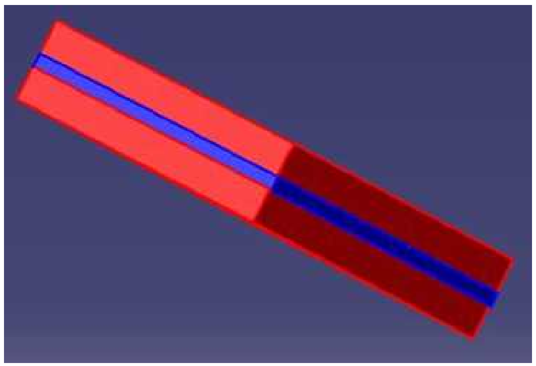
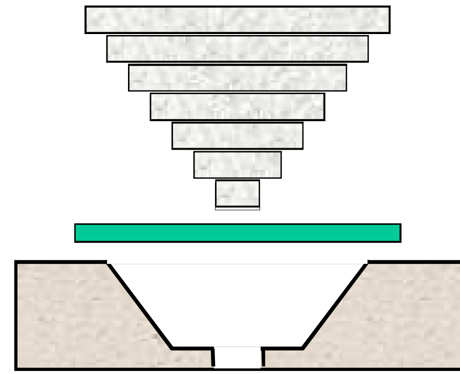
SAND2006-6535C

Enhanced Inspection Methods to Characterize Bonded Joints: Moving Beyond Flaw Detection to Quantify Adhesive Strength





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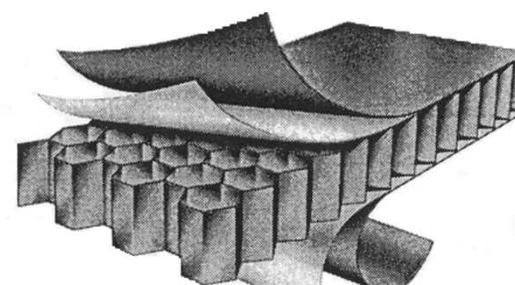

National Nuclear Security Administration

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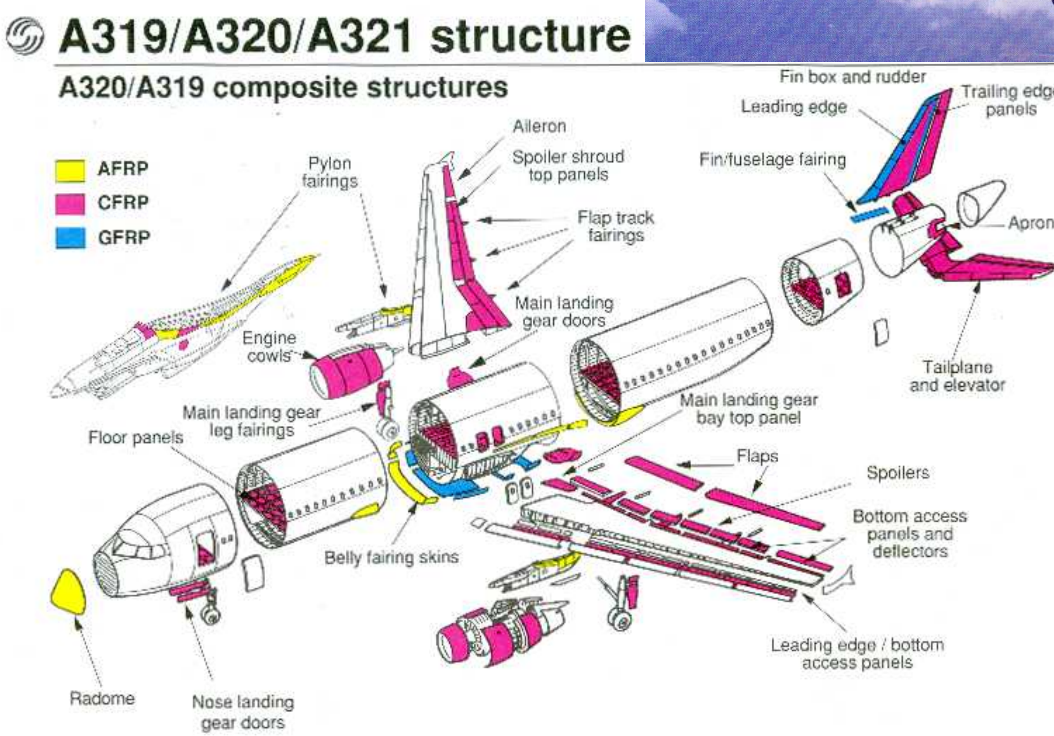
Bonded Structures (Composite Structures)

- Advantages – design flexibility, improved fatigue performance, decreased weight, reduced manufacturing costs
- Cannot depend on process control alone to ensure satisfactory bond strength
- Must consider joint degradation - environmental effects of moisture, aging, stress, fatigue
- Can NDI move beyond flaw detection (disbonds, delaminations) to quantify the strength of a bond?
- Method must be a stiffness-based technique and/or able to assess material properties
- Wave transmission modes may be sensitive to in-plane displacements (interfacial changes)
- Requires high sensitivity (S/N) and possibly noise reduction methods to recognize small changes in bonds

Program Motivation - Extensive/increasing use of composites & bonded joints on commercial aircraft and increasing use of NDT to inspect them



