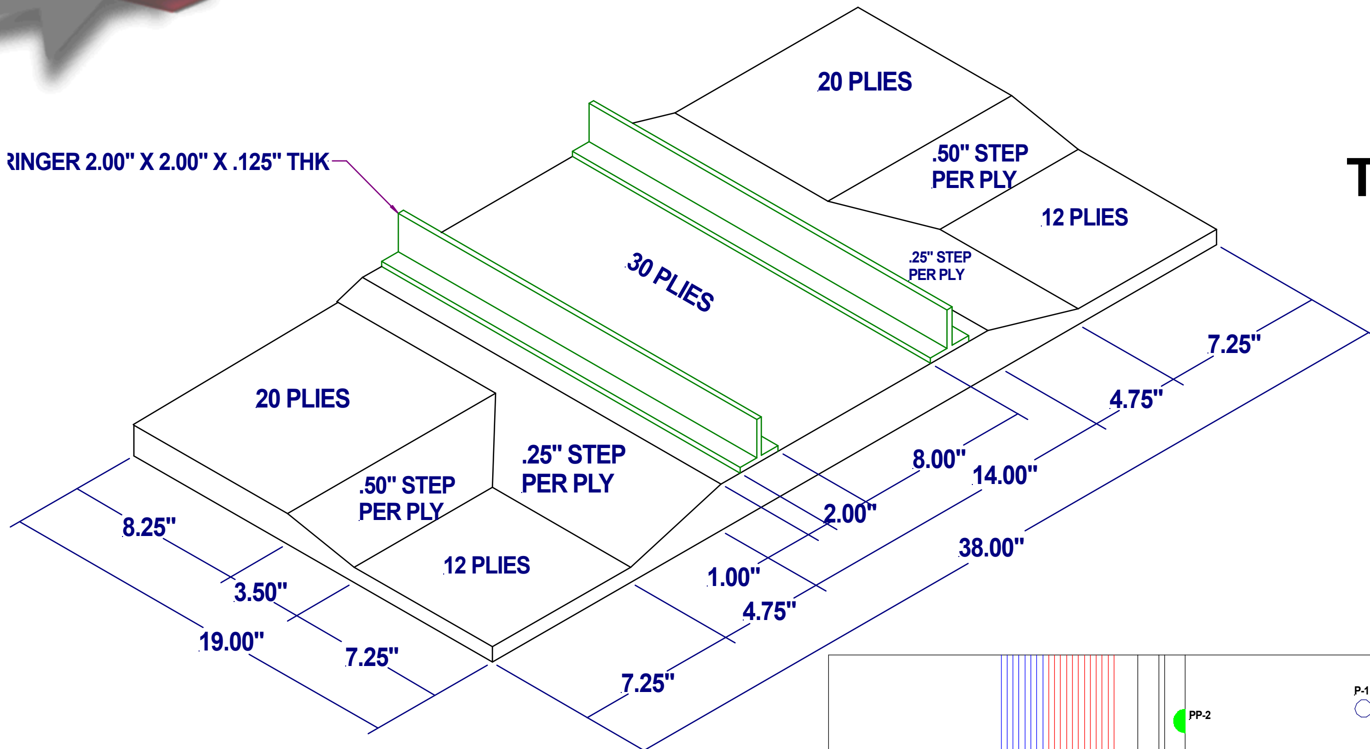
Flaw templates - ensure proper location of flaws



