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VALIDATION OF LASER BOND INSPECTION (LBI) TECHNOLOGY

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ABSTRACT

While the aerospace industry is continuously striving to achieve more affordable and more efficient composite structures, full composite weight-saving benefits have not yet been realized for unitized, integrated structures due to lack of confidence in the quality of adhesively bonded joints. Specifically, robust nondestructive inspection (NDI) techniques are needed to verify safety-of-flight-critical bonded structure for certification. Traditional NDI techniques are not adequate for determining bond strength in structure, which limits bonded joint acceptance. Because the ability to inspect bonded joints is considered a high priority within the composites community, the Air Force Research Laboratory has funded efforts to validate laser bond inspection (LBI). The LBI technology uses controlled high intensity stress waves formed by pulsed laser excitation as a method to test the strength of bonded joints. The current effort is aimed at validating that LBI can be used to reliably measure composite bond strength integrity and develop a strategy for LBI technology transition as a step forward towards certification. LBI results will be shown for two bonded material systems, using panels with controlled bond strength, followed by correlation to the results of mechanical coupon testing. Models developed based on these results will then be applied and compared to testing on large complex contoured tapered panels. LBI testing in this validation effort is conducted with two independent systems to determine reproducibility. Laser fluence thresholds and inspection levels for the various bond strength panels will be established and verified with post-test characterization via traditional NDI techniques and photomicroscopy. An LBI implementation strategy will be developed, and technology gaps will be identified for technology transition.

1 INTRODUCTION

Full weight-saving benefits have not yet been realized for unitized, integrated bonded composite structures due to lack of confidence in the process control and quality of adhesively bonded joints. Specifically, robust nondestructive inspection (NDI) techniques are needed to verify safety-of-flight-critical bonded composite structure for certification. Traditional NDI techniques are not adequate for determining bond strength in structure, which limits bonded joint acceptance. The ability to inspect bonded joints is considered a high priority within the composites community of the aerospace industry to ultimately achieve more affordable and more efficient composite structures; therefore, the Air Force Research Laboratory funded programs in this area [1, 2]. This effort aims to transition and validate laser bond inspection (LBI) using multiple material systems in bonding and manufacturing representative complex contoured bonded test panels as a step forward towards a validated certification approach.

2 SCOPE

This effort is aimed at validating that LBI can be used to reliably measure composite bond strength integrity and develop a strategy for LBI technology transition. The LBI technology uses controlled high intensity stress waves formed by a pulsed laser excitation as a method to test the strength of bonded joints. LBI results will be shown for two separate laminate/adhesive material systems, using panels with controlled bond strengths, followed by correlation to the results of mechanical coupon testing. Models developed based on these results will then be applied and compared to testing on large complex contoured tapered panels. LBI testing in this validation effort will be conducted with two independent LBI systems to determine reproducibility. One LBI system is located at the Boeing Company, and the other system is located at Northrop Grumman Aerospace Systems (NGAS) and operated by LSP Technologies (LSPT) and NGAS for this effort.

3 METHODS, ASSUMPTIONS, AND PROCEDURES

LBI is a post-bond inspection method providing a localized proof test that can identify weak adhesive bonds by leaving an 8-10 mm detectable indication but is nondestructive to properly prepared, nominal bonds. LBI is a stress wave method that sends a controlled laser energy pulse into the structure perpendicular to the bondline. A compression wave travels through the structure and reflects off the back surface, stressing the bondline in tension as it passes back through, breaking weak bonds. Traditional NDI techniques are conducted before and after the laser pulse to ascertain if the laser pulse broke weak bonds (or weak composite laminates). Engineering calibration is required to determine laser energies for given applications, ensuring only unacceptably weak bonds fail due to the tension wave. A high peak pulse energy, short-pulse laser (5-50 J pulse energy, ~200 ns pulse width, 1054 nm wavelength) is used with a spot size of about 8-10 mm. The Neodymium-doped phosphate glass laser system is built on a rugged cart for limited maneuverability, and the delivery system includes an articulating arm with a reach of 1.74 m (5.7 ft) (or optional 4.57 m (15 ft) available). The LBI device and inspection head are shown in Figure 1 and Figure 2. A schematic of the inspection methodology is shown in Figure 3.

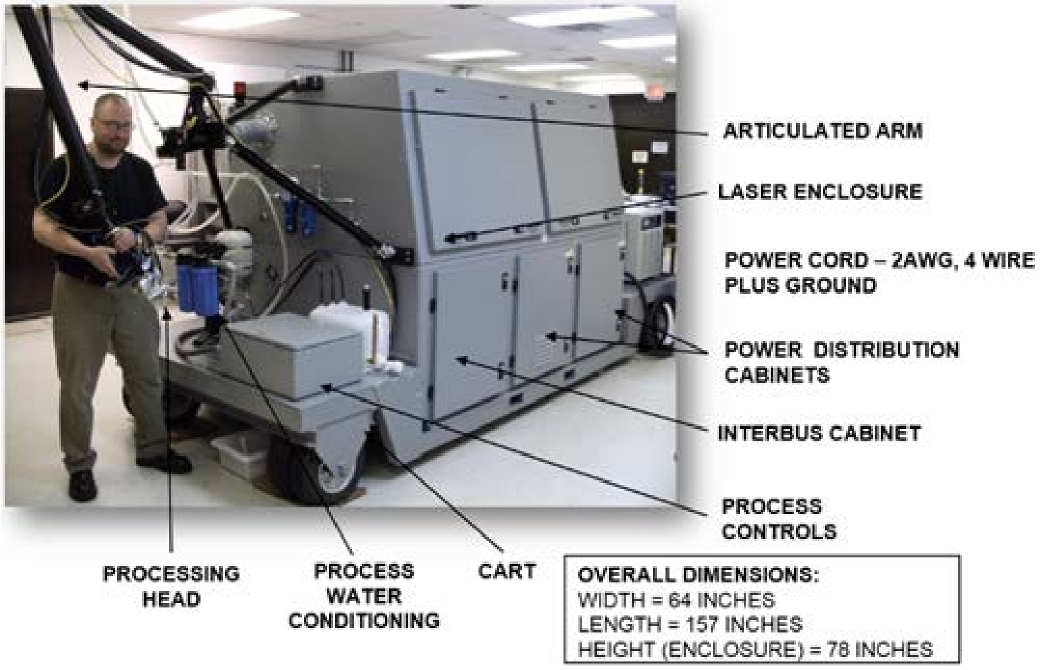


Figure 1: LBI device.