Sample Composite Structures on Airbus Aircraft

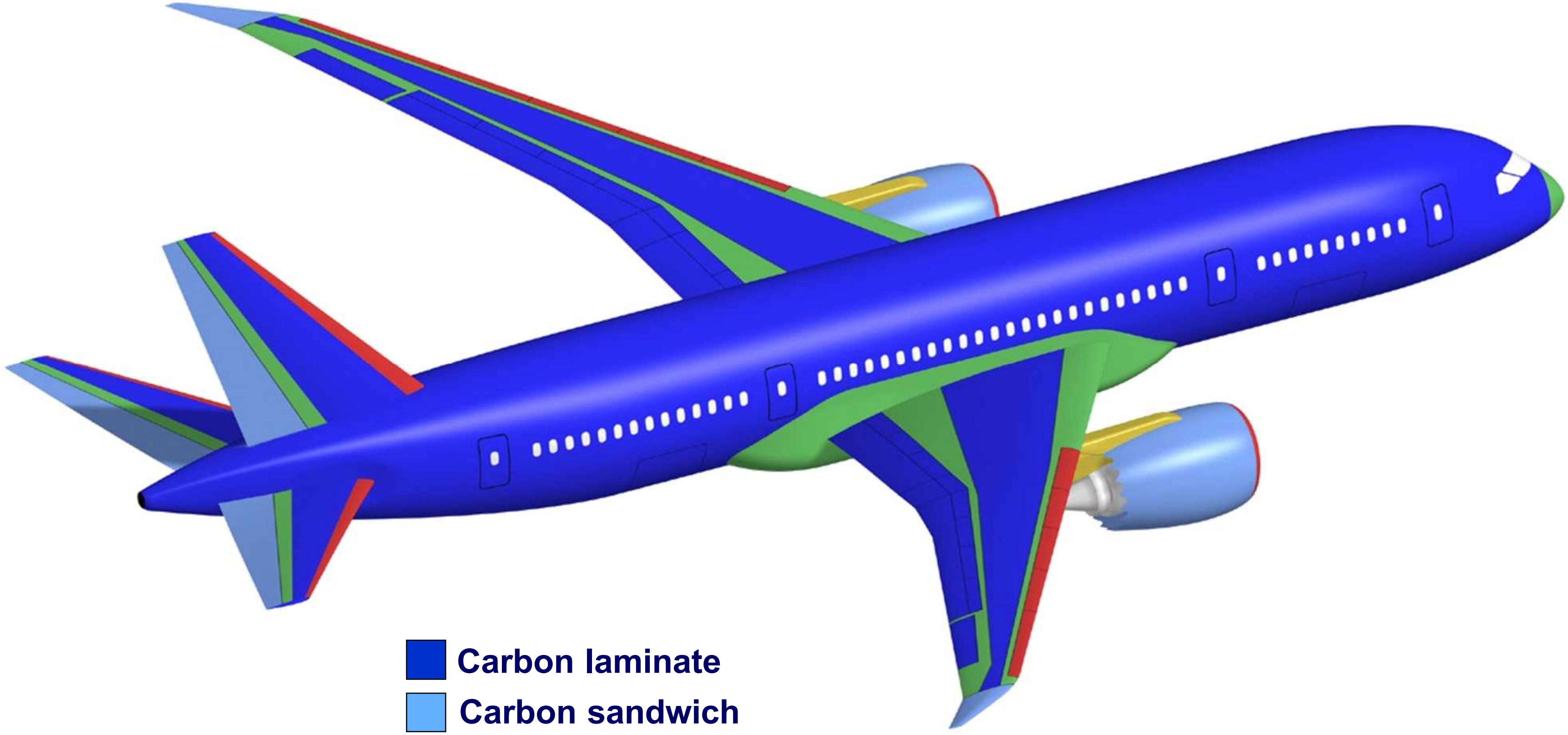

A380 Fuselage Section 19


Center Wing Box


A340 HTP Skin


A380 Pressure Bulkhead

Composite Structures on Boeing 787 Aircraft



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

What is a Weak Bond ?

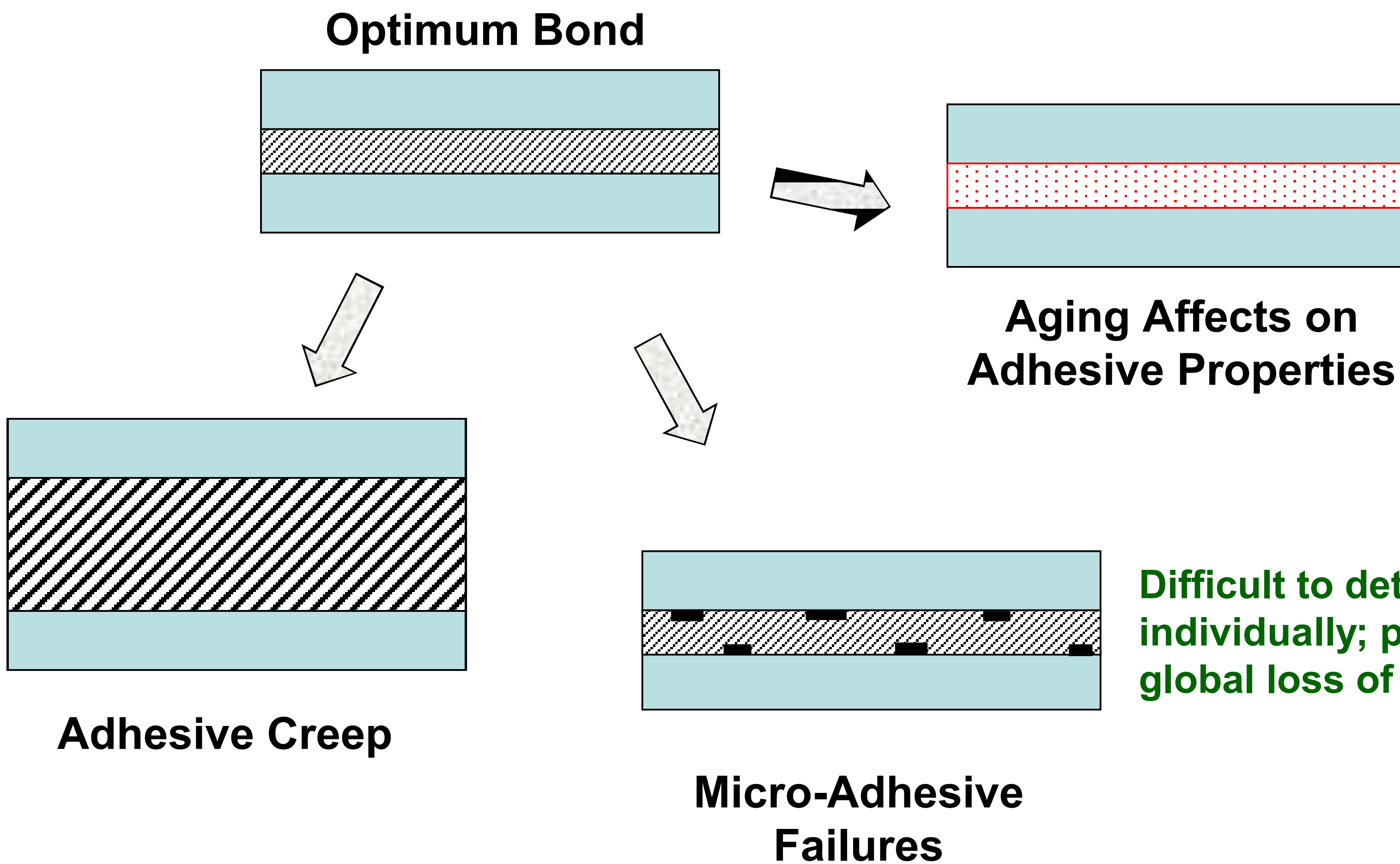
- **Gross Disbond** – separation of adherends
- **"Kissing" Disbond** – tight contact between adherends but no adhesive strength
- **Change in Mechanical Properties of Adhesive** – environmental conditions cause modulus to change (moisture, thermal, fatigue) or adhesive to creep (stress); inadequate cure
- **Local or Global Surface Degradation** – stemming from contamination, corrosion; inadequate surface preparation or cure; impact damage

NDI Approaches to Attack the Problem

- NDI to characterize material properties
- NDI to measure non-linear response
- NDI that investigates stiffness without damaging the structure
- Interrogate out-of-plane response – longitudinal wave
- Interrogate in-plane response – shear wave (joints designed for shear loads)

