SAND99-0540J

Development of Composite Honeycomb and Solid Laminate Reference Standards to Aid Aircraft Inspections

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Abstract

The rapidly increasing use of composites on commercial airplanes coupled with the potential for economic savings associated with their use in aircraft structures means that the demand for composite materials technology will continue to increase. Inspecting these composite structures is a critical element in assuring their continued airworthiness. The FAA's Airworthiness Assurance NDI Validation Center, in conjunction with the Commercial Aircraft Composite Repair Committee (CACRC), is developing a set of composite reference standards to be used in NDT equipment calibration for accomplishment of damage assessment and post-repair inspection of all commercial aircraft composites. In this program, a series of NDI tests on a matrix of composite aircraft structures and prototype reference standards were completed in order to minimize the number of standards needed to carry out composite inspections on aircraft. Two tasks, related to composite laminates and non-metallic composite honeycomb configurations, were addressed.

A suite of 64 honeycomb panels, representing the bounding conditions of honeycomb construction on aircraft, were inspected using a wide array of NDI techniques. An analysis of the resulting data determined the variables that play a key role in setting up NDT equipment. This has resulted in a prototype set of minimum honeycomb reference standards that include these key variables. A sequence of subsequent tests determined that this minimum honeycomb reference standard set is able to fully support inspections over the full range of honeycomb construction scenarios. Current tasks are aimed at optimizing the methods used to engineer realistic flaws into the specimens. In the solid composite laminate arena, we have identified what appears to be an excellent candidate, G11 Phenolic, as a generic solid laminate reference standard material. Testing to date has determined matches in key velocity and acoustic impedance properties, as well as, low attenuation relative to carbon laminates. Furthermore, comparisons of resonance testing response curves from the G11 Phenolic prototype standard was very similar to the resonance response curves measured on the existing carbon and fiberglass laminates. NDI data shows that this material should work for both pulse-echo (velocity-based) and resonance (acoustic impedance-based) inspections. Additional testing and industry review activities are underway to complete the validation of this material.

Introduction

After developing a Composite Inspection Handbook [1], the 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 purpose of this project is to develop a set of composite calibration standards to be used in NDT equipment calibration for accomplishment of damage assessment and post-repair inspection of all commercial aircraft composites. In order for the standards to be accepted for worldwide use they will incorporate the pertinent structural configurations of Boeing, Douglas, Airbus, and Fokker aircraft. The standards will be representative of damage found in the field and include typical flaw scenarios such as disbonds and delaminations. Furthermore, this activity seeks to produce a workable number of reference specimens. Currently, the recognized number of variables makes the resulting number of specimens very large and unmanageable. Inspection characterizations and equipment responses have been used to determine the important variables needed in a composite reference standard thus eliminating unnecessary standard configurations.

The advantages of industry-wide accepted composite standards include: 1) providing a consistent approach to composite inspection thus helping to minimize false calls, 2) reducing standard procurement costs, and 3) aiding the assessment of composite inspection technologies. Through the active participation of the OEM's, this project represents a harmonized approach by aircraft manufacturers.

The goal of this project is to develop standards that will allow for repeatable, accurate inspections. Many composite inspections are performed by visual inspections and tap tests. Composite inspection requirements are increasing and may soon surpass the capabilities of the tap test. This effort will aid the composite inspection process through the use of engineered reference standards and the utilization of more sensitive NDT equipment.

The basic tasks necessary to support this effort are as follows: 1) review composite structure designs of each OEM and determine the spectrum of reference standard needs, 2) develop a series of processes for producing the various engineered flaws in the specimens, 3) apply NDI techniques 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 NDT equipment. The following discussion describes the activities completed thus far to develop composite laminate and composite honeycomb standards.

TASK 1: COMPOSITE HONEYCOMB TASK

Determining Key Factors Affecting Inspection

Developing Appropriate Range of Honeycomb Specimens - A set of 64 honeycomb specimens were fabricated to isolate the effects of the following variables (construction materials and flaw type) and bounding conditions on NDT: 1) laminate material (carbon; fiberglass), 2) honeycomb core material (Nomex; fiberglass), 3) laminate thickness (3 plies; 12 plies), 4) honeycomb core thickness (0.25"; 2"), 5) honeycomb cell size (0.125"; 0.25"), 6) honeycomb core density (2-8 lb/ft^3), and 7) disbond and delamination flaws. The bounding conditions on each parameter, shown in parenthesis, represent the extreme values found in aircraft construction. The goal of this approach is to allow the results from this program to be applied to aircraft from all manufacturers. Figure 1 shows the design of the composite honeycomb panels used in this parametric study. Sixteen panels contained four different construction types (four quadrants) and isolated the effects of each of the variables listed above (2 extremes, 6

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variables creates $2^6 = 64$ different specimens). NDI was applied to the specimens in order to assess the difficulties presented by the engineered flaws. The inspection results were used to identify the important variables which should be included in composite honeycomb reference standards. In this manner, the effects of each variable on NDI could be assessed.