- Features:
  - Eye Safe
  - LED Indicators
  - Overlay Water Removal System
  - Modular Design
  - Quick Disconnects
  - Electromagnetic Acoustic Transducer (EMAT) Sensor

Figure 2: LBI inspection head.

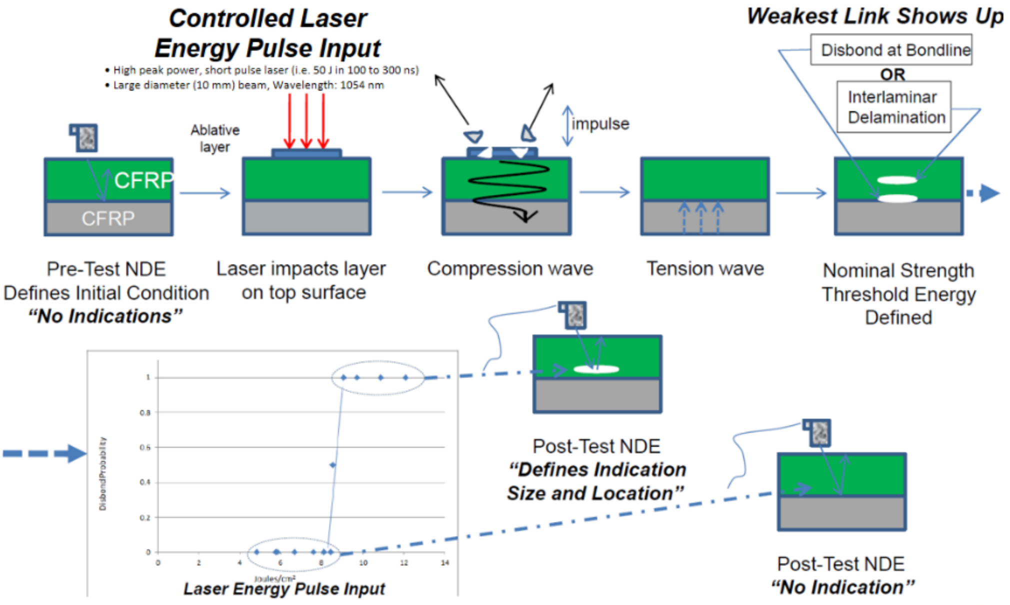


Figure 3: Fundamental LBI process.

3.1 LBI Theory

The fundamental process of laser-generated stress wave evolution in a bonded composite joint is illustrated in Figure 3. The energy delivered by the laser is absorbed in a sacrificial overlay such as black tape (i.e. ablative layer) at the incident top surface of the joint. No sample heating takes place, and there is no surface damage. Vaporization of some elements of the overlay produces locally high pressure that is enhanced by inclusion of a transparent water tamping layer, which confines vapor expansion. The shock from the laser pulse produces a compression wave that propagates to the back surface of the composite joint where it reflects back in tension. It is this tensile wave propagating through the joint that provides the proof-test loading. The actual three-dimensional case of practical interest is considerably more complex, but the basic principles are the same [1]. In this work, the pathlength is defined as the total distance the shockwave travels through to the back surface of the composite joint and then reflected to the bondline.

3.2 Design of Experiments / Test Panel Design

A Design of Experiments (DOE) was created which incorporated two carbon fiber reinforced plastic (CFRP)/epoxy material systems of interest along with two epoxy film adhesives. To support the DOE, a series of bonded panel gauges representative of actual structures were fabricated with varying controlled bond strengths (nominal, intermediate, and weak). The DOE also captured the effects of critical parameters related to LBI. The drawing tree of one of the CFRP systems is shown in Figure 4 with all of the bond assemblies labeled in blue for both multi-gauge and symmetric (i.e. similar gauge or number of CFRP prepreg plies) panels (a total of 13 discrete bond assemblies). A total of 6 discrete detail laminate test panels are identified in green at the bottom of the matrix. The first row of bond assemblies in the drawing tree are all nominal strength panels, meaning they are designed to produce the nominal or typical strength with this CFRP and adhesive bonding system. AFLB045 is an intermediate strength panel, meaning the surface preparation was slightly compromised to produce bond assemblies with a slightly lower average strength. The bottom row of bond assemblies are all controlled weak strength panels, meaning the surface preparation was severely compromised. These panels were fabricated using a Boeing patented process [2].

NDI, using production-type NDI ultrasound (UT) equipment and laminate standards, was used to inspect the composite laminates prior to bonding, the bond assemblies after bonding, and the bond assemblies again after testing with LBI. Pre- and post-LBI NDI was conducted using two methods: pulse echo (PE) and through transmission ultrasound (TTU). In addition, portable hand-held equipment with either single element transducers or a 16 element phased array probe was used to capture UT waveforms (A-scans) before and after each LBI test.

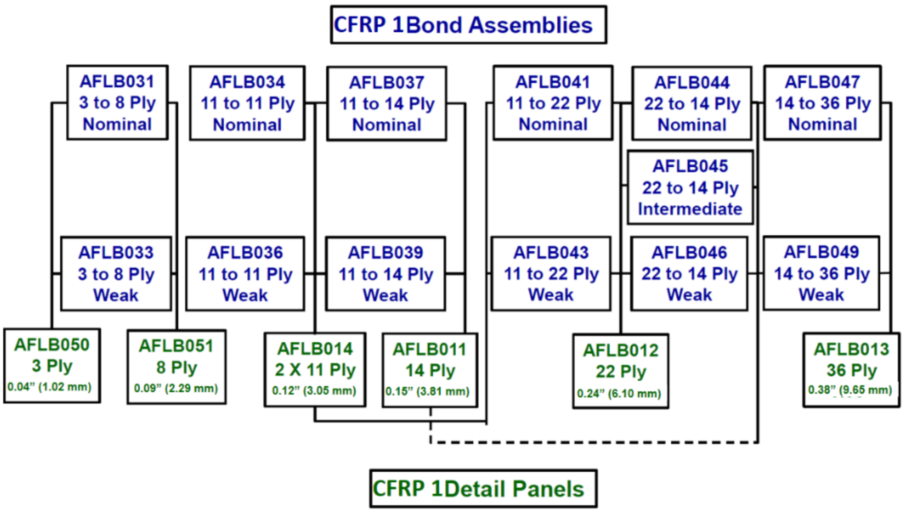


Figure 4: Drawing tree for bond assembly panels – CFRP 1 fabrication.