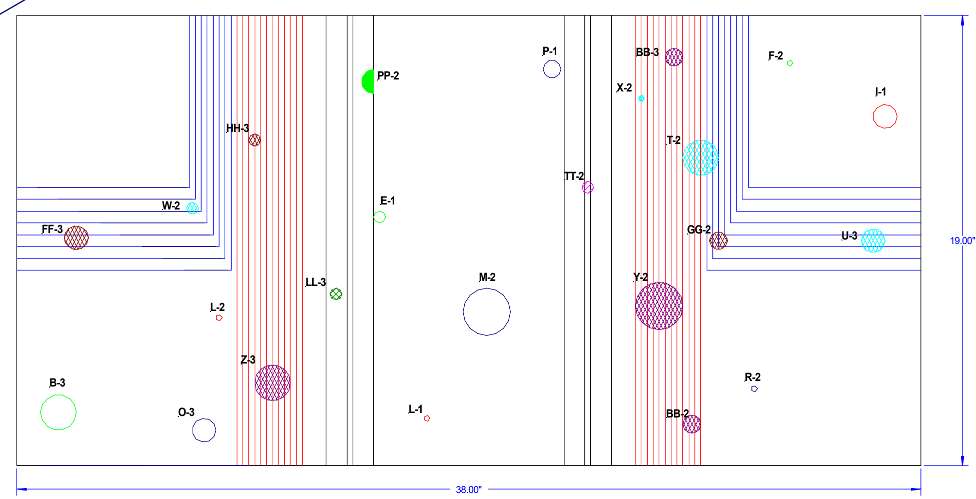


Thick Laminate With Complex Taper - Fabrication

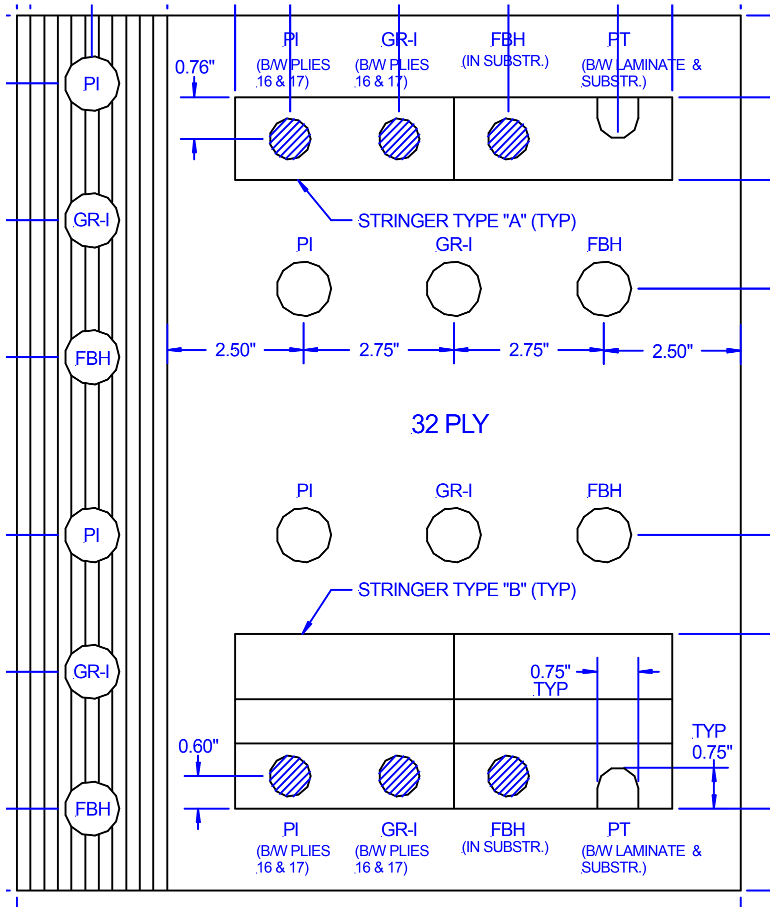
Thick Laminate With Complex Taper

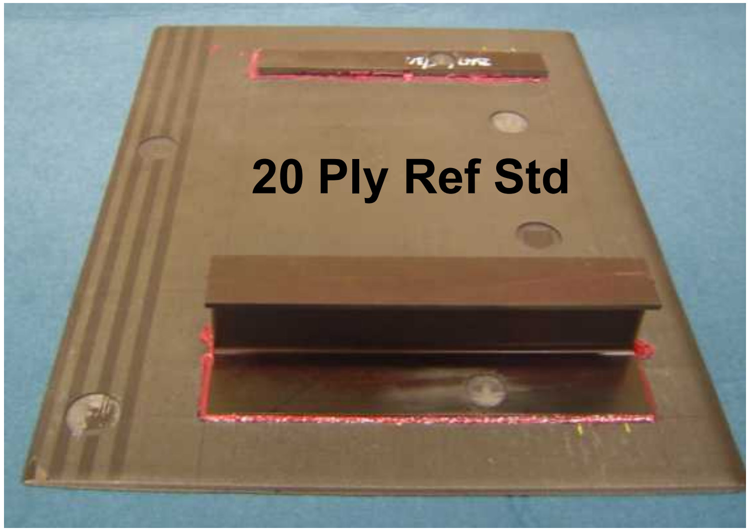


Type I Specimen



Reference Standards – Feedback Panels





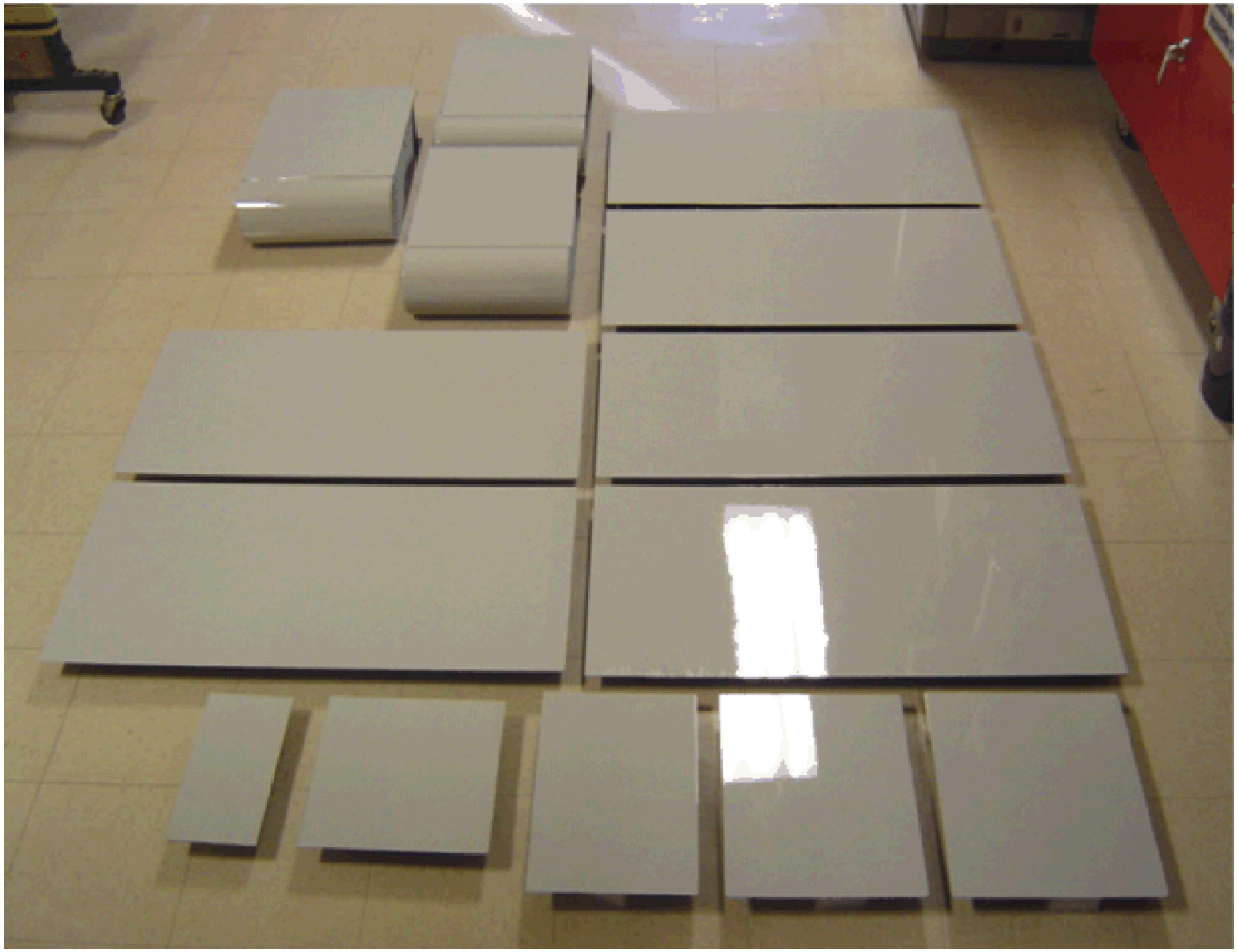
Specimen Set - Flaw Detection in Solid Laminate Composites

Thickness Range:
12 – 64 plies

Inspection Area:
46 ft.^{2}

Number of Flaws:
202

Specimen Set - Flaw Detection in Solid Laminate Composites



Thickness Range: 12 – 64 plies

Simple Tapers

Complex tapers

Substructure Flaws

Curved Surfaces

Array of flaw types

NDI Ref. Stds.