Mechanisms of Weak Bonds

Time-Based Damage

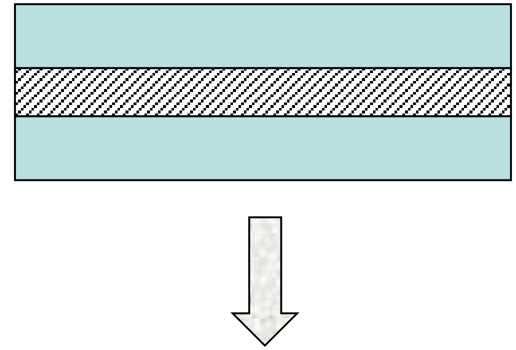


Difficult to detect individually; produces global loss of strength

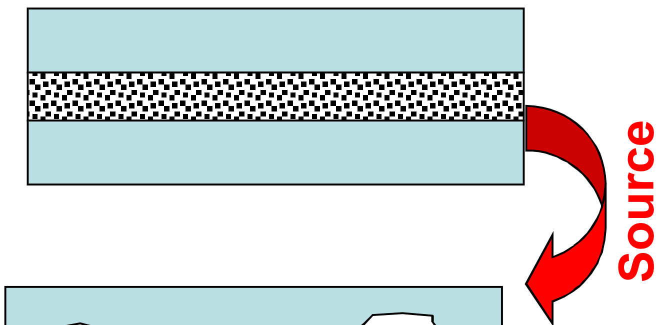
Mechanisms of Weak Bonds

Damage Seeded During Manufacture

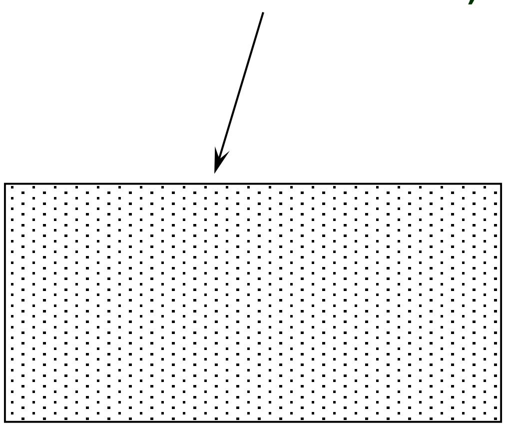
Optimum Bond

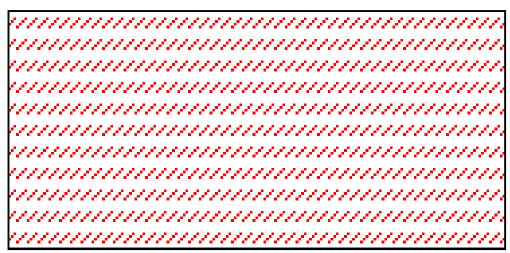


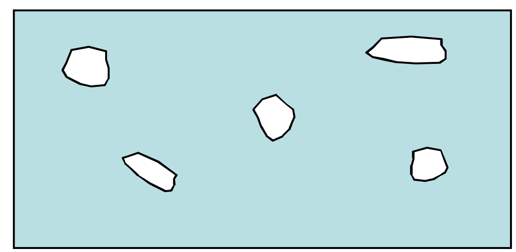
Non-optimum (weak) bond



Ultimate tests would produce cohesive failure but at a reduced level (full potential of adhesive is not achieved)







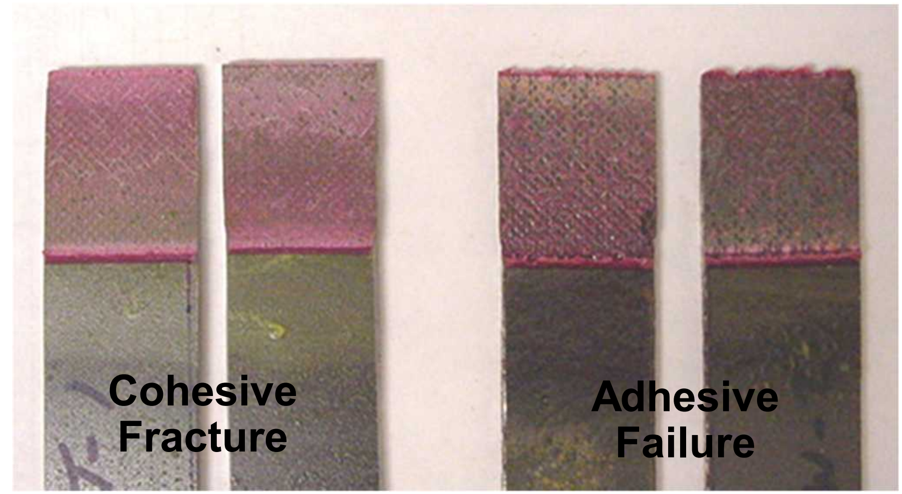
Local or global changes in adhesive properties due to off-design cure

General poor adhesion; uniform but non-optimal surface prep (e.g. contamination or improper process)

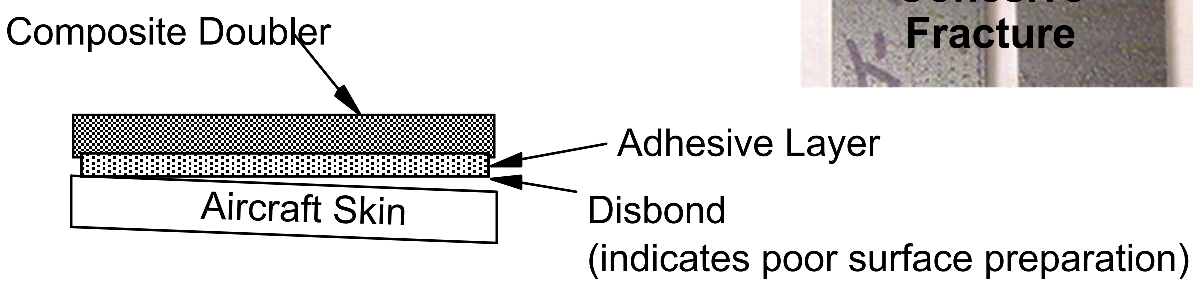
Pockets of kissing or weak bonds

Adhesive vs. Cohesive Failure

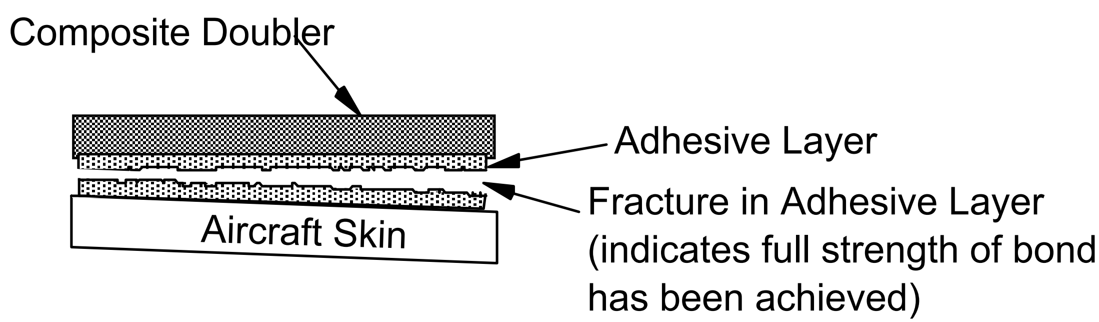
Percent cohesive fracture from shear and peel tests