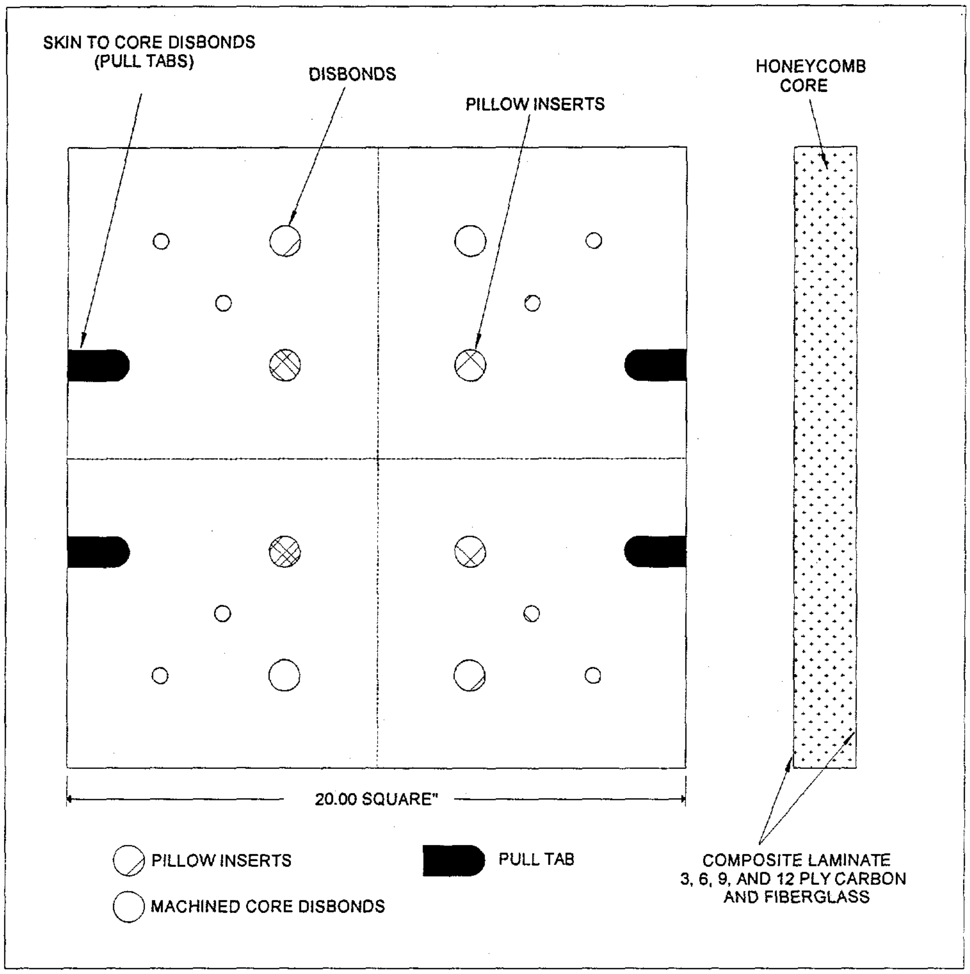


Figure 1: Design Drawing of Composite Honeycomb Panel Containing Four Different Construction Types and Engineered Flaws

Application of NDT Equipment - Methods using various inserts and pull tabs were developed to induce realistic disbond and delamination flaws in composite honeycomb specimens. Multiple NDI techniques were applied to the 64 sandwich construction test specimens defined by the variable options. Upper and lower bounds were intentionally used for each construction variable in order to demonstrate which variable extremes have little or no effect on NDI. Common NDI responses at both ends of the variable extremes provided the engineering justification for minimizing the number of necessary reference standards.

The NDI techniques and specific equipment that were applied to the matrix of honeycomb test specimens were: low/high frequency bond testers (S-9 Sondicator, Bondmaster, and MAUS in resonance mode), through-transmission and pulse-echo ultrasonics (Staveley 136, MAUS in

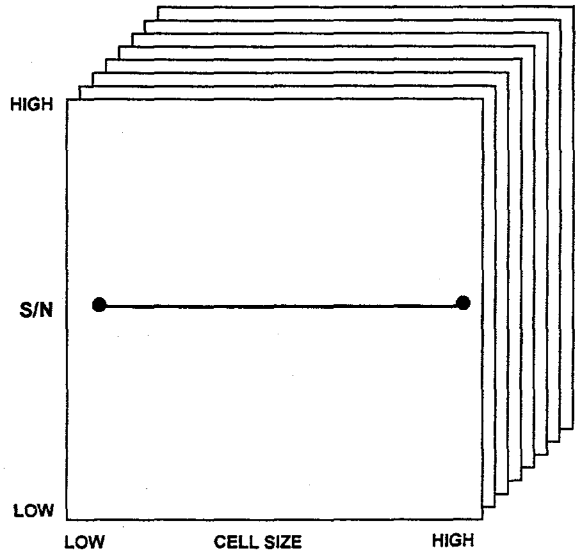
PE mode), tap test (Mitsui Woodpecker), thermography (Thermal Wave Imaging), and mechanical impedance analysis (MIA-3000, V-95 Bondcheck).

Use of Signal-to-Noise Values to Identify Key NDI Variables - In order to intercompare the results from different NDI methods that use different indicators to infer the presence of defects, each inspection measured the signal-to-noise ratio of each defect vs. the surrounding good structure. The noise level was determined by examining the output variation corresponding to inspections along adjacent sections of good structure. This was compared to the signal obtained during inspections of the flawed areas.

BS = base signal; peak signal at unflawed area
NS = noise signal; (max-min)/2 over range of unflawed area in each quadrant
FS = flaw signal; peak signal at each flaw site
S/N = signal-to-noise ratio