Solid Laminate Experiment Participants

UNITED

JAL

OLYMPUS

American Airlines

Delta

nwa NORTHWEST AIRLINES

ANA

TOSHIBA Leading Innovation

CATHAY PACIFIC

Continental Airlines

DANTEC DYNAMICS

CHINA AIRLINES

THAI

Thermal Wave Imaging

movimed custom imaging solutions

SINGAPORE AIRLINES

GOODRICH

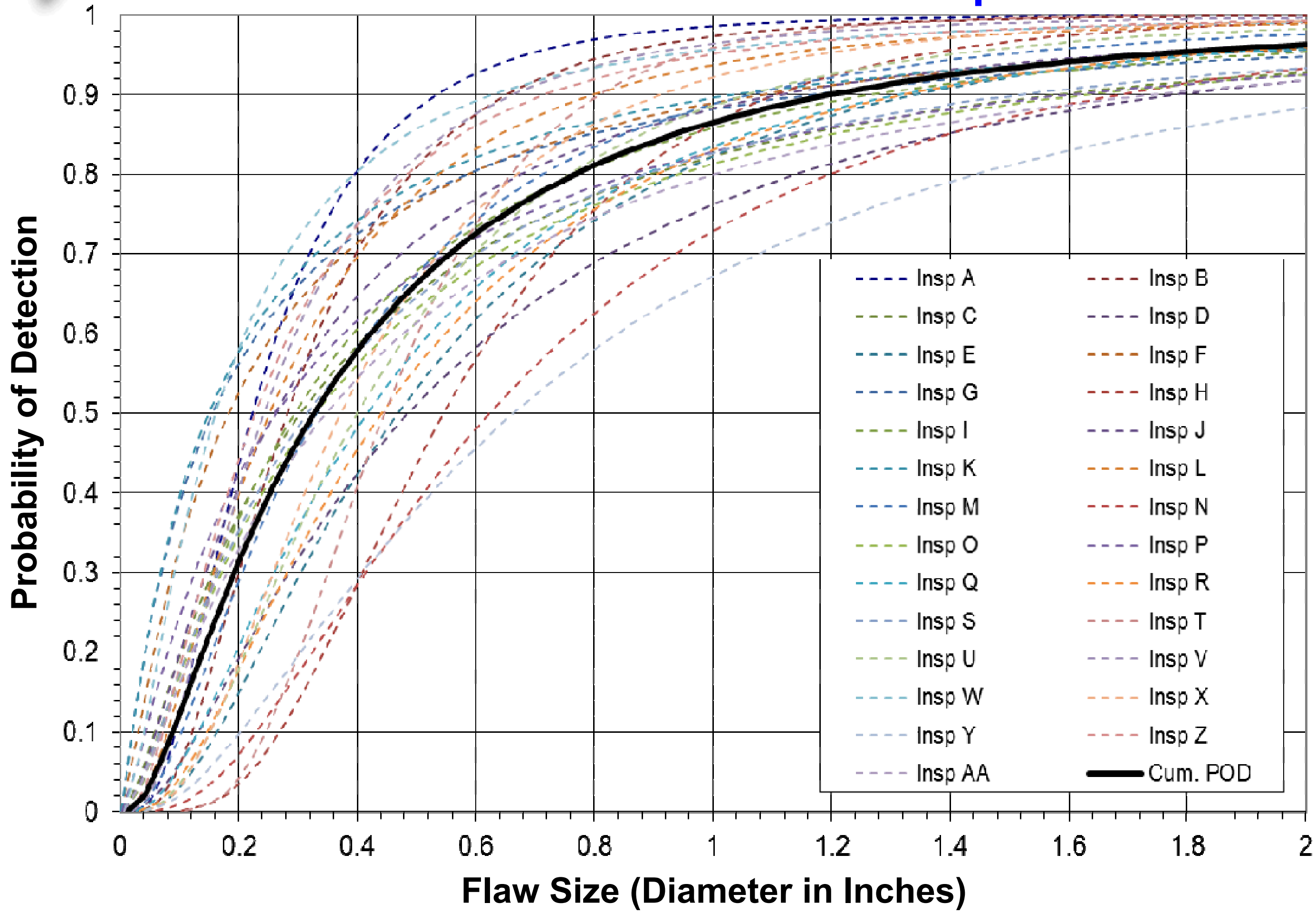
FedEx

Solid Laminate Flaw Detection Experiment Implementation

PODs calculated for overall laminate, by thickness family, by substructure effects, by complex geometry effects, by flaw types, etc. ➡ 57 inspectors

POD Curves for 12-20 Ply Solid Laminate Family

Individual and Cumulative Comparisons



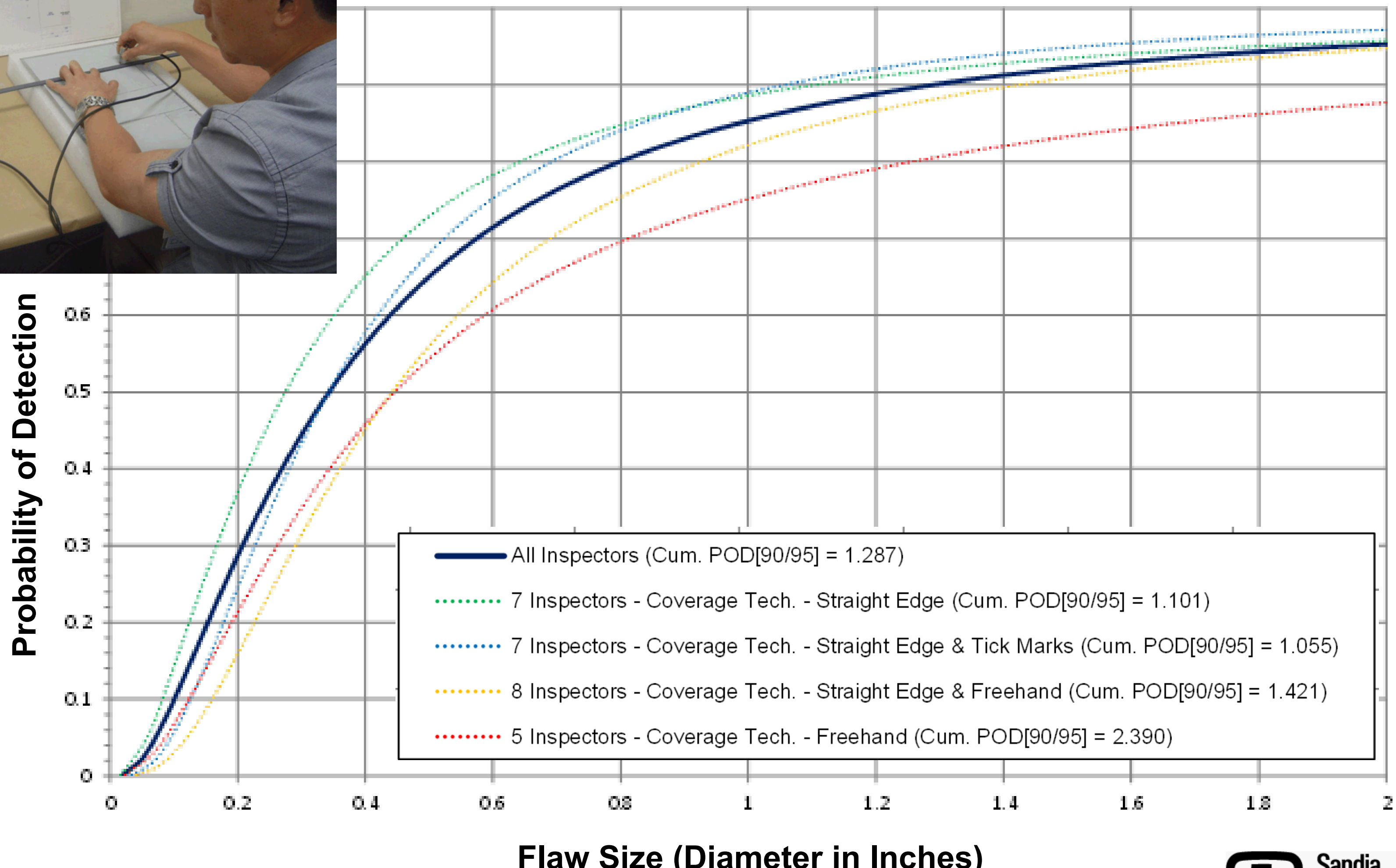
Overall:
$POD_{[90/95]}$ = 1.29" dia.

Constant Thickness
(12, 20, 28 plies):
$POD_{[90/95]}$ = 0.86" dia.