Two Potential Bondline Failure Modes:



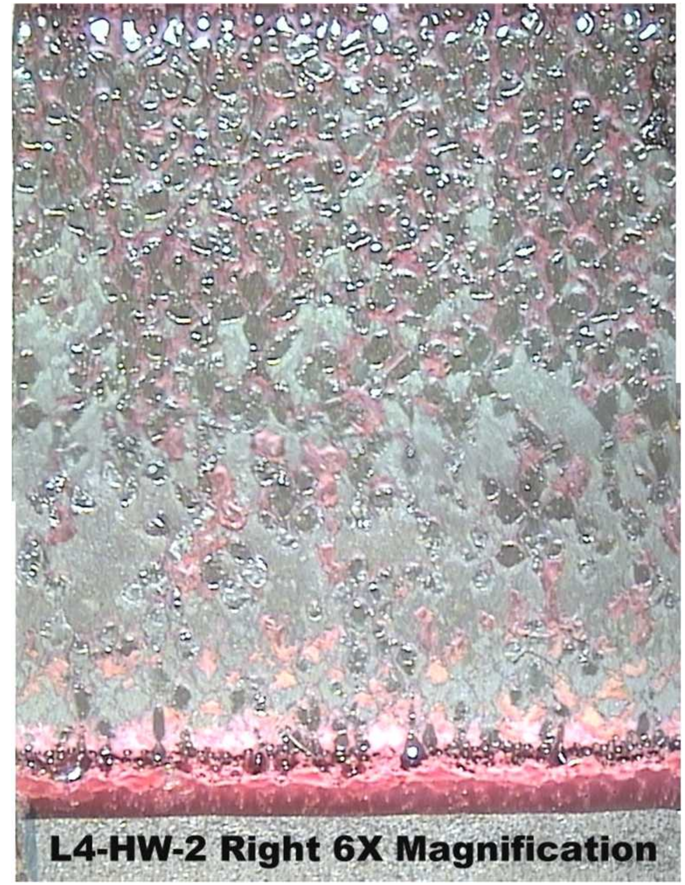
Adhesive Failure



Cohesive Failure

Adhesive vs. Cohesive Failure (cont.)

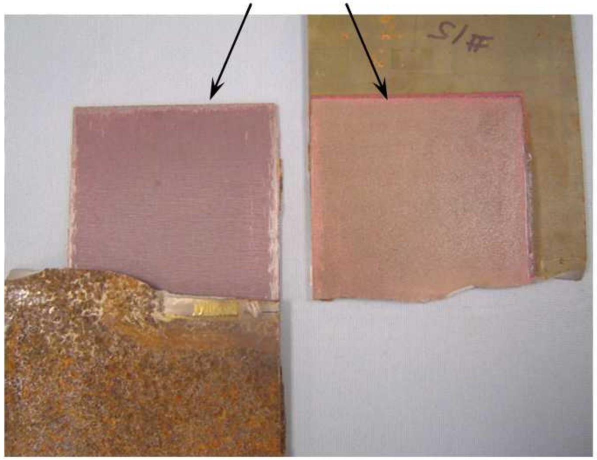
Cohesive Fracture of Adhesive Film
(Option 6 silane treatment)



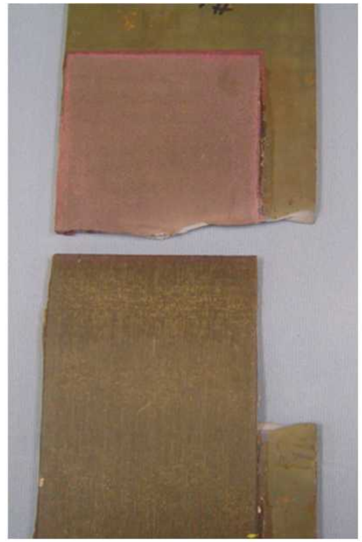
Adhesive Failure at Interface
(Option 4 no chemical treatment)