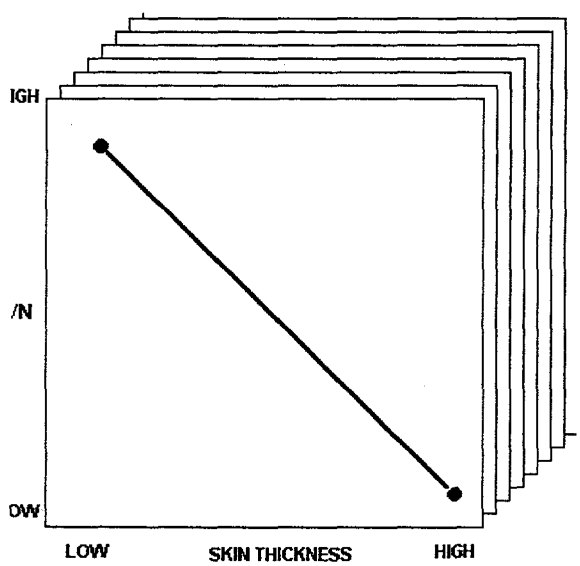
$$S/N = \frac{FS - BS}{NS} \tag{1}$$

Testing using this scheme does not require calibration on a "median" or "neutral" reference standard. The key measurement for each case is the difference between "good" areas of the test panel and the defect area. Hypothetical signal-to-noise testing results for different variable effects are as follows. If a signal-to-noise value remains constant over the full range of honeycomb cell sizes (see Figure 2), then it can be inferred that increasing cell size has no effect on defect detectability. Therefore a reference standard with any cell size can be used to inspect structure with cell sizes of 1/8" to 1/4". However, if the signal-to-noise ratio changes significantly as panels of different skin thickness are inspected (see Figure 3), then skin thickness is an important factor in setting up for honeycomb inspections. Therefore the reference standards must have skins which closely represent the structure to be inspected (small step increments).



Effect of Cell Size
(8 replicates)

Figure 2: Unchanged Signal-to-Noise Ratio Indicates That Increasing Cell Size Has No Effect on Defect Detectability



Effect of Skin Thickness
(8 replicates)

- Result: reference standards must have skins which closely represent the structure to be inspected (small step increments)

Figure 3: Changing Signal-to-Noise Ratio Indicates That Increasing Skin Thickness Has A Major Effect on Defect Detectability

NDT Data Analysis - The inspection results were used to identify the important variables which should be included in composite honeycomb reference standards. The raw X-Y and C-scan data was analyzed using a variance analysis. The statistical analysis of the data was conducted in order to place the effects of flaw and construction variables into "major," "minor," and "minimal" categories. The analysis determined the effect of variables alone (e.g. impact of material thickness) and in two and three variable combinations (e.g. impact of core type in combination with laminate type). The flaw types and construction variables listed above were assessed. The statistical analysis of the round-robin test series showed that for typical composite honeycomb flaws, the dominant factors affecting inspections are laminate thickness, laminate type, and honeycomb type. This data indicates that composite honeycomb reference standards should include the following variable ranges: laminate thickness (3 ply to 12 ply), laminate type (both fiberglass and carbon), and honeycomb type (fiberglass and Nomex).

Validation of Minimum Honeycomb Reference Standard Set

Prototype Minimum Reference Standard Set - The results presented above led us to the production of a prototype minimum reference standard set that include the important variables for the successful inspection of composite honeycomb structure: laminate thickness, laminate type, and honeycomb type. The construction characteristics of the prototype honeycomb set are summarized in Table 1. Disbonds and delaminations were placed together in a single standard. Thus, there were eight standards manufactured: a 3, 6, 9, and 12 ply laminate with carbon or fiberglass skins and each containing both Nomex and fiberglass cores. Figure 4 shows the basic honeycomb design approach.

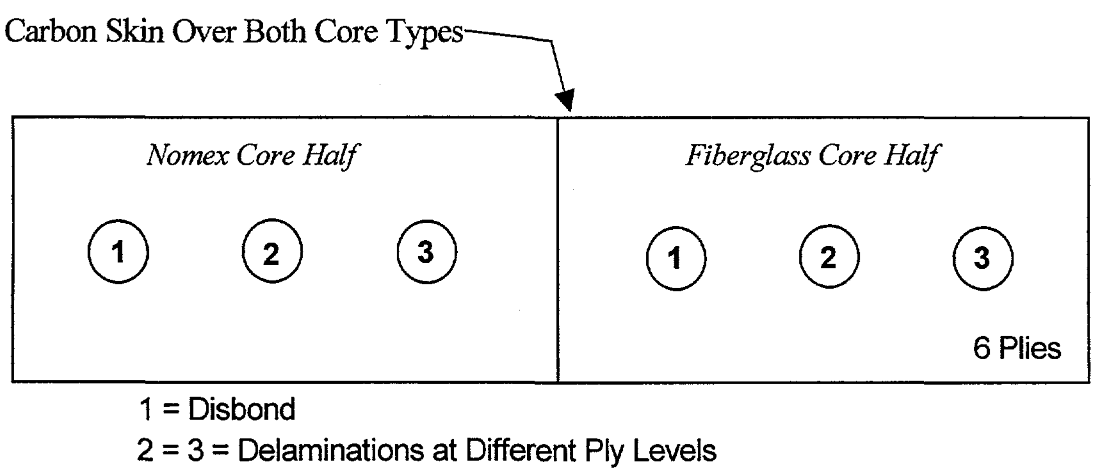


Figure 4: Sample of Basic Honeycomb Standard Design

Variables Addressed in Prototype Composite Honeycomb Standard Set						
Flaw	**Laminate Type**	**Laminate Thickness**	**Honeycomb Type**	**Honeycomb Thickness**	**Cell Size**	**Cell Density**
Delam.	Carbon	3, 6, 9, 12 plies	Nomex	1"	3/16"	3 lb.
Disbond	Carbon	3, 6, 9, 12 plies	Nomex	1"	3/16"	3 lb.
Delam.	Fiberglass	3, 6, 9, 12 plies	Nomex	1"	3/16"	3 lb.
Disbond	Fiberglass	3, 6, 9, 12 plies	Nomex	1"	3/16"	3 lb.
Delam.	Carbon	3, 6, 9, 12 plies	Fiberglass	1"	3/16"	4 lb.
Disbond	Carbon	3, 6, 9, 12 plies	Fiberglass	1"	3/16"	4 lb.
Delam.	Fiberglass	3, 6, 9, 12 plies	Fiberglass	1"	3/16"	4 lb.
Disbond	Fiberglass	3, 6, 9, 12 plies	Fiberglass	1"	3/16"	4 lb.