Complex Geometry
(tapered, curved, substructure, fasteners, honeycomb):
$POD_{[90/95]}$ = 1.49" dia.

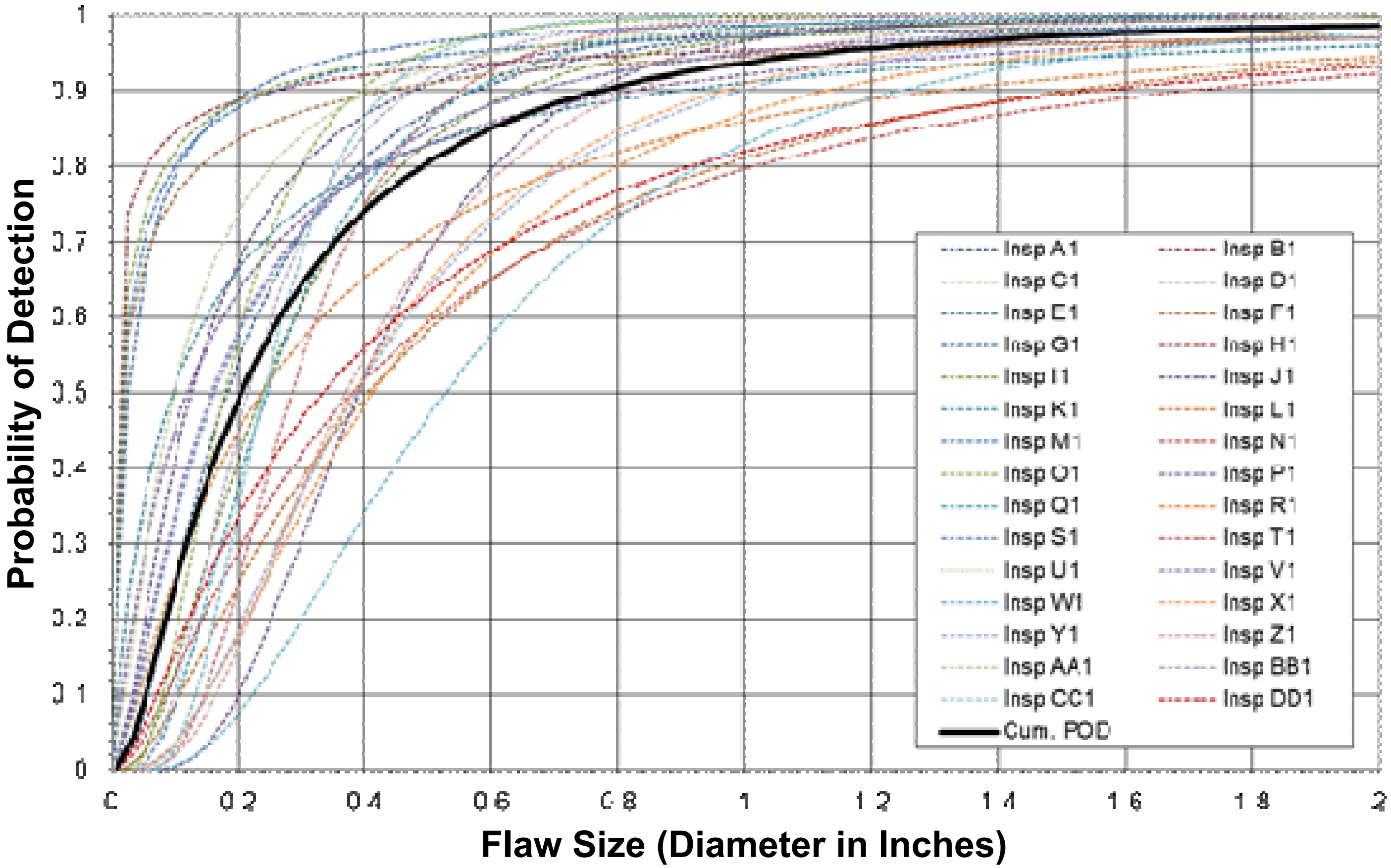
False Calls: Constant thickness = 0.4/inspector
Complex Geometry = 4.0/inspector
34 ft.^{2} inspection area

POD Improvements from Use of Methods to Ensure Proper Coverage



POD Curves for 20-32 Ply Solid Laminate Family

Individual and Cumulative Comparisons



Overall:
$POD_{[90/95]}$ = 0.82" dia.

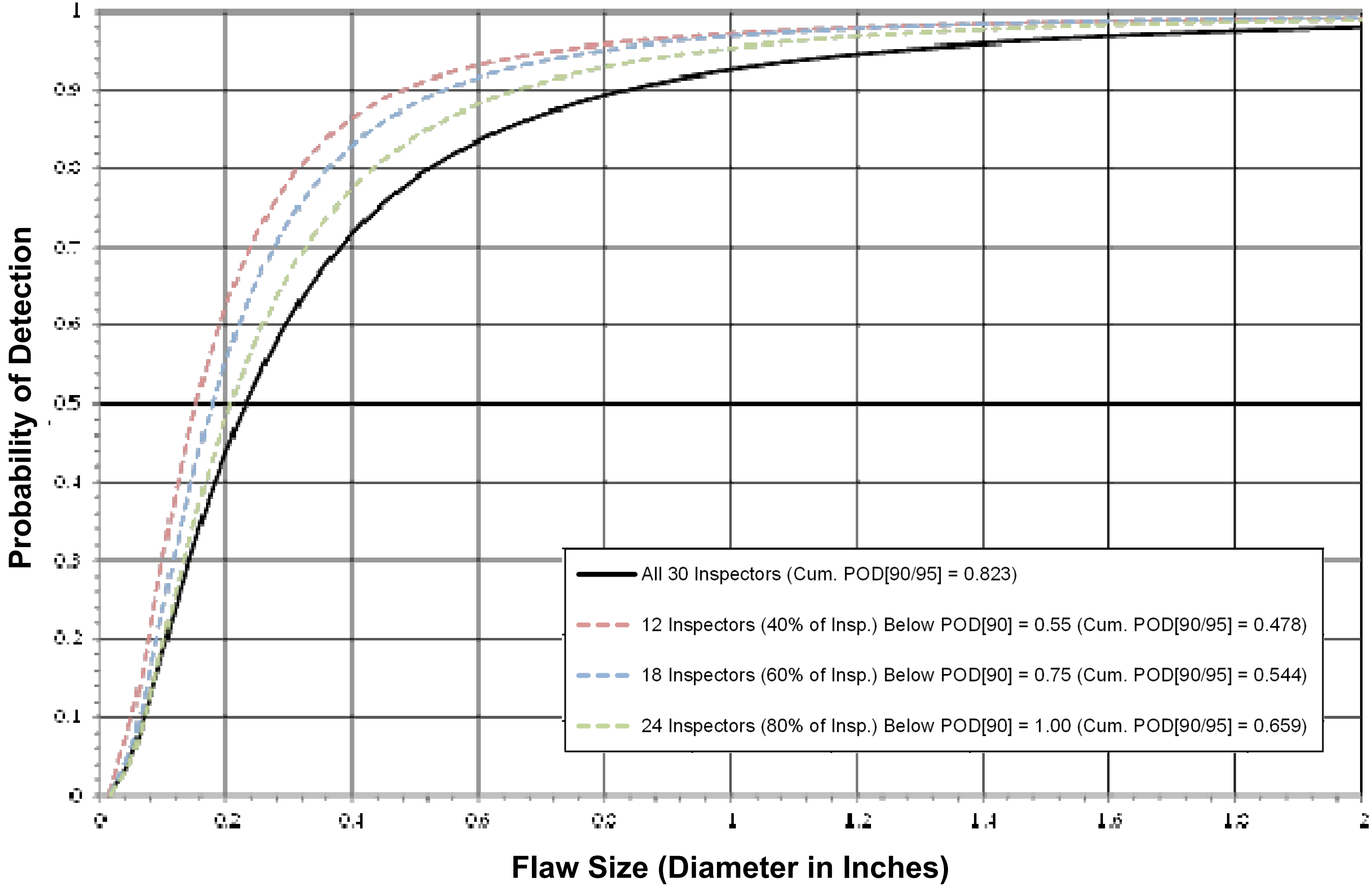
Constant Thickness (32 plies):
$POD_{[90/95]}$ = 0.74" dia.