3.3 LBI Testing and Analysis of NDI Data

LBI testing in this validation effort was conducted with two independent LBI systems to determine reproducibility. To determine the threshold level or breaking strength, the bonded panels were tested via LBI over a range of LBI fluence levels. A limited number of multi-shot LBI tests (i.e. multiple LBI inspections in the same location on a bonded panel) were performed to help determine an appropriate “inspection” level (i.e. a reduced LBI fluence to determine if the bond is sufficiently strong, but the fluence is not high enough to damage acceptable bonds).

Following the LBI tests, UT was performed to detect indications that represent failure of the bond. The interpretation of the UT waveform at the LBI test location was used to set a criteria for whether a signal was considered an indication or noise. This issue exists in all NDI applications. “Red” threshold signals were set to represent “Hits” for the LBI fluence level at those test locations. The “Hits” indicated detectable damage via the NDI. All other LBI test locations represented “Misses,” or no damage was detectable (i.e. any signal was considered noise or variation below NDI threshold inspection criteria). By plotting the “Hits” and “Misses” as a function of the LBI fluence, it was possible to determine a probability for the threshold value. The mathematical fit to the data was based on probability of detection (POD) analysis used in the NDI community as described in MIL-HDBK-1823 [3]. While the POD analysis is normally applied to the detection of flaws against flaw size, the mathematics were applied to the detection of bond failure against LBI fluence in this program. Design curves/models were then developed applying this POD approach and a_{50} criteria (target at 50% POD) for NDI data.

3.4 Mechanical Testing and Failure Analyses

Mechanical strength testing, consisting primarily of Mode I, Double Cantilevered Beam (DCB) for similar gauge panels and Flatwise Tension (FWT) for multi-gauge panels, and Mode II, Single Lap Shear (SLS), was conducted on the bond assemblies to correlate to LBI performance. Testing was conducted according to ASTM International standards. The failure modes of all mechanical test specimens were reviewed and reported; high-resolution microscopy was used if required. In addition to static testing, fatigue testing was conducted on both DCB and FWT specimens. Some DCB specimens were also tested after LBI testing had been performed. To further validate the LBI process, photomicroscopy was performed after LBI testing at known fluences of interest.

3.5 Technology Validation and Transition

To evaluate scale from flat panel bond assembly panel testing to aircraft-sized configured joint details, two configured demonstration articles, one of each CFRP and adhesive system, were fabricated, approximately 1.52 m (5 ft) by 3.05 m (10 ft) in size. The configured demonstrations were simulated wing skins with seven bonded stringers sections having varying bond quality (both nominal and weak areas) similar to the flat panel bond assemblies. Three stringers were of nominal strength, two were of weak strength, and two were “blind” in which there are 10 weak areas approximately 10.2 cm by 10.2 cm (4 in by 4 in) interspersed within the two blind stringers. LBI testing was carried out with the energy levels determined from the design guidance created by the flat panel bond assemblies (Section 3.3) to validate the LBI process and methodology. In addition, LBI procedures and implementation plans will be documented, and technology gaps will be identified for technology transition.

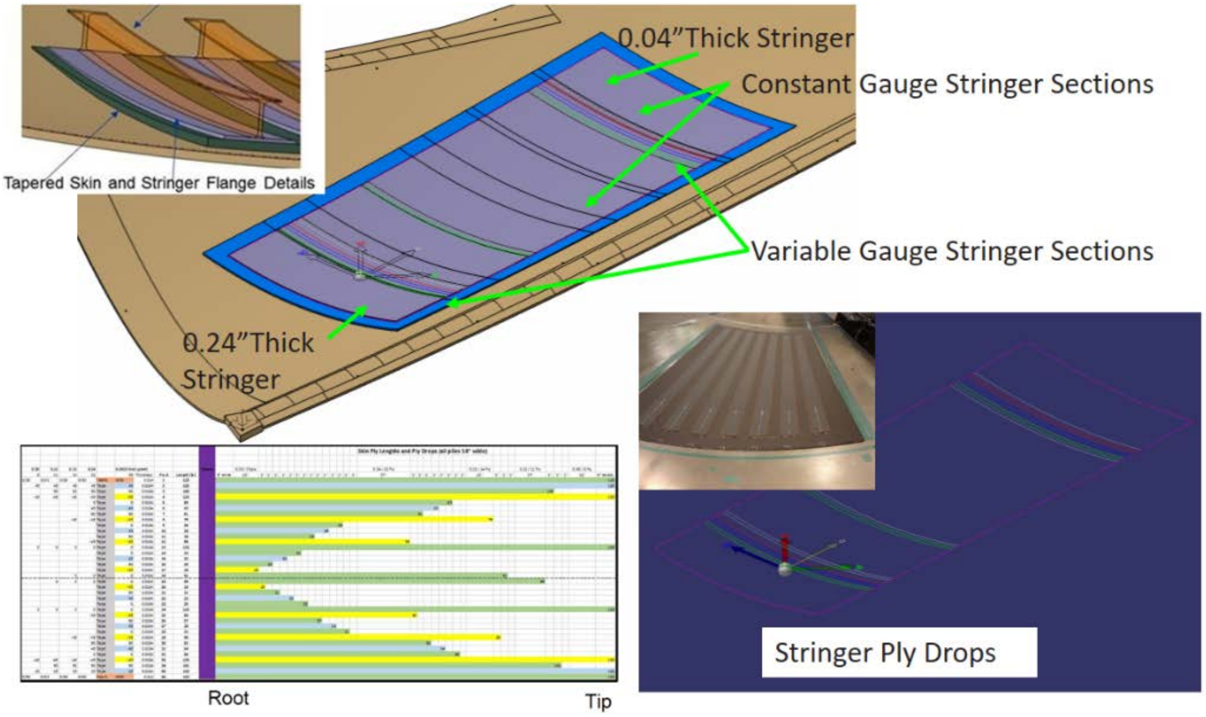
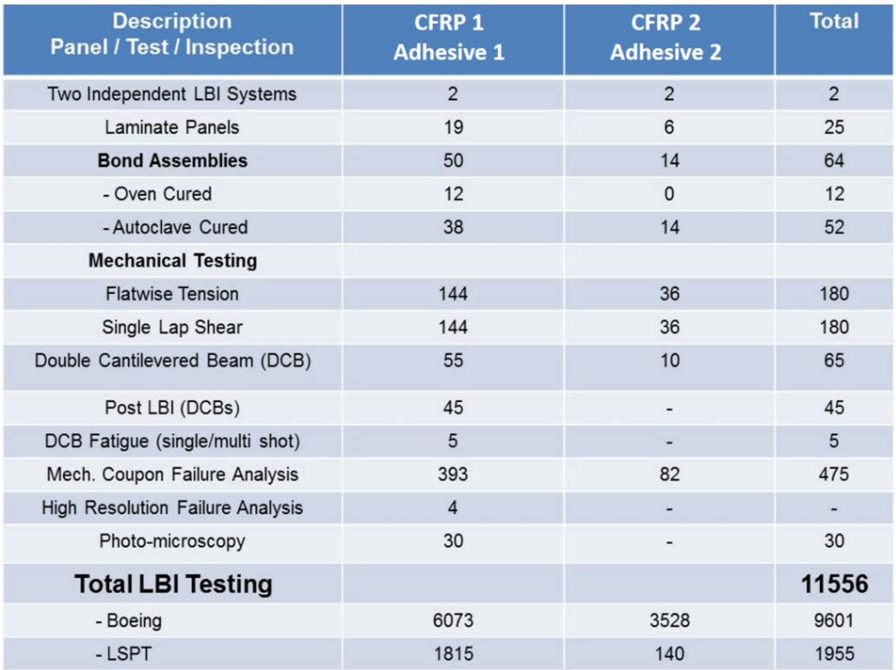