Table 1: Honeycomb Reference Standards to Be Used to Set Up NDT Equipment for Inspection Exercise

Validation Testing and Results - Validation testing on this minimum set was conducted using the S-9 Sondicator device. After setting up the equipment on each flaw/skin thickness scenario, the set of 64 "aircraft" panels were inspected. Amplitude and phase data were used to assess the viability of the standards. If the full array of 64 specimens – which bound the composite honeycomb structure on aircraft - could be adequately inspected using the minimal standard set, we will have successfully identified the key variables and provided justification for excluding other honeycomb construction variables from the set. Furthermore, by setting up the equipment on 6 ply laminates and then inspecting 3, 9, and 12 ply specimens we determined whether or not exact laminate thickness matches are required (i.e. the allowable variation between laminate thickness used in set-up and laminate thickness in part being inspected).

Signal-to-noise (S/N) results from the panels indicated acceptable flaw detection over the entire range of honeycomb types. Thus, the set of eight prototype honeycomb reference standards described above are able to support the inspection of honeycomb aircraft structure. After setting up the NDT instrument on a 6 ply standard, it was possible to inspect 3 and 9 ply aircraft panels, however, the flaw sensitivity was not as good as when closer ply matches were used for calibration. As a result, the prototype standard set was not altered and it was concluded that 3, 6, 9, and 12 plies are needed to set up NDT equipment for the expected range of laminate thicknesses. Finally, NDI testing using bond testers (high and low frequency), pulse-echo ultrasonics, and machanical impedance analysis demonstrated the difficulty of inspecting structures with 12 or more plies. While acceptable S/N results could often be obtained, the inspection results were not consistent.

Reference Standard Design & Fabrication – Further field testing was identified to complete the validation of the prototype honeycomb reference standard set (see "Future Activities" section below). However, before proceeding with this final phase of the validation, it was decided to reach some conclusions on the standard fabrication process. Several of the NDI tests highlighted some inconsistencies in the flaw manufacturing methods. Pillow insert flaws were used because it was thought that they could provide realistic flaw responses. However, it was determined that the response from the disbonds and delaminations engineered with pillow inserts sometimes did not provide a sufficient deviation from the noise floor to allow for clear flaw detection. Inspection results from the entire suite of specimens generated thus far in the study proved that machining the honeycomb core (recessing) away from the laminate provides the best way of producing reliable skin-to-core disbond flaws. This method also produces flaw sites that can support tap testing. The remaining question is how to realistically and repeatably produce interply delamination flaws.

To answer this question, two trial standards were manufactured that included three candidate methods for engineering delamination flaws. Figure 5 shows the engineering drawing for these evaluation honeycomb specimens; one carbon and one fiberglass skin specimen was produced with this flaw layout. The three methods employed to engineer the delamination flaws were as follows: 1) pillow insert consisting of Kapton tape around 4 layers of tissue paper, 2) brass shims coated with a Silicon mold release to prevent bonding to the plies, and 3) Teflon inserts. Each flaw method was used to generate three like delamination flaws in order to test for repeatability, as well as, to statistically determine the amount of NDI signal disruption generated by the flaw method. Note also that the trial specimen includes potted core and core splice areas. In order to expand the utilization of these standards, potted core and core splice areas were included as a tool to aid the interpretation of NDI signals. This will help minimize false calls caused by the presence of potted cores or core splices that will alter NDT equipment readings.

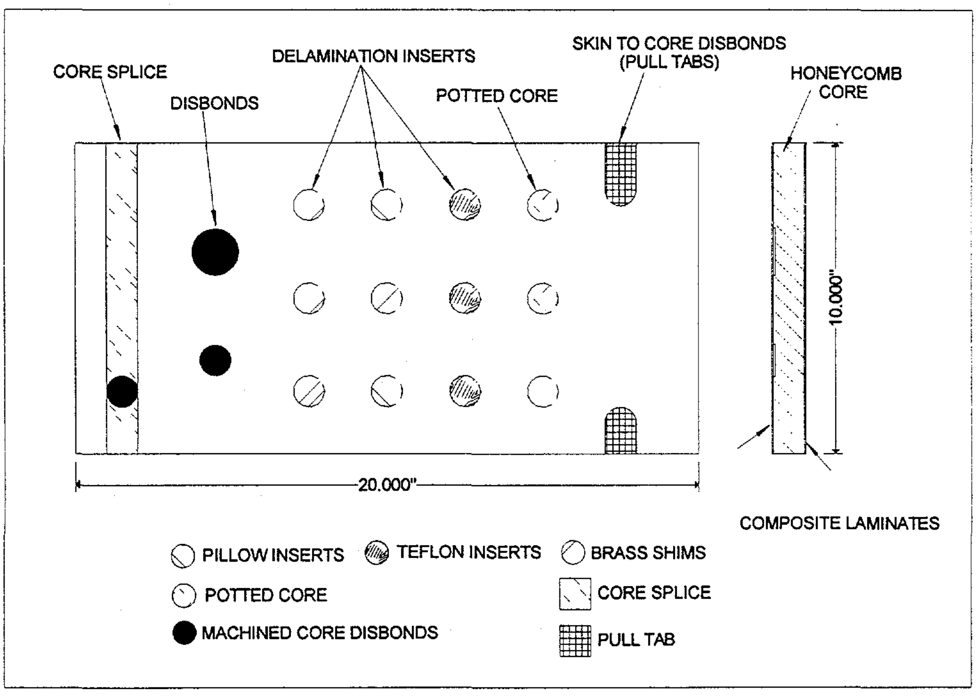


Figure 5: Engineering Drawing to Evaluate Honeycomb Reference Standard Design and Fabrication

Future Activities

The following set of tasks have been established to complete the validation of the minimum honeycomb NDI reference standard set:

1. Finalize the standard fabrication process by determining the optimum way to engineer flaws. The S-9 Sondicator device, the Bondmaster device, and thru-transmission ultrasonics in an immersion tank will be applied to make this assessment. A minimum of 18 dB attenuation will be required at the flaw sites.