Complex Geometry (tapered, curved, substructure, fasteners, honeycomb):
$POD_{[90/95]}$ = 0.93" dia.

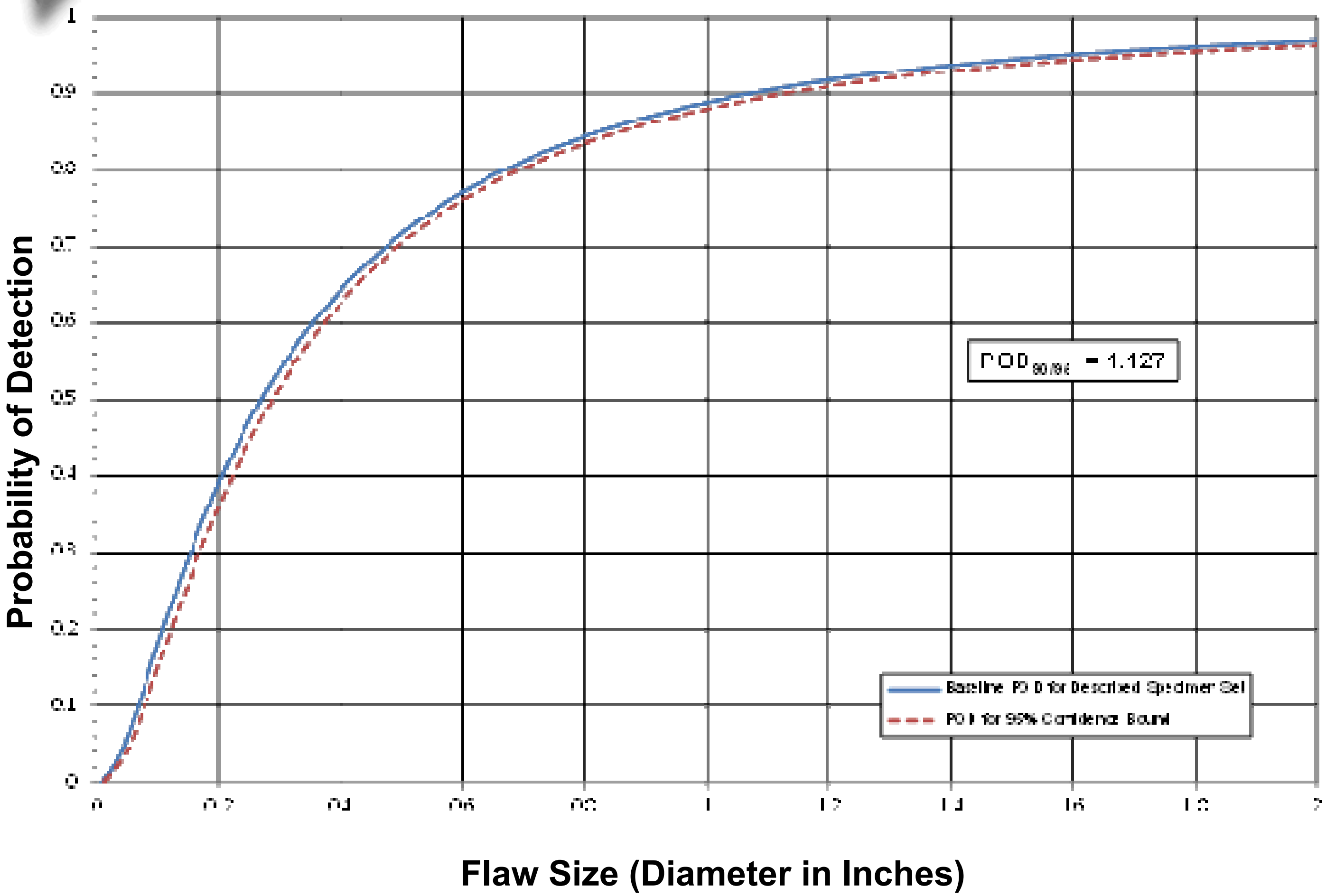
Substructure:
$POD_{[90/95]}$ = 1.50" dia.

False Calls: Constant thickness = 0.8/inspector
Complex Geometry = 0.3/inspector
12 ft.^{2} inspection area

Desire to Transition Inspectors from "Average" to "Good" to "Outstanding"



Overall Performance of Pulse-Echo UT for Flaw Detection in Composite Laminates



Overall:
$POD_{[90/95]}$ = 1.13" dia.

Constant Thickness (32 plies):
$POD_{[90/95]}$ = 0.80" dia.

Complex Geometry (tapered, curved, substructure, fasteners, honeycomb):
$POD_{[90/95]}$ = 1.33" dia.

Ramp Damage Check Experiment (RDCE) – "Spin Off" Subset of Solid Laminate Experiment

Purpose: to assess new, ultrasonic-based "Go"/"No-Go" equipment that OEM's plan to deploy at airports and other non-scheduled maintenance depots using non-NDI personnel (e.g. A&Ps).

Usage Scenario: the equipment will be deployed whenever visual clues or other events occur which warrant closer scrutiny of a composite laminate structure; ground personnel, with appropriate training on such equipment, will set up the equipment in accordance with OEM-supplied procedures, and then make an assessment of the region in question.