Ultimate Failure Modes

Adhesive on Steel Surface &
Back of Laminate



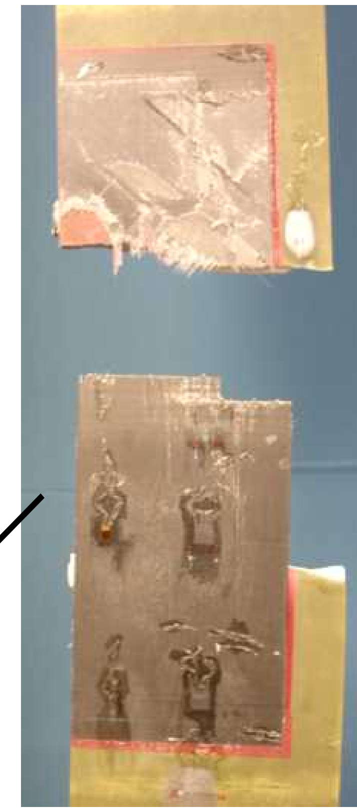
Laminate
Back View

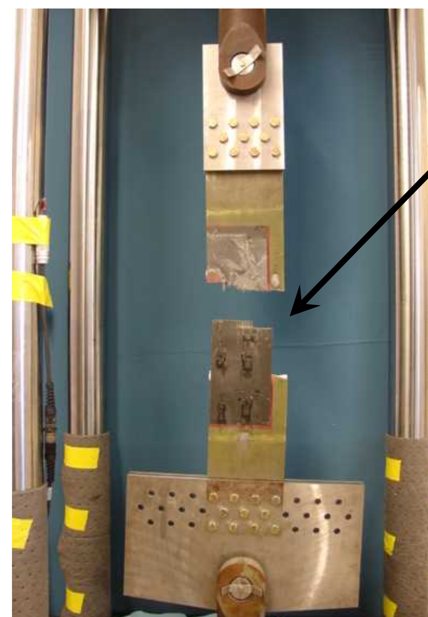


Laminate
Front View

Cohesive Fracture of the Adhesive Layer Between the Laminate and the Steel

Interply Fracture of the Composite Laminate



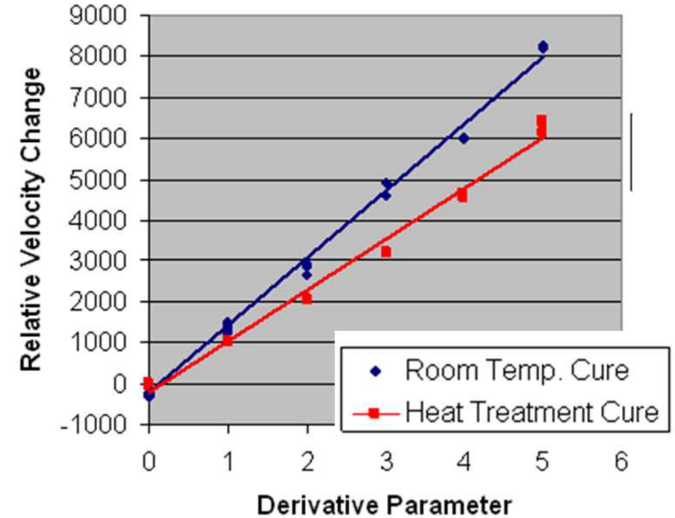


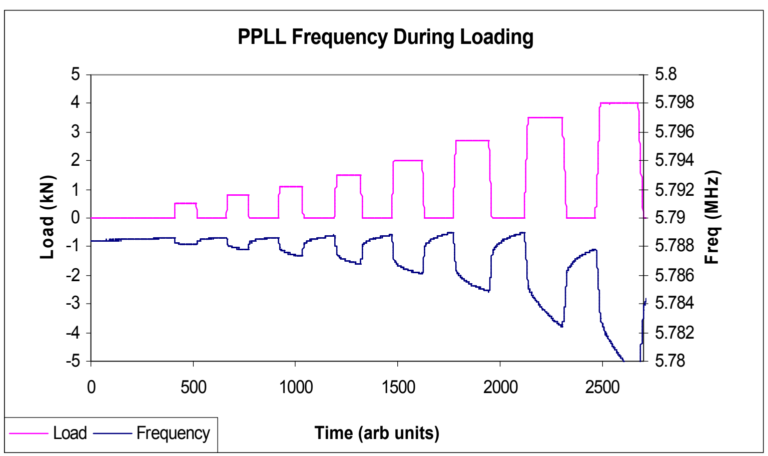
Some Candidate NDI Methods for Quantifying Weak Bonds

- **Ultrasonic Spectroscopy** – compare received and transmitted waveforms in frequency domain; study frequency and amplitude shifts
- **Nonlinear Ultrasonics** – exploit contact nonlinearity in imperfect bonds; incident UT energy generates unique harmonics; potential for introducing damage because incident energy levels must be high
- **Shear Wave Ultrasonics** – guided waves generate shear resonances; study frequency shift and change in damping of FRF
- **Vibrothermography** – use vibratory loads to interrogate a strained interface and measure viscoelastic losses (change in heat transfer)
- **Laser Shot Peening** - stress wave bond inspection; laser-generated stress wave of sufficient intensity to assess bond; use surface velocity measurements; damage/failure stemming from inspections (?) – detailed calibration needed

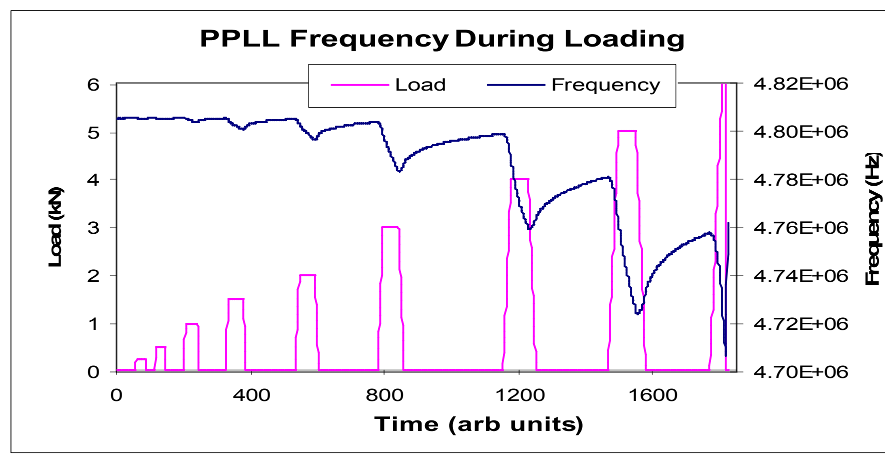
Nonlinear UT Bond Strength System (PHLITE/NUBS) – Luna Innovations

- **Velocity is proportional to elastic constant**
- **Measure velocity changes in bonded joint under load**
- **PHLITE output is a shift in reference frequency "f", as velocity "V" and path length "L" change.**
- **PHLITE measures changes in ultrasonic propagation (blue) as a bond is loaded (pink).**





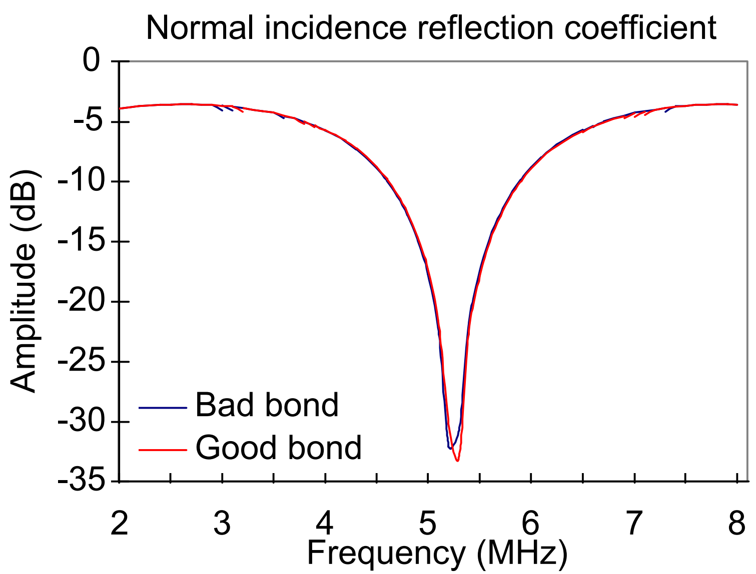
Good Bond

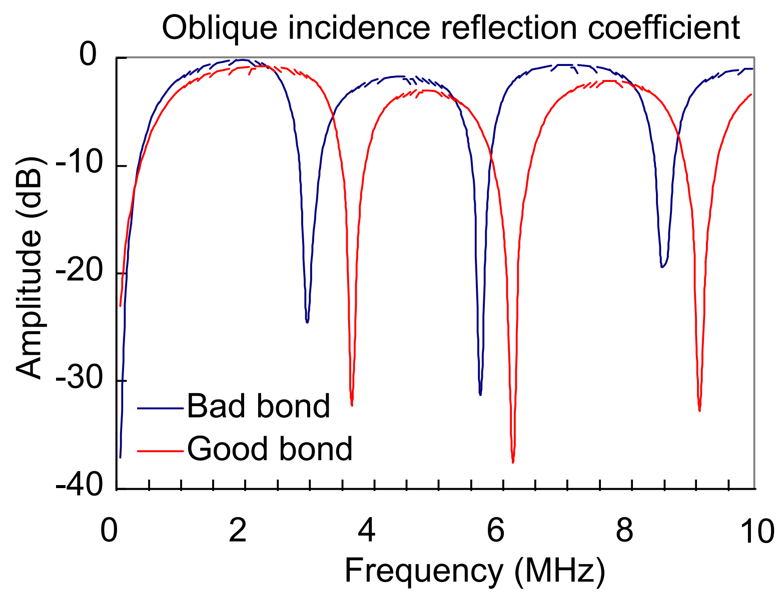


Weak Bond

Angle Beam Ultrasonic Spectroscopy (ABUS) – Adler Consultants, OSU

- **Oblique wave (broadband UT beam) introduces shear stress in the bond line**
- **Difference between longitudinal wave and shear wave interrogation**