2. After completing item #1, the suite of 64 aircraft panels will be revisited with the S-9 Sondicator (both A-scan and C-scan mode). Appropriate OEM inspection procedures and manufacturer equipment calibration procedures will be followed. An alarm box (as opposed to alarm threshold) will be set and flaws in the standard will be assessed. Next, the set of 64 aircraft panels will be inspected following equipment set-up on the honeycomb reference standards. If acceptable detection is achieved on the array of flaws then we will infer that the important construction variables have been included in the standard set.

3. Field Tests - The prototype honeycomb reference standard set will be delivered to United Airlines and Northwest Airlines to study how they function in the field. They will be evaluated on damaged honeycomb structure removed from aircraft (on as-available basis) and on honeycomb structure currently on aircraft.

4. Design Optimization - The final design will minimize the overall size of each standard and will provide for the fewest number of separate honeycomb standards. The final specimen size must accommodate probe deployment on both good and flawed structure and eliminate any edge effects or effects from adjacent flaws.

TASK 2: SOLID COMPOSITE LAMINATE STANDARDS

Overview

The goal of this effort is to establish a single, generic composite laminate reference standard that will accommodate inspections on the full array of fiberglass and carbon laminates found on aircraft. Optimally, we would like to substitute a single material for both carbon and fiberglass solid laminate inspections. The material would need to provide the same NDI response to both carbon and fiberglass. In addition, in order to improve on existing solid laminate standards, the material should be inexpensive, reliably manufactured and easy to machine into a solid laminate standard (i.e. plate with multiple thicknesses).

The first step in this effort was to apply thru-transmission ultrasonics to the series of existing Boeing, Douglas, and Airbus laminate specimens (step wedges of various materials at different thicknesses) in order to measure the key velocity, acoustic impedance, and attenuation characteristics in the laminates. A subsequent material search identified what appears to be an excellent candidate as a generic solid laminate reference standard material. Testing to date has determined matches in key velocity and acoustic impedance properties, as well as, low attenuation relative to carbon laminates. Furthermore, comparisons of resonance testing response curves from the G11 Phenolic prototype standard was very similar to the resonance response curves measured on the existing carbon and fiberglass laminates. Resonance tests on three carbon composite standards showed that variability across "similar" standards was similar to the variability observed between G11 and carbon or fiberglass. Additional insight from experienced aircraft inspectors is needed to make a final assessment of the viability of G11 material as a suitable generic solid laminate standard.

Search for a Generic Solid Laminate Material

The following issues were addressed to arrive at the G11 generic material candidate.

1. Attenuation Data - A significant number of the attenuation values varied substantially in a single step wedge (common material). Numerous factors affect attenuation measurements and this parameter is difficult to use to correlate one laminate with another. In fact the carriers indicated that they use laminate standards to set up their equipment (functionality) but not to establish flaw call "levels." Attenuation in the laminate standards doesn't exactly represent the actual part on the aircraft. Inspectors base flaw calls on consistency across the part being inspected (in-situ measurements determine appropriate signal levels). However, this parameter does provide a basis of comparison with existing laminate standards. We want to match the attenuation of the existing laminates and not induce additional attenuation through the introduction of a new generic material.

2. Velocity Data - Longitudinal velocity data was acquired using 1 MHz, 2.25 MHz, and 5 MHz transducers. The velocity data was very consistent across each step wedge and even similar from one material to another. The maximum difference between the minimum and maximum velocities for all OEM standards including fiberglass and carbon materials was less than 10%. The velocities ranged from 0.112 in/μs to 0.120 in/μs. These results are logged in Table 2 and produced the target values shown for our generic material.

3. Pulse Laminate Standards for Pulse-Echo (Velocity-Based) Testing - Based on the velocity results, it was determined that for velocity-based equipment the standard should be made from a material with a median velocity (0.115 in/μs). Ease of manufacture, material cost, and ease of use are important factors. The basic design approach is to machine flat-bottomed holes in a plate which is large enough to accommodate scanner heads. This plate design will be less susceptible to breakage than the existing wedge specimens.

4. Laminate Standards for Resonance Testing - Velocity measurements alone do not allow for proper resonance equipment set-up. Furthermore, resonance testing requires that the equipment be set-up on laminates with similar thickness to the part being inspected. Thus, the necessary laminate reference standard(s) should have the appropriate material property. The key property may be acoustic impedance, Z, where ρ = density and

$$Z = \rho \times \text{Velocity} \qquad (2)$$

5. Search for Suitable Material - Based on the above observations, a search was performed to locate a material with the appropriate velocity and density (thus, acoustic impedance) properties. Other desirable attributes were that the material be inexpensive, easy to machine, and able to be reliably produced. Table 2 lists candidate materials along with the data from the current carbon and fiberglass material which we attempted to match. For resonance mode inspections, a close match with acoustic impedance is necessary. Also, attenuation characteristics are important. In order to accommodate inspections through thick laminates (0.25" - 0.5" thick), the allowable material attenuation was 8-10 dB relative to the existing step wedges.

   Based on cataloged property values, a number of materials were selected to go through the prototype fabrication and testing process. An extensive study of Phenolic materials was performed and two types, G10 and G11, were proven to be excellent candidates. They both provide close matches to the critical material properties and have low attenuation relative to carbon.

6. Generic Standard Design - A laminate standard design, which includes thickness ranges from one ply (0.010") to 1.0", was developed. Prototype laminate standards, as shown in Figure 6 below, were fabricated from candidate "generic" materials listed in Table 2. The results below address the material our team is proposing as the new laminate standard: G11 Phenolic.