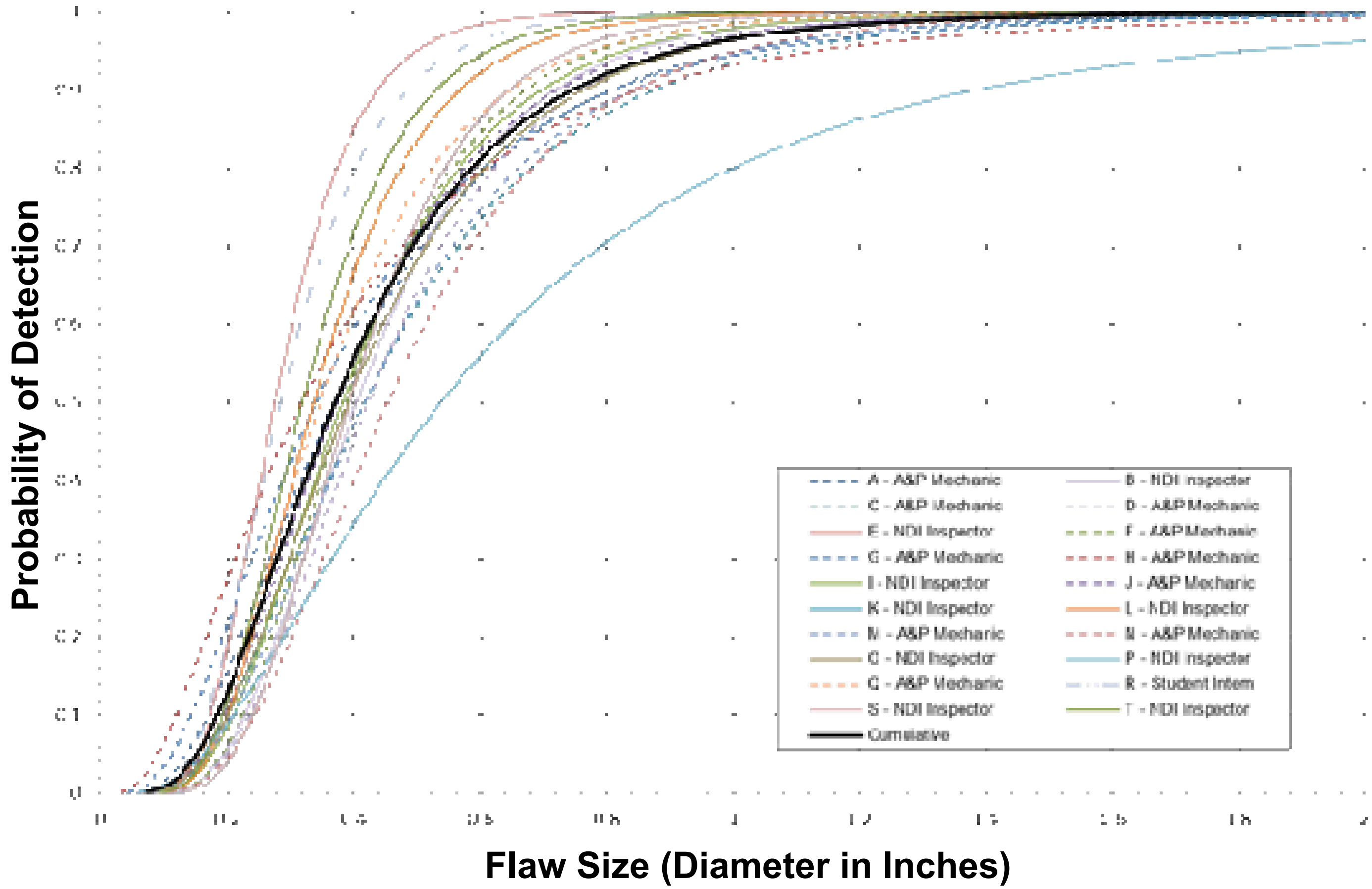
Limitations: such "Go"/"No-Go" UT equipment is intended to be used to assess local indications or regions only, not for wide-area inspections; equipment operators are directed to very distinct locations.

Ramp Damage Check Experiment – Ultrasonic Devices with "Go"/"No-Go" Capabilities

General Electric –
"Bondtracer"

Olympus –
"Ramp Damage Checker"

Ramp Damage Check Experiment – POD Curves for Composite Laminates



- **Overall**: $POD_{[90/95]}$ = 0.78" dia.
- **Similar results for GE Bondtracer and Olympus Ramp Damage Checker**
- **Similar performance from both inspectors and A&P mechanics**
- **Less spray in individual performances**

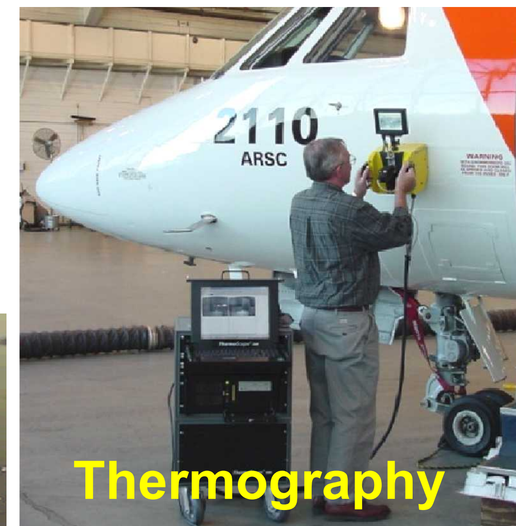
False Calls = 0.6/inspector
14 ft.^{2} inspection area