Figure 5: Large scale demonstration – simulated wing skin with seven stringers.

4 RESULTS AND DISCUSSION

A summary of the number of tests and LBI inspections is shown in Table 1. To date, around 9800 LBI tests have been completed (~85%) with the remaining tests planned to be conducted on large demonstration articles.



Description Panel / Test / Inspection	CFRP 1 Adhesive 1	CFRP 2 Adhesive 2	Total
Two Independent LBI Systems	2	2	2
Laminate Panels	19	6	25
Bond Assemblies	50	14	64
- Oven Cured	12	0	12
- Autoclave Cured	38	14	52
Mechanical Testing			
Flatwise Tension	144	36	180
Single Lap Shear	144	36	180
Double Cantilevered Beam (DCB)	55	10	65
Post LBI (DCBs)	45	-	45
DCB Fatigue (single/multi shot)	5	-	5
Mech. Coupon Failure Analysis	393	82	475
High Resolution Failure Analysis	4	-	-
Photo-microscopy	30	-	30
Total LBI Testing			**11556**
- Boeing	6073	3528	9601
- LSPT	1815	140	1955

Table 1: Summary of coupons/test/inspections.

Figure 6 is an example of the mechanical test data generated on this program. These are FWT test results for CFRP 1 bond assemblies. Static testing is complete, but fatigue testing is still ongoing. Nominal bond assemblies exhibit strengths of 30.34 MPa (4400 psi) while weak bond assembly strengths average around 11.03 MPa (1600 psi). Error bars are shown along with a graph (in the upper right hand corner) of one of the nominal panels illustrating the typical scatter in strength observed for the nominal bond assembly.

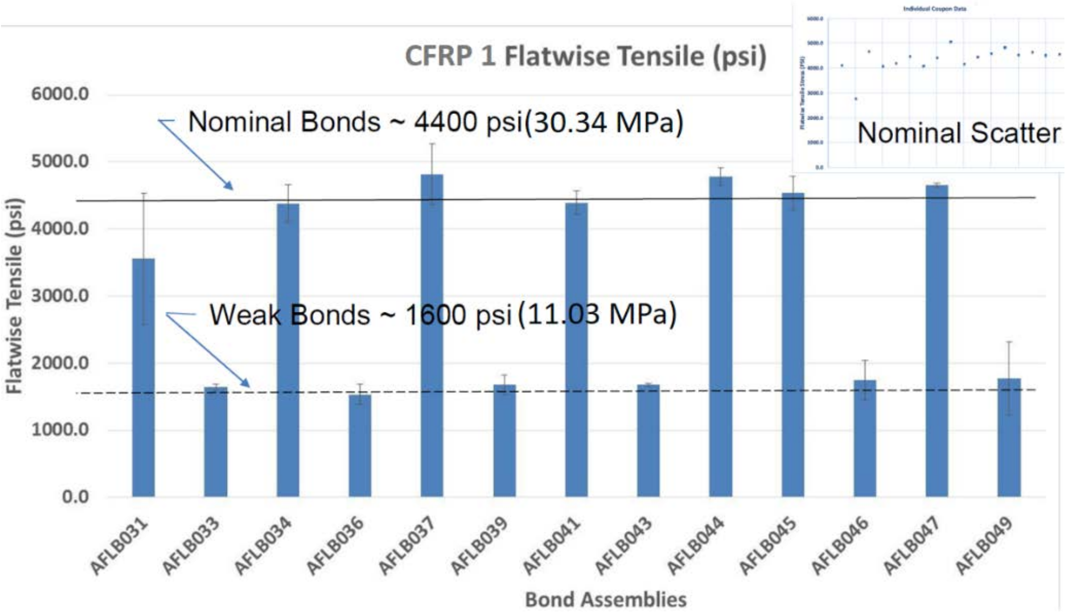
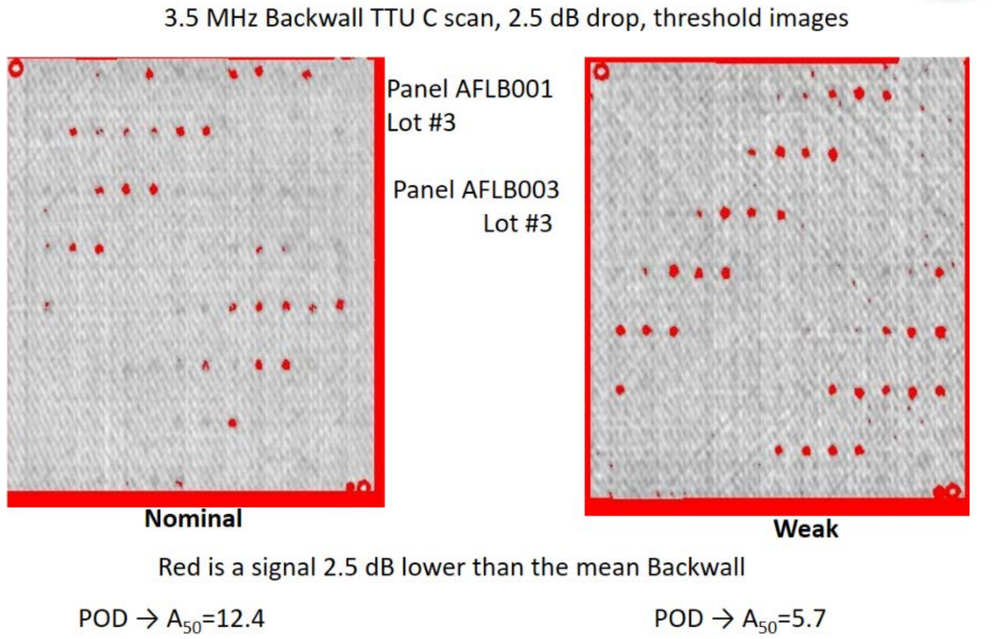


Figure 6: FWT tests results for CFRP 1 bond assemblies.