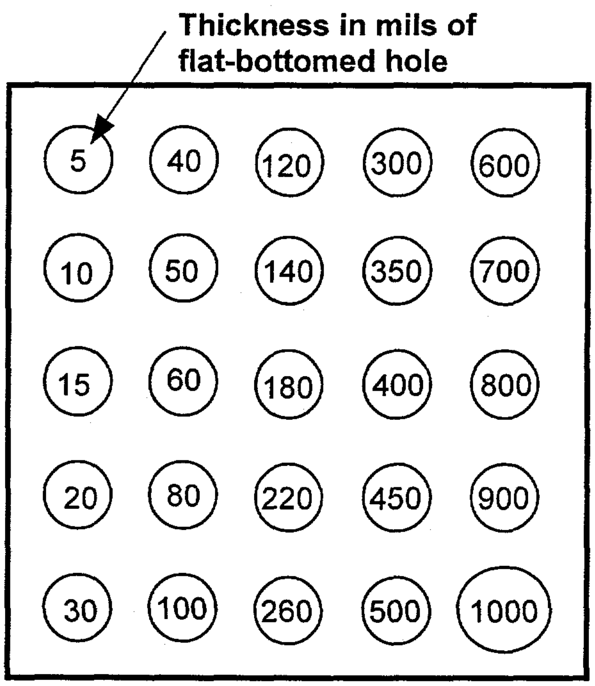


Figure 6: Generic Composite Laminate Standard

Material	Velocity in/μs (mm/μs)	Density g/cm^3	Acoustic Impedance g/cm^2·μs	Relative Attenuation*
Carbon Graphite Boeing Std ST8870 (BMS 8-212)	0.1218 (3.070)	1.589	0.488	-
Carbon Graphite Boeing Std ST8871 (BMS 8-276)	0.1150 (2.912)	1.589	0.463	-
Fiberglass (50 V%)	0.1150 (2.912)	1.917	0.605	20 dB (0.2" th) 30 dB (0.5" th)
Boron-Epoxy (50 V%)	0.1310 (3.317)	1.920	0.639	Not Measured
Ivory	0.1185 (3.000)	2.170	0.653	Not Measured
Hysol Potting Material EE4183	0.1010 (2.562)	1.518	0.390	10 dB (0.2" th)
Phenolic [United Airlines supply]	0.1100 (2.873)	TBD	TBD	12 dB (0.2" th) 18 dB (0.5" th)
Phenolic G7	0.0834 (2.110)	1.700	0.358	
Phenolic G9	0.1474 (3.730)	1.950	0.727	
Phenolic G10	0.1193 (3.020)	1.850	0.559	4 dB (0.2" th.) 9 dB (0.5" th)
Phenolic G11	0.1158 (2.930)	1.850	0.541	4 dB (0.2" th.) 9 dB (0.5" th)
Phenolic LE	0.1047 (2.650)	1.320	0.350	
Phenolic XXX	0.1071 (2.710)	1.300	0.352	
Zero Impedance Material	0.0843 (2.141)	1.240	0.2655	Not Measured
Generic Material Targets	**0.1150 (2.911)**	**1.6 - 1.8**	**0.48 - 0.54**	< 10 dB

* As compared with Boeing step wedge ST8870, 0.2" th. and Boeing step wedge ST8871, 0.5" th.

Table 2: Important Material Properties for Candidate Laminate Standard Materials

7. Manufacturing Specifications - Through-transmission ultrasonic inspections of G11 showed that it can be manufactured as very pure material with very little porosity (basically none was measured). Ultrasonic C-scans showed less than 2 dB's variation in response across the entire 12" X 12" area. The G11 Phenolic type can be uniformly and repeatably made and is readily and inexpensively available. In the machining process, the plates were first faced to assure a uniform thickness and depth accuracy in the flat-bottomed holes. Next, the flat-bottomed holes were machined as per Figure 6. Thickness areas as low as 0.010" (0.990" deep hole) could be produced in the Phenolic material.

NDI Validation Test Results

Through-transmission ultrasonics (TTU), pulse-echo ultrasonics (Quantum device from NDT Engineering Inc.) and resonance (Bondmaster device) inspection techniques were applied to the prototype laminate standards in order to measure the material properties and to assess the prototype standards use on simulated aircraft structure. Following is a summary of the inspection results.

1. Velocity and Attenuation Measurements - TTU was used to measure velocity and attenuation in both the candidate and existing laminate standards. Attenuation measurements were made in an immersion tank to produce consistent and repeatable test results. Relative attenuation values shown in Table 2 are as compared with the Boeing ST8870 step wedge at 0.2" thick and the Boeing ST8871 step wedge at 0.5" thick.

2. Pulse-Echo Ultrasonics - Measurements were made using a Quantum device in order to study the ability of P-E UT to resolve the full array of thicknesses in the laminate standard. Using 1 MHz, 2.25 MHz, and 10 MHz transducers it was possible to resolve thickness areas from 0.010" to 1.0". Since this is a velocity-based method, the close match between the G11 (2.93 mm/μs), carbon (2.90 mm/μs), and fiberglass (2.91 mm/μs) velocities should eliminate the need for any conversion factors when using the generic (G11) material.