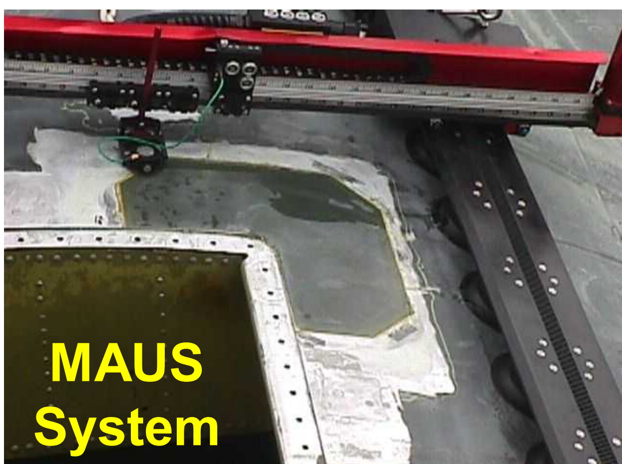
Wide Area and C-Scan Inspection Methods


SAM System


Shearography


UltraImage Scanner


Thermography

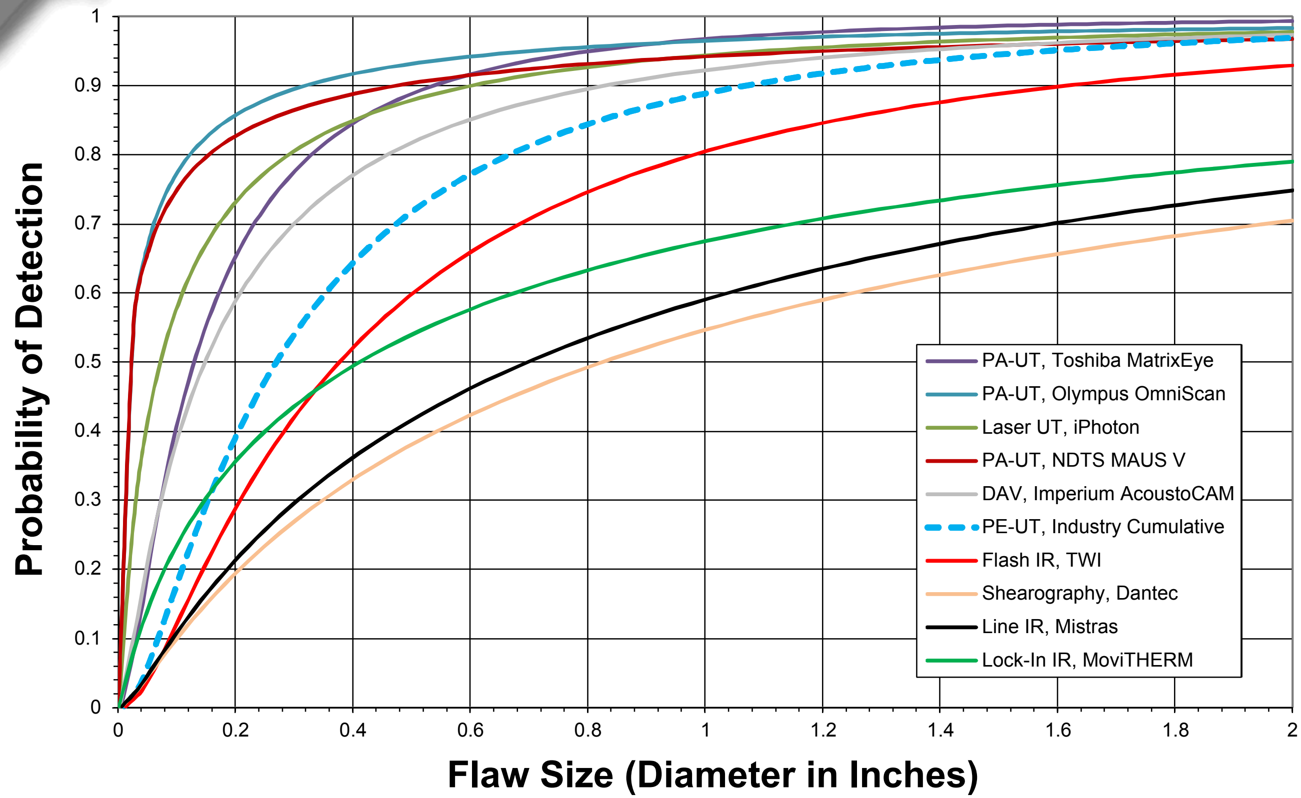

MAUS System


PE Phased Array UT
UT Wheel Array

Solid Laminate Experiment – Advanced NDI Testing Evaluations

- Pulsed Thermography – Thermal Wave Imaging
- Phased Array UT – Olympus Omniscan
- Phased Array UT – Toshiba Matrix Eye
- Phased Array UT – Sonatest RapidScan
- Phased Array UT – Boeing MAUS V
- Phased Array UT – GE RotoArray & Phasor
- Microwave – Evisive
- Digital Acoustic Video – Imperium Acoustocam
- Ultrasonic Video - DolphiCam
- Line Infrared – Mistras
- Shearography – LTI
- Shearography – Dantec
- Backscatter X-ray – Scannex
- Acousto Ultrasonics – Physical Acoustic Corp. T-SCOUT
- Locked-In Infrared – MovieTherm
- Laser UT – iPhoton

Sample of POD Results for Composite Flaw Detection Performance of Advanced NDI



	PA-UT, Toshiba MatrixEye	PA-UT, Olympus OmniScan	Laser UT, iPhoton	PA-UT - NDTS MAUS V	DAV, Imperium AcoustoCAM	PE-UT, Industry	Flash IR - TWI	Shearography - Dantec	Line IR - Mistras	Lock-In IR, MoviTHERM
POD$_{[90/95]}$	0.69	0.72	0.85	0.88	1.12	1.13	2.3	>3	>3	>3
False Calls	1	0	0	0	0	5.5	0	1	NA	26

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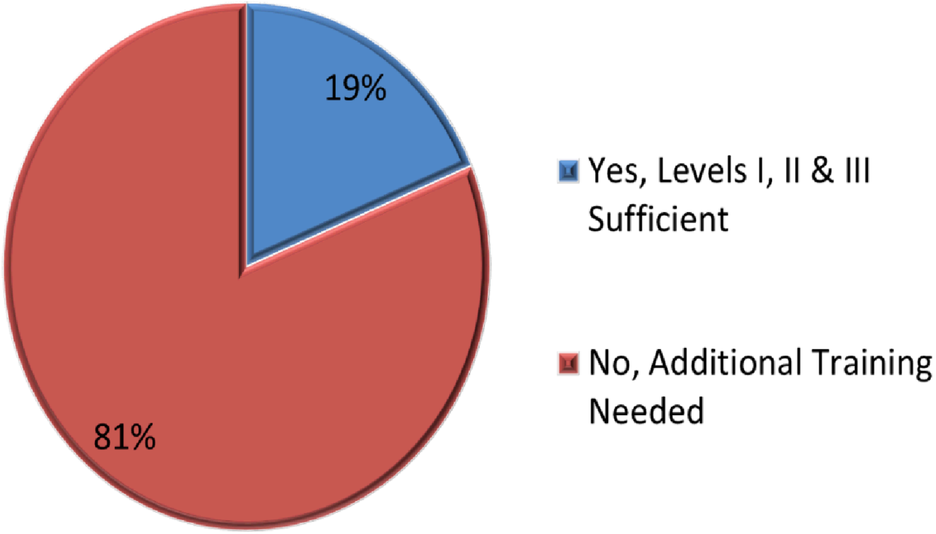
Survey of Industry Composite NDI Training

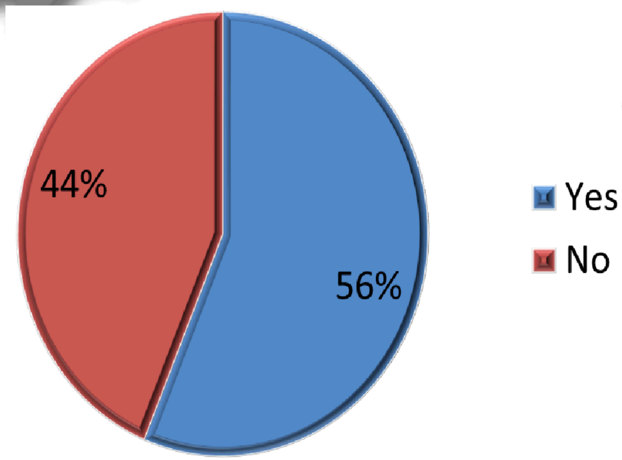
Question 16 - In your opinion, do Level I, II, and III training/qualifications provide the necessary expertise for both metal and composite NDI or should additional training take place for composite inspections?