Examples of how NDI signals were evaluated are illustrated in the UT threshold images in Figure 7. A 2.5 dB backwall drop criteria is used for the nominal strength bonded panel (left) and weak panel (right). The signal analysis was performed on waveforms and displayed as images. The red threshold signals represent “Hits” for the LBI fluence level at those test locations. All other LBI test locations represent “Misses.” By plotting the “Hits” and “Misses” as a function of the LBI fluence, it is possible to arrive at a probability for the threshold value as shown in Figure 8 [4]. The fluence is plotted on the x-axis, and the POD is on the y-axis. For the nominal panel the a_{50} is 12.4 J/cm^2 while the a_{50} is 5.7 J/cm^2 for the weak panel. Similar to what is observed in the mechanical test data, there is much more scatter in the nominal bond assemblies than the weak panels as indicated from this figure (i.e. slope of the POD curves). Furthermore, this program has proven the failure modes can be correlated with these curves as indicated in Figure 8.

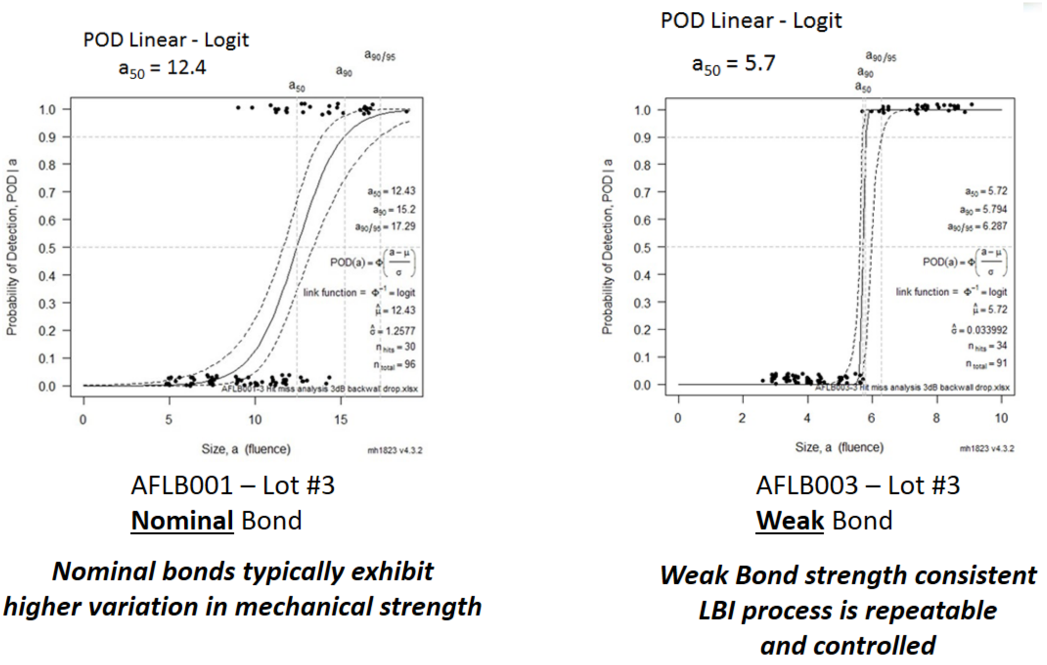

3.5 MHz Backwall TTU C scan, 2.5 dB drop, threshold images

Red is a signal 2.5 dB lower than the mean Backwall

POD → A_{50}=12.4

POD → A_{50}=5.7

Figure 7: NDI signal analysis.



AFLB001 – Lot #3
Nominal Bond

Nominal bonds typically exhibit higher variation in mechanical strength

AFLB003 – Lot #3
Weak Bond

Weak Bond strength consistent LBI process is repeatable and controlled

Figure 8: POD approach and determining a_{50} value.

From the LBI testing, preliminary design curves demonstrating how the technology will be implemented were generated as shown in Figure 9. Figure 9 is a plot of the fluence (y-axis) versus pathlength to the bondline (x-axis). The pathlength is the total distance to the bondline for the reflected tensile wave as shown in the example in the upper right hand corner. The nominal threshold fluence a_{50}

is shown by the blue triangles in the figure while the green circles designate a_{50} of the weak panels determined by POD and NDI criteria as described previously. Each data point is the a_{50} of approximately 60 or more LBI tests. Unfilled data points indicate testing is still in progress. The yellow line was set at an inspection fluence of 50% of the nominal threshold based on testing in this program (including the multi-shot testing). For an example, a CFRP 1 laminate with thickness of 5.08 mm (0.2 in) bonded to a 2.54 mm (0.1 in) thick laminate (with negligible bondline thickness as would be expected of one layer of epoxy film adhesive) should be inspected at 20 J/cm^2. Figure 10 presents the status of the model. It is a preliminary design curve comparison relating CFRP 1 to CFRP 2. The design curves are similar for both epoxy systems, but CFRP 2 exhibits slightly lower strength which is corroborated by the mechanical test data.

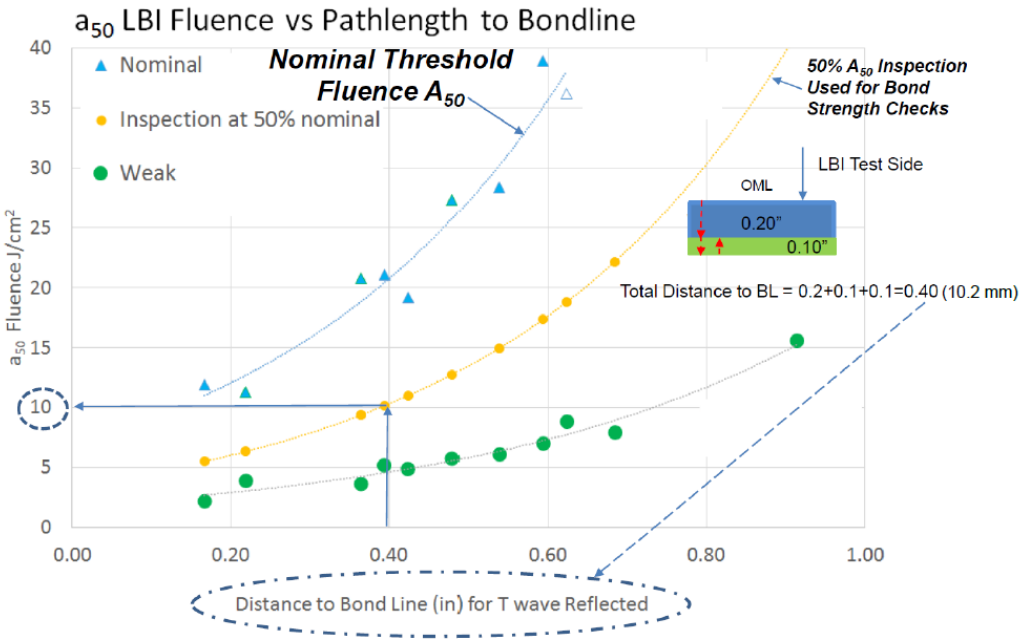


Figure 9: LBI design curve for CFRP 1.