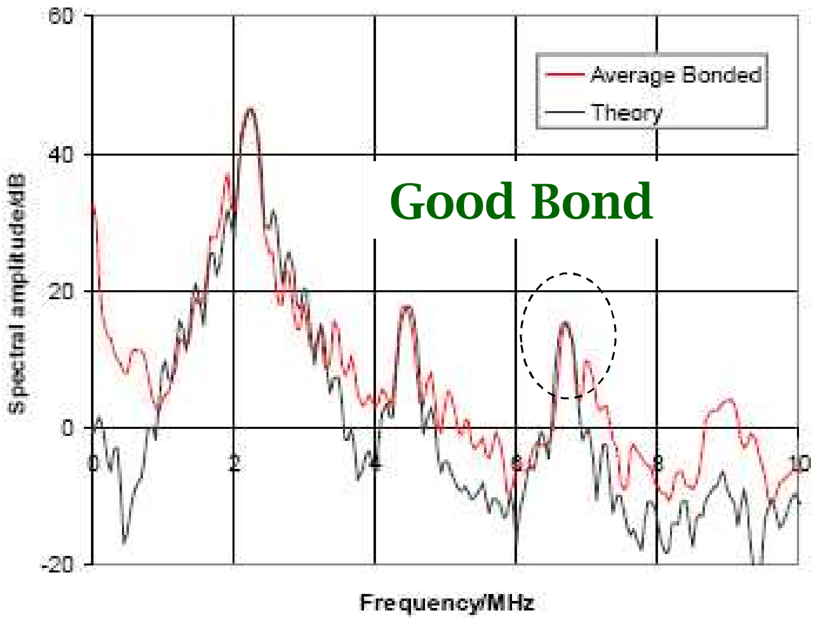


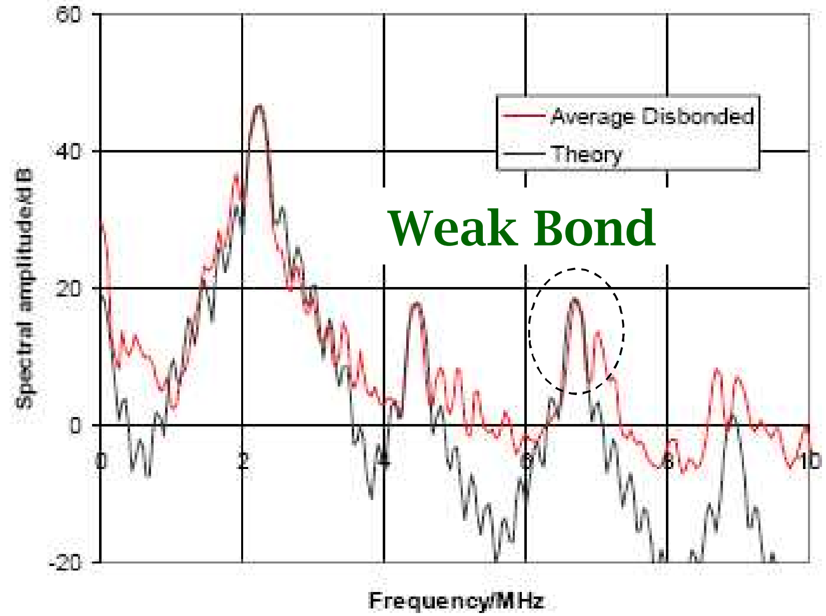
Negligible Affects on Normal Wave (?)

Frequency and Amplitude Shifts Differentiate Bonds

Nonlinear Ultrasonics – QinetiQ Ltd.

- Swept frequency or chaotic drive signals to generate harmonics
- Exploit nonlinear aspect of bonds
- Potential for introducing damage because incident energy levels must be high

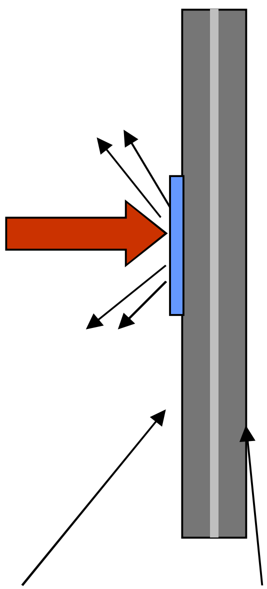




Requires high fidelity to avoid missed/false calls - signal changes may be small (low S/N)

Stress Wave Bond Inspection – Boeing, Laser Shot Peening Tech.

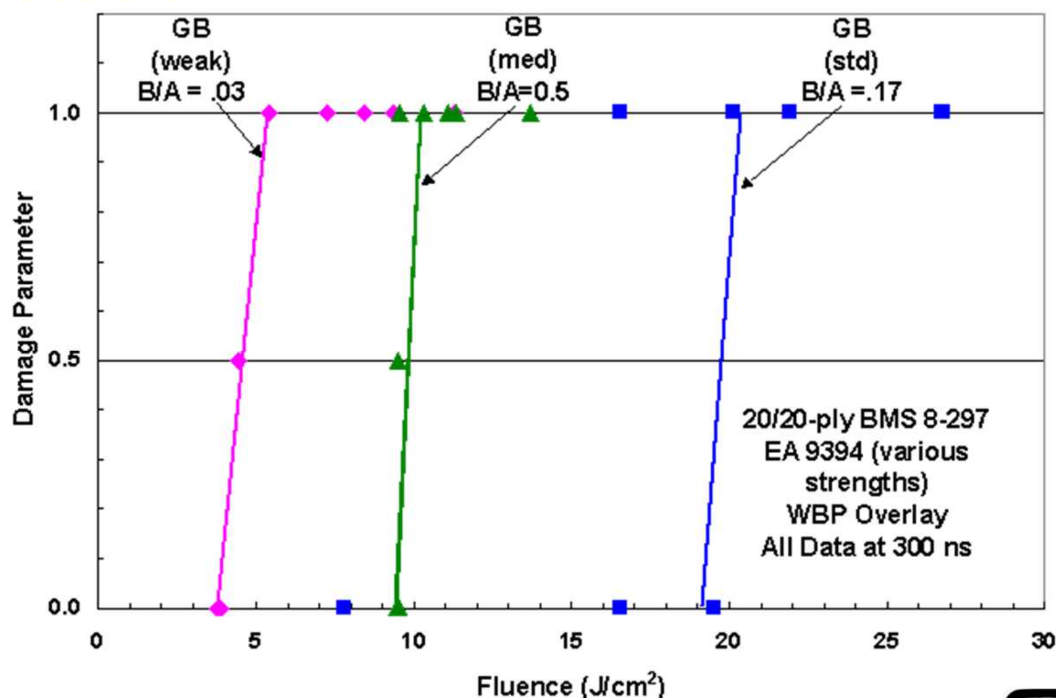
- **Adjust laser pulse, measure velocity & relate to stress**
- **Demonstrated ability to identify variations in surface preparation, contamination and adhesive mixing**
- **Potential to adversely affect bond – nondestructive? (magnitude & no. of exposures)**