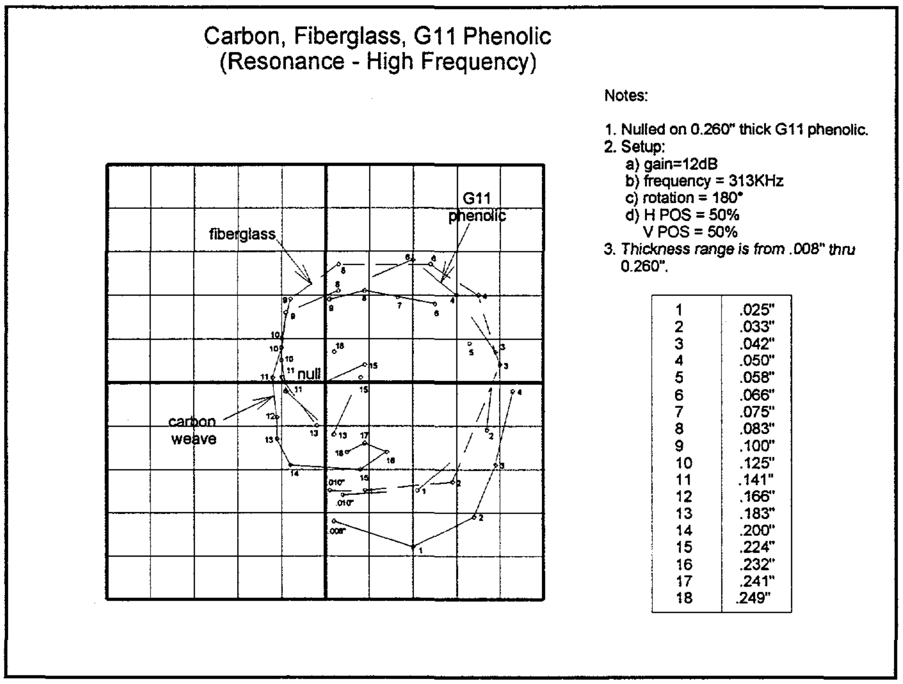
3. Resonance (Bondmaster) Test Procedure - A number of different resonance inspection tests were conducted in order to relate the response curves between the G11 candidate material and existing composite laminate standards. Resonance inspections were also carried out on a set of three similar carbon graphite (plain weave) step wedge specimens which were produced by United Airlines' composite shop. The resonance tests were performed to study the degree of spread (variation) in the response curves for supposedly similar specimens. This gives us some perspective when assessing the spread between G11, carbon, and fiberglass curves.

   Resonance response curves were obtained for high frequency (314 KHz) and low frequency (156 KHz) inspections over a range of high (12 - 14 dB), medium (9-10 dB), and low (6-7 dB) gains. High frequency inspections were used to measure the Bondmaster response over the thickness range of 0.010" to 0.250" while low frequency inspections measured the Bondmaster response over the thickness range of 0.050" to 0.600". For the comparison between carbon, fiberglass, and G11 Phenolic, a null point was taken only on the G11 Phenolic. Subsequent measurements were taken on the carbon and fiberglass without renulling the instrument. This gives an indication of the response variation between the different materials in specific thickness ranges with setup parameters based on G11.

4. Resonance Spiral Curves - Figure 7 shows the results from the high frequency inspections and compares the fiberglass and carbon response curves to the G11 material. This figure shows that even at high gain, the "spiral" curves are closely clustered. It can be seen that the G11 spiral curves compare even better with fiberglass. This is reasonable since the attenuation and acoustic impedance values are almost identical. Additional data

comparisons are shown in Figures 8 and 9 where specimens made of identical or similar materials are compared against each other to show variations that might occur in the fabrication process (e.g. cure pressure, temperature, etc.). Instrumentation setup for these data included nulling on each individual material.

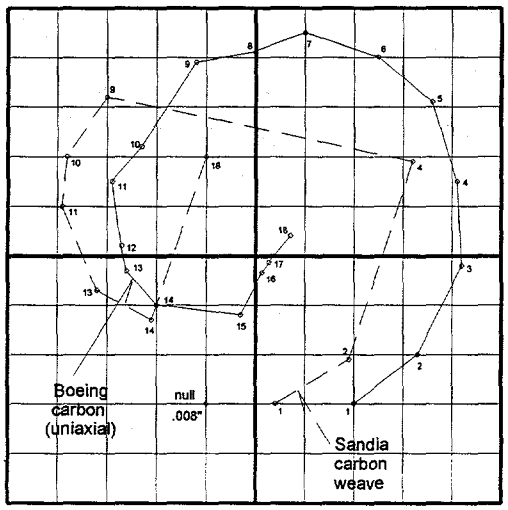
In order to provide some perspective for the resonance inspection data and to better assess the spread observed in Fig. 7, several resonance inspections were conducted on "similar" materials. Figure 8 shows resonance response curves comparing the Boeing uniaxial step wedge with the carbon graphite prototype standard (BMS 8-276) produced by NDT Engineering for this study. Most of the common thickness points plotted close together, however, data spreads similar to the G11-to-carbon comparisons were observed. Figure 9 compares the response curves from three similar carbon graphite (plain weave) step wedge specimens which were produced by United Airlines' composite shop. The specimens were produced with the intent of simulating the porosity, surface roughness, and irregularities of actual aircraft structure. The irregularities would typically be the result of variations in the fabrication process. These variations, within allowable tolerances, can include parameters such as cure pressure, cure temperature, debulk steps, and other manufacturing specifications.