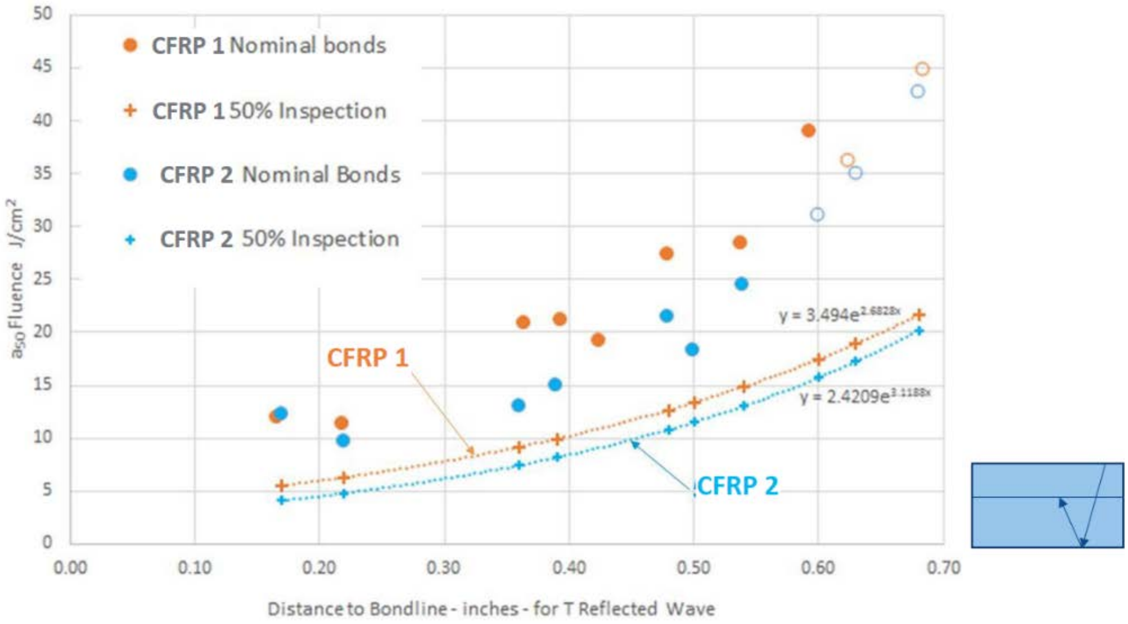
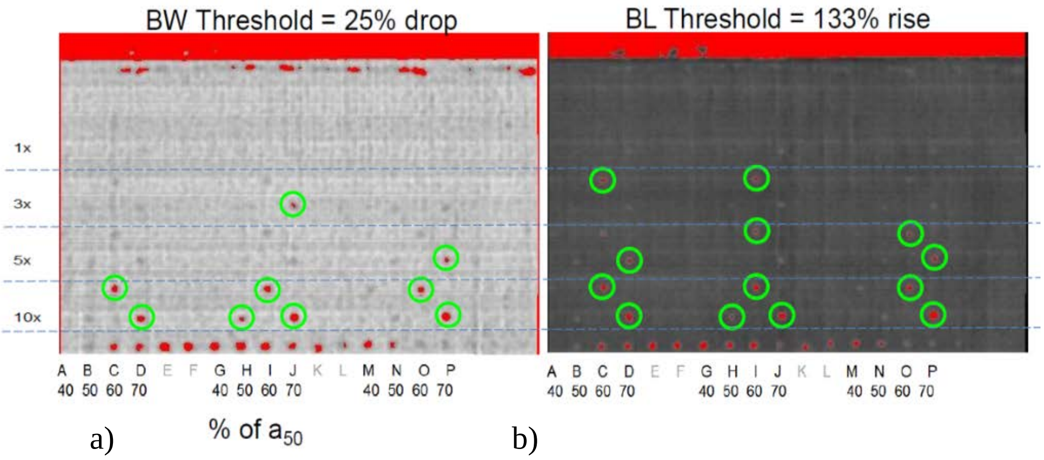


Figure 10: Preliminary design curve comparison between two different bonding systems.

Multi-shot LBI testing is displayed in Figure 11 with the left image showing the UT data with the back wall threshold gated at a 25% drop in signal while the right image is the bondline threshold gated at a 33% signal increase. Testing in this program has revealed it is necessary to use the bondline threshold NDI criteria to accurately assess symmetric bonded assemblies (Figure 11b). Three tests were conducted at four different fluence levels (40%, 50%, 60%, and 70% of a_{50}) and four different multi-shot LBI test levels (either 1 (single test in one location), 3 (three tests in the same location), 5 (five tests in the same location, or 10 ten tests in the same location). On the bottom of the images in Figure 11 is the LBI fluence level tested as a percent of a_{50} (in which the a_{50} value has already been determined through NDI signal analysis on flat bonded panels of nominal strength of comparable thickness as visually shown in the examples of Figure 7). The number of LBI tests conducted in that location (1, 3, 5, or 10 times) is presented on the left hand side of the images in Figure 11. From Figure 11b, indications of damage appear for one out of three test spots at 50% a_{50} with 10x LBI shots (column H), two out of three test spots with 60% a_{50} at 3x LBI shots (columns C and I), and two out of three test spots with 70% a_{50} at 5x LBI shots (columns D and P). These data suggest inspecting with LBI at levels higher than 50% a_{50} of nominal strength may not be sensible.