20 ply (0.17 inch) laminate

0.020 inch adhesive

Laser pulse tests



Vibrothermography – TWI, WSU

Vibro IR Setup

Ultrasonic Transducer

IR Camera

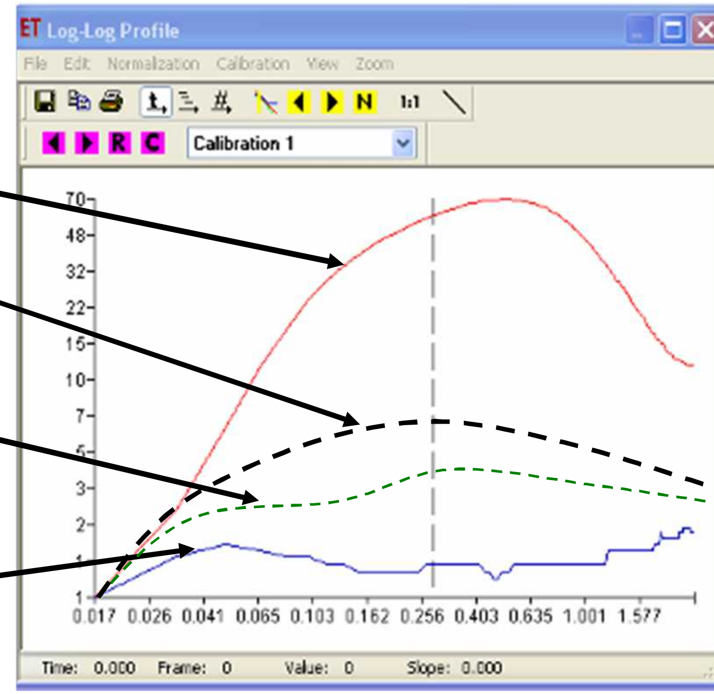
Temperature vs. Time in Log-Log Plot

Disbonded Area

Weak Bond Area (5-10% Bond Strength)?

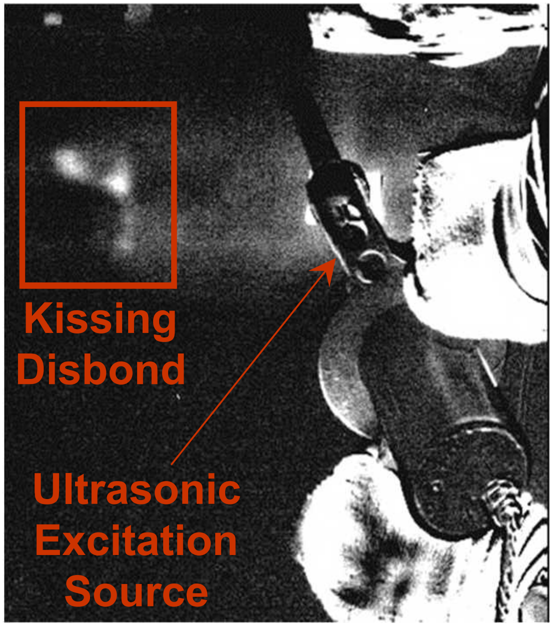
Weak Bond Area (20-30% Bond Strength)?

Bonded Area



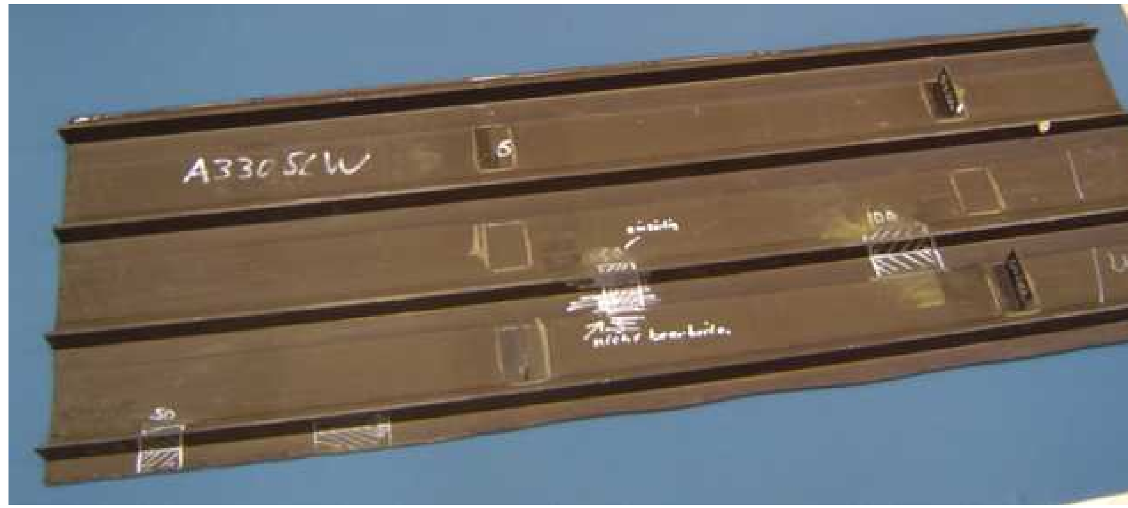
Study variations in slope, magnitude, & duration of heat transfer plot