1	.025"
2	.033"
3	.042"
4	.050"
5	.058"
6	.066"
7	.075"
8	.083"
9	.100"
10	.125"
11	.141"
12	.166"
13	.183"
14	.200"
15	.224"
16	.232"
17	.241"
18	.249"

Figure 7: Comparison of Resonance Response Curves for G11, Fiberglass, and Carbon Materials - High Frequency, High Gain

Boeing Carbon Uniaxial (Step Wedge)
Sandia Carbon Weave (12" X 12" Plate)
(Resonance - High Frequency)



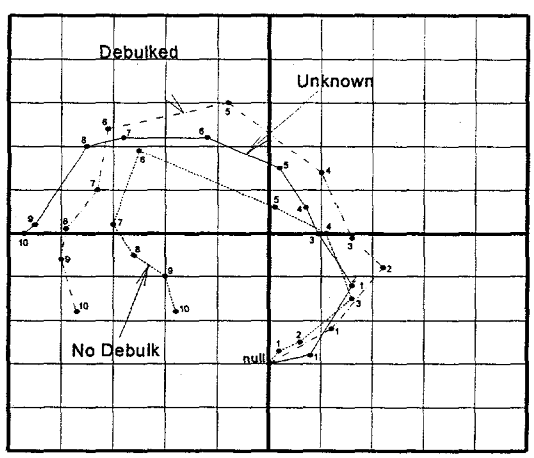
Notes:

1. Nulled on 0.008" thick Boeing specimen and 0.010" Sandia specimen.
2. Setup:
   a) gain=14dB
   b) frequency = 313KHz
   c) rotation = 180°
   d) H POS = 40%
      V POS = 20%
3. Thickness range is from .008" thru 0.260".

1	.025"
2	.033"
3	.042"
4	.050"
5	.058"
6	.066"
7	.075"
8	.083"
9	.100"
10	.125"
11	.141"
12	.166"
13	.183"
14	.200"
15	.224"
16	.232"
17	.241"
18	.249"

Figure 8: Comparison of Resonance Response Curves for Similar Carbon Reference Standards - High Frequency, High Gain

Carbon Weave
Comparison Samples
(Resonance - High Frequency)



Notes:

1. Nulled on 0.020" thick carbon weave section.
2. Setup:
   a) gain=14dB
   b) frequency = 313KHz
   c) rotation = 150°
   d) H POS = 50%
      V POS = 20%
3. Thickness range is as follows:

null	0.020
1	0.030
2	0.040
3	0.050
4	0.060
5	0.070
6	0.080
7	0.090
8	0.100
9	0.110
10	0.120

Figure 9: Comparison of Resonance Response Curves for Similar Carbon "Aircraft Structures" - High Frequency, High Gain

5. C-Scan Resonance Inspection Results - In order to eliminate data variations stemming from changes in probe deployment during testing, a series of specimens were inspected side-by-side using the MAUS scanning NDI system in resonance mode. Existing fiberglass and carbon step wedge reference standards, along with other carbon laminates representing fabrication variability, were inspected along with the candidate G11 prototype standard (see Fig. 6 for design). The color coded images provided by the MAUS system showed that common NDI responses (i.e. same color in C-scan image) were obtained for similar thicknesses on all of the specimens. This provides further evidence that the G11 material can be used as an NDI reference standard to support inspections of both fiberglass and carbon solid laminate structures.

Future Activities

The following set of tasks have been established to complete the validation of the generic G11 solid laminate reference standard:

1. Personnel from Boeing's NDT Engineering Dept. will use the generic standard to support inspections on a number of in-house solid laminate aircraft structures with flaws. Additional insights will be solicited from industry and aircraft inspectors.

2. Solid laminate inspection procedures will be revisited to determine if any modifications or additions are necessary to accommodate the use of a generic laminate standard.

3. Optimize the Generic Laminate Design - Issues to be addressed include minimizing size and weight, ease of machining, handling, and ease of use in the field (e.g. identifying locations and thickness of flat-bottomed holes on the top side of the standard to allow for proper positioning of the transducer).

CONCLUSIONS

While seeking the optimum, yet minimum number, of composite honeycomb reference standards needed to conduct inspections on commercial aircraft structure, this study has determined the honeycomb construction parameters that have a major effect on NDI. These results were used to produce a prototype minimum honeycomb reference standard set. The reference standard set successfully completed a preliminary NDI validation phase. Current efforts are aimed at determining the best and most repeatable methods for engineering realistic flaws in the reference standards.

An extensive material search, accompanied by key NDI response studies, has produced a generic solid composite laminate reference standard that will accommodate inspections on the full array of fiberglass and carbon laminates found on aircraft. A prototype solid laminate standard made from G11 Phenolic material was demonstrated to provide the same NDI response as existing carbon and fiberglass standards. In addition, the G11 material improves on existing solid laminate standards because it is inexpensive, can be reliably manufactured and is easy to machine into a solid laminate standard (i.e. plate with multiple thicknesses). NDI validation of this material consisted of both pulse-echo (velocity based) and resonance (acoustic impedance based) mode inspections.

Overall, this effort will produce a uniform approach to the inspection of composite structures on aircraft. Following final validation, field testing, and design optimization on both solid laminate and honeycomb reference standards, formal modifications to appropriate OEM manuals will be addressed. Through the active participation of the OEM's, this project represents a harmonized approach by aircraft manufacturers worldwide. The end result will be more streamlined inspection set-ups for aircraft maintenance depots and improved inspections through the use of optimized NDI reference standards.

ACKNOWLEDGMENTS

This work is a joint effort of the FAA's Airworthiness Assurance Center operated by Sandia National Labs and the Commercial Aircraft Composite Repair Committee (CACRC), Inspection Task Group. In addition to the authors, key CACRC participants include Jeff Kollgaard (Boeing), Tom Dreher (United Airlines), Glae McDonald (US Airways), Gerry Doetkott (Northwest Airlines), Jim Hofer (Boeing), John Hewitt (British Airways), and Bruce Garbett (Airbus Industries). This work was sponsored by the FAA William J. Hughes Technical Center under a U.S. Dept. of Transportation contract. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the U.S. Dept. of Energy under Contract DE-AC04-94AL85000.

REFERENCES

1. "Composite Repair NDT/NDI Handbook," SAE Aerospace Recommended Practice ARP5089, issued Nov. 1996, prepared by the ATA/IATA/SAE Commercial Aircraft Composite Repair Committee, Inspection Task Group.