Bond line Threshold criteria is needed for symmetric panels

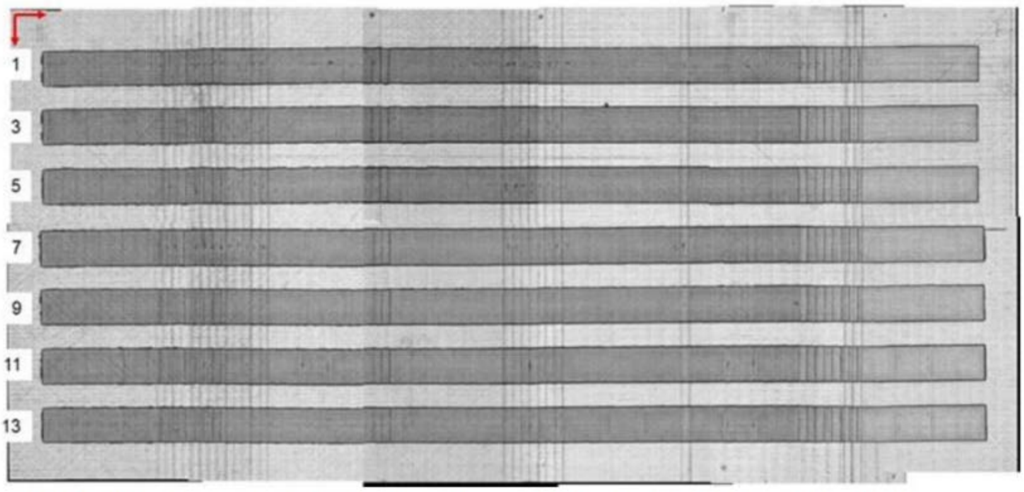
Indications occur at 10x for 50% a_{50} ← ***One out of three test spots***

3x for 60% a_{50} ← ***Two out of three test spots***

5x for 70% a_{50} ← ***Two out of three test spots***

Figure 11. Multi-shot LBI testing. a) NDI image with 25% reduction in back wall threshold signal and b) NDI image with 33% increase in bondline threshold signal

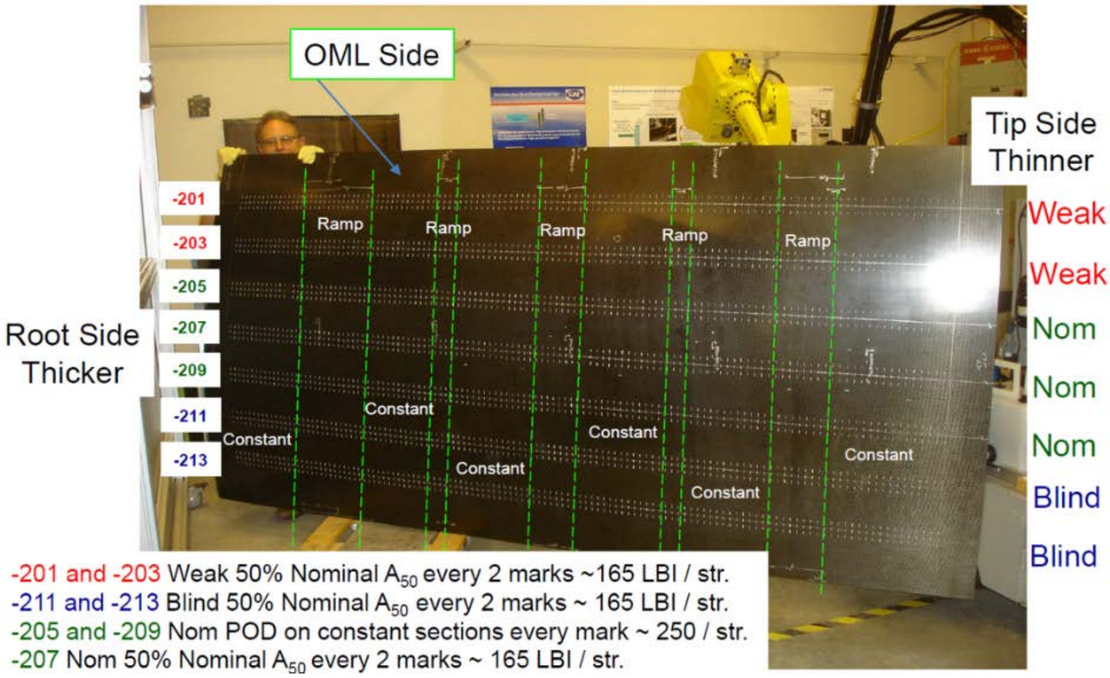
To validate the design curves, two large scale wing skin (with bonded stringers) demonstrations were fabricated (CFRP 1 and CFRP 2). After successful fabrication, the articles were scanned via a UT PE array NDI system. The amplitude image is shown in Figure 12. Both parts successfully passed NDI and looked well-bonded. However, two entire stringers were weak and another two stringers had 10 weak areas approximately 10.2 cm by 10.2 cm (4 in by 4 in) in size interspersed within the two stringers. All these weak areas were undetected by traditional UT.



CFRP 1 Configured Demo 3.5 MHz, 64 Element Linear Array, Olympus OmniScan MX2 and glider with VACRS scan system

Figure 12: NDI results – CFRP 1 article after fabrication and before LBI testing.

The LBI testing for the configured demonstrations was designed (Figure 13). At least 1325 targeted LBI locations were planned. The two weak stringers (201 and 203), the two blind stringers (211 and 213), and one of the nominal stringers (207) were tested at the inspection fluence (i.e. 50% of the nominal threshold a_{50} or yellow line on design curve of Figure 9). A POD study was performed on the remaining two nominal stringers (205 and 209) to determine how these compared to the POD results from the flat bonded panel with the same materials and process (i.e. blue data on Figure 9). Figure 14 shows the LBI testing on the CFRP 1 configured article. It should be noted LBI began in the constant gauge sections with the ramp areas not tested in the first iteration.



-201 and -203 Weak 50% Nominal A_{50} every 2 marks ~165 LBI / str.
-211 and -213 Blind 50% Nominal A_{50} every 2 marks ~ 165 LBI / str.
-205 and -209 Nom POD on constant sections every mark ~ 250 / str.
-207 Nom 50% Nominal A_{50} every 2 marks ~ 165 LBI / str.

Figure 13: LBI test plan for the configured demonstrations.