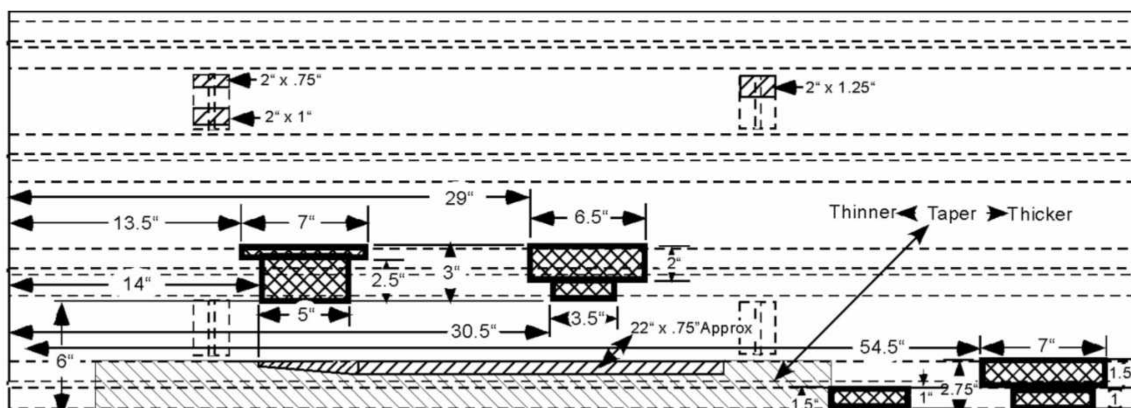
Vibrothermography – TWI, WSU



Sonic Infrared

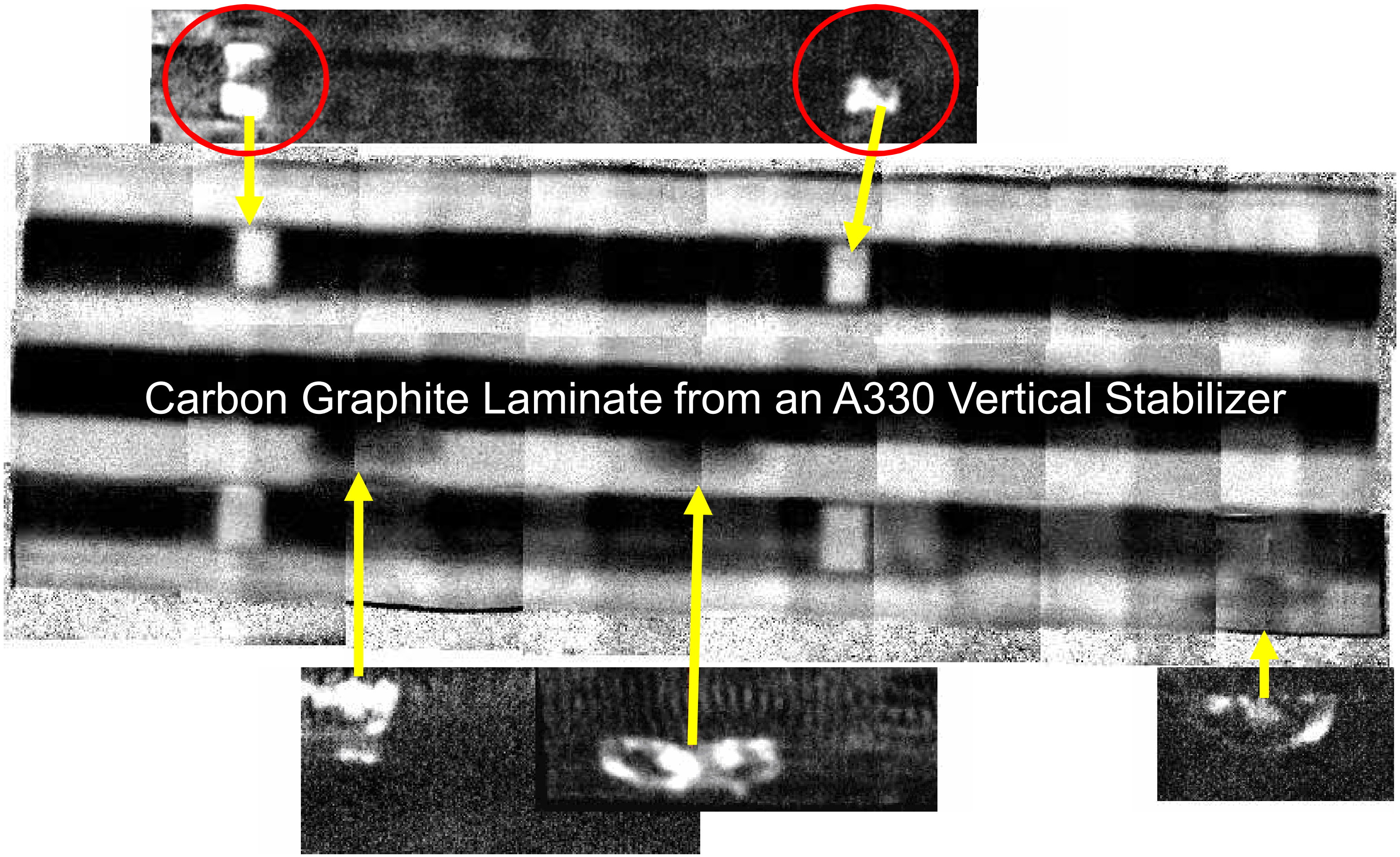
Composite Vertical Stabilizer with Poor Substructure Bonds





Vibrothermography – TWI, WSU

Partially Bonded Areas (circled in red) missed by Pulsed Thermography are detected with Vibrothermography



Generation of Repeatable Weak Bond Specimens is an Impediment to Studies

Contaminants – introduce oil, release agents, water in diluted or screened fashion

Cure – adjust temperature, pressure, and duration

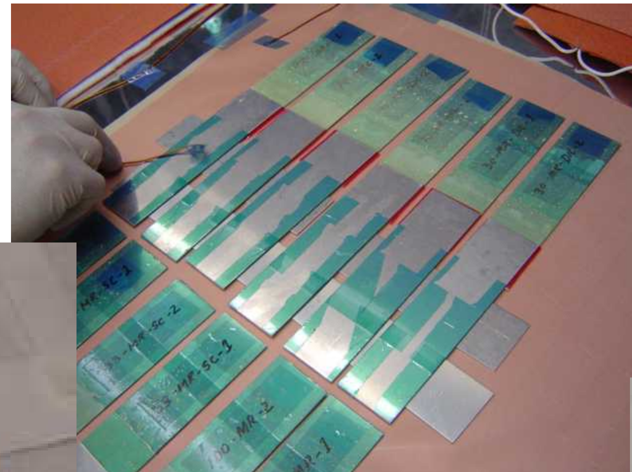
Environmental – generate natural surface corrosion, moisture exposure

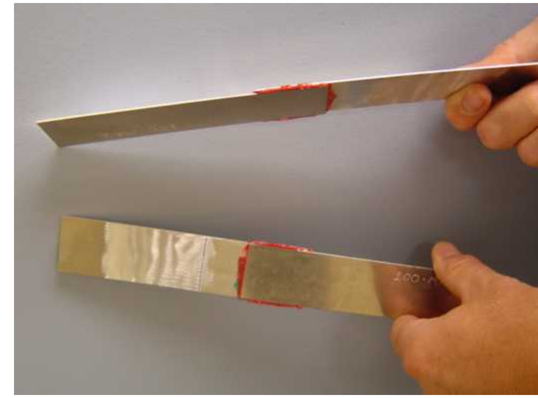
Surface Preparation – inadequate mechanical or chemical processes

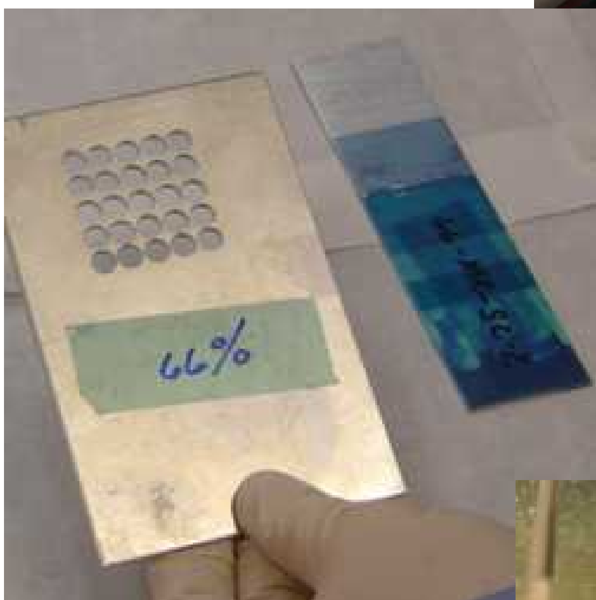
Adhesive – use inaccurate mix ratios in two-part epoxy systems; incompatible adhesive/adherend mix; expired or mishandled adhesive