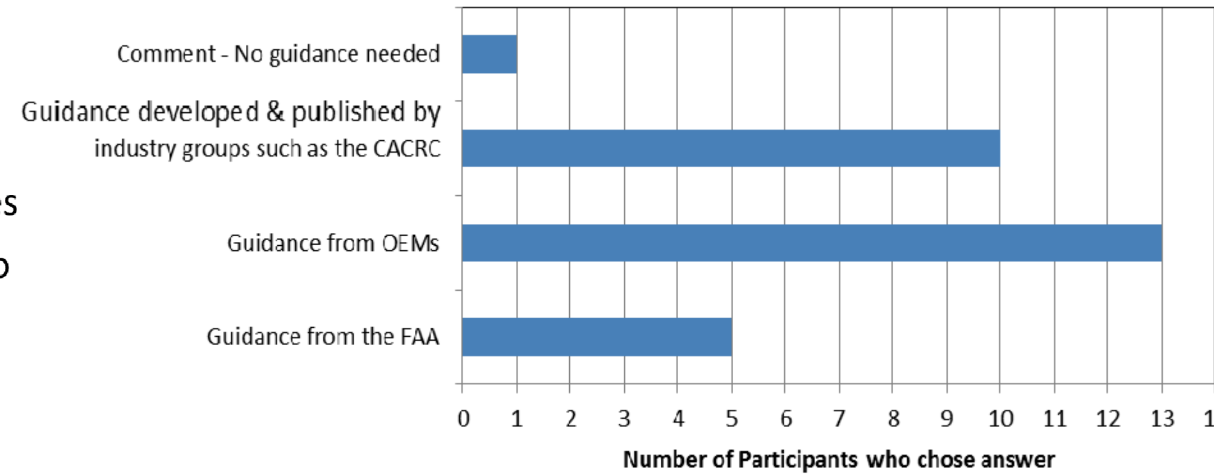
Composite NDI Training Survey Participants	
Company	**Completed Survey**
AAR-ASI (Indy)	Yes
American Airlines (Tulsa)	Yes
Aviation Technical Services, Inc (Seattle)	Yes
Delta Air Lines (Atlanta)	Yes
Delta Air Lines (MN)	Yes
FedEx (Indy)	Yes
FedEx (Los Angeles)	Yes
Goodrich Aerostructures (Chula Vista)	Yes
Kalitta Air LLC (Michigan)	Yes
Rohr Aero Services LLC (Alabama)	Yes
Southwest Airlines (TX)	Yes
Timco (Georgia)	Yes
United Airlines (Houston)	Yes
United Airlines (San Fran)	Yes
UPS (KY)	Yes
US Airways (PA)	Yes



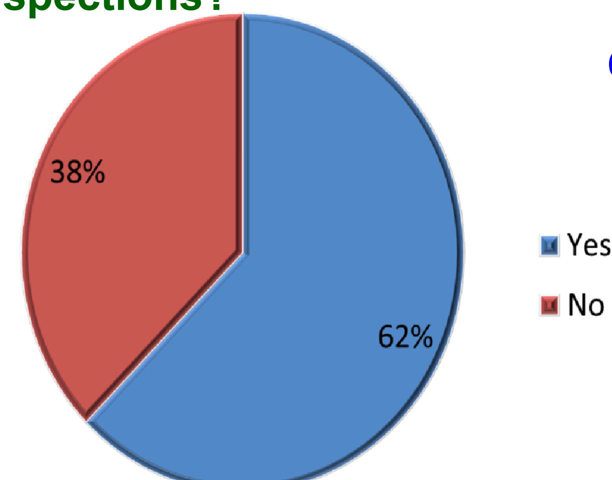
Only 25% of responders currently have special composite NDI training in place

Question 21 - In what areas is additional guidance needed to help ensure comprehensive composite training programs for the aviation industry?





Question 15 - If experience level is a factor in determining qualification to perform certain inspections, do you use some sort of <u>apprentice program</u> to expose newer inspectors to such inspections?



Question 5 – Do inspectors also receive general composite training to understand composite materials, plies, lay-ups, scarfed repairs, composite design, composite processing, etc.?

Conclusions – Inspection of Solid Laminate Structures

- Results can be used by OEMs and airlines to: 1) define detectability for various flaws/damage, 2) guide NDI deployment & training; used by FAA to produce guidance documents.
- Flaw Detection - Conventional, manually-deployed PE-UT: $POD_{[90/95]}$ = 1.12" dia.; skin flaw detection is higher, flaw detection in substructure is more challenging ($POD_{[90/95]}$ = 1.34" dia.)
- False Call rates were extremely low: 1 false call per 17 $ft.^2$ (flaws ≥ 0.25 $in.^2$)
- Optimum inspection rates = 2 $ft.^2$ /hour
- NDI Performance Obstacles – attenuation, complex signal reflections, confounding presence of signal harmonics, rapid variations produced by changing/complex geometry, optimum deployment and difficulty with inspecting large areas
- Controlled and Proper Use of Ramp Damage Check "Go"/"No-Go" equipment can produce good performance ($POD_{[90/95]}$ = 0.77" dia.)
  - Caution – proper calibration area must be used; requires good schematics (available?)
  - Cannot be used in taper or changing geometry regions

Recommendations – How to move inspections from "average" to "good" to "outstanding"

- Increased exposure to representative composite inspections – common industry NDI Feedback Specimens
- Increased, focused composite NDI training (ARP covering 1st two bullets)
- Use of NDI and composite shop apprenticeships (OJT, awareness training, formal/uniform use of this tool)
- Enhanced NDI procedures – deployment, signal interpretation, clearer schematics showing structural configuration
- Use of inspection coverage aids should be required
- Divide large area inspections into a number of smaller regions
- Add audible alarms & detection lights to probe in "Go"/"No-Go" devices
- Prepare additional industry guidance to address training, use of NDI Reference and Proficiency specimens, procedures, composite construction awareness – produced by joint effort of OEMs, Airlines, FAA & industry groups

POD Studies to Quantify Flaw Detection in Composite Laminate Structures

Dennis Roach
Tom Rice
FAA Airworthiness Assurance Center
Sandia National Laboratories

Composites have many advantages for use as aircraft structural materials including their high specific strength and stiffness, resistance to damage by fatigue loading and resistance to corrosion. The aircraft industry continues to increase its use of composite materials, most noteworthy in the arena of principle structural elements. This expanded use, coupled with difficulties associated with damage tolerance analysis of composites, has placed greater emphasis on the application of accurate nondestructive inspection (NDI) methods. Traditionally, a few ultrasonic-based inspection methods have been used to inspect solid laminate structures. Recent developments in more advanced NDI techniques have produced a number of new inspection options. Many of these methods can be categorized as wide area techniques that produce two-dimensional flaw maps of the structure. An experiment was developed to assess the ability of both conventional and advanced NDI techniques to detect voids, disbonds, delaminations, and impact damage in adhesively bonded composite aircraft structures. A series of solid laminate, carbon composite specimens with statistically relevant flaw profiles were inspected using conventional, hand-held pulse echo UT and resonance, as well as, new NDI methods that have recently been introduced to improve sensitivity and repeatability of inspections. The primary factors affecting flaw detection in laminates were included in this study: material type, flaw profiles, presence of complex geometries like taper and substructure elements, presence of fasteners, secondarily bonded joints, and environmental conditions. This experiment utilized airline personnel to study Probability of Detection (POD) in the field and to formulate improvements to existing inspection techniques. In addition, advanced NDI methods for laminate inspections – such as thermography, shearography, scanning pulse-echo UT, ultrasonic spectroscopy, laminography, microwave and phased array UT – were applied to quantify the improvements achievable through the use of more sophisticated NDI. This paper presents the experiment design used to evaluate applicable inspection techniques and the key results from the POD testing conducted at multiple airline facilities.