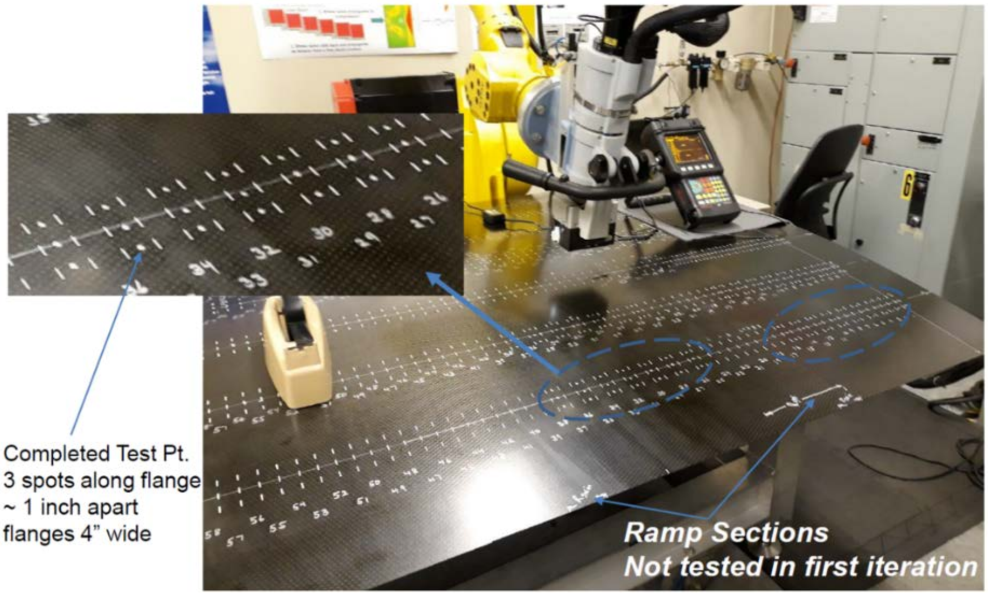


Figure 14: LBI testing on CFRP 1 configured demonstration.

LBI testing, NDI, and data analysis is ongoing for the configured demonstrations. Approximately 900 of the 1325 planned LBI locations on the CFRP 1 article have been inspected post-LBI. These results are shown in Figure 15. All of the weak bonded stringers were found, and 6 out of the 6 blind weak bond areas that have been tested thus far have been discovered. The criteria used for NDI have led to consistent results. Furthermore, results have been consistent when scaling from thin to thick areas on the demonstration article, and the flat panel "design curve" approach/model has been validated.

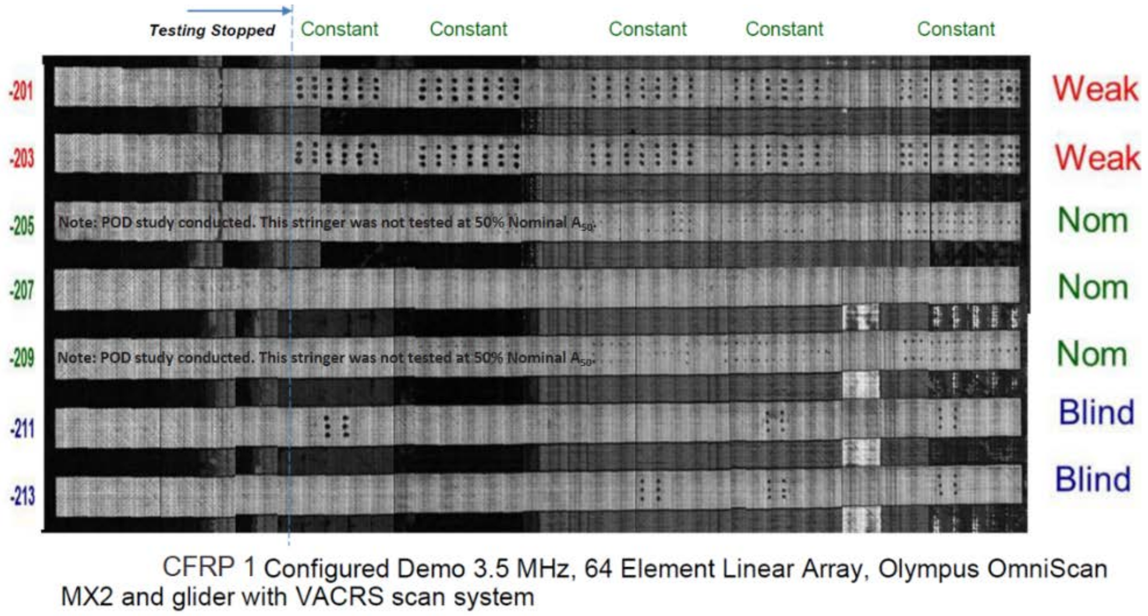


Figure 15: Post-LBI NDI results – CFRP 1 article.

During this program, a few limitations or challenges of the LBI system have been identified. For instance, LBI head access can be a constraint; however, efforts for a smaller head with less diagnostic capability are in progress (contracts FA8650-19-P-5055 and FA8650-19-P-5056). The reach of articulated arm is also a constraint, and a fiber optic delivery program is in progress working a solution (contract FA8650-17-C-5621). It should also be noted honeycomb structures are difficult to inspect; the core to facesheet is not inspectable by LBI, but laminated structure bonded to facesheets of honeycomb structures (i.e. clips, brackets, or other structures) are inspectable. Hybrid structures (i.e. metal to composite) with only access from metallic side and metal to metal inspection are two types of structures not evaluated in the program, and these need additional development. Finally, reliable LBI system calibration is of great importance (i.e. pre- and post-inspection shot) and has been highlighted as an area of importance under current program. A more refined system calibration is being addressed under the implementation plan of the current program. Ultimately, this effort is proving a highly capable LBI technology and system, and these limitations are being worked by an industry-focused team [5].

5 SUMMARY AND CONCLUSIONS

LBI's exact role in enabling the USAF to adhesively bond safety-of-flight adhesive bonds is not yet defined, though this type of capability has for years been believed by the USAF Certification Authority to be enabling technology for this purpose. Important considerations include the number of test spots that would need to be assessed across a bondline and whether LBI inspection would be required at intervals during service. Since concerns about degradation of composite-to-adhesive interfaces during exposure to the service environment are not nearly as great as those for metal-adhesive bonds, periodic inspection during service may not be as critical for composite joints. Current LBI efforts focus on composite-adhesive systems for both this reason and the fact future safety-of-flight bonds are expected to unitized composite structures due to anticipated structural and cost benefits. This work has demonstrated a proven design curve model approach for varying geometry and thickness with multiple CFRP material systems. It has identified some limitations (i.e. the current LBI devices cannot reach limited access areas and are relatively large in practice), but ongoing and proposed work are aimed at resolving these disadvantages. LBI addresses a key technology gap associated with bonded joints, with the potential to greatly increase the reliability of bonded primary structure and reduce the use of fasteners, part count, assembly time, and structural weight, saving time and money in manufacturing and repair applications [6].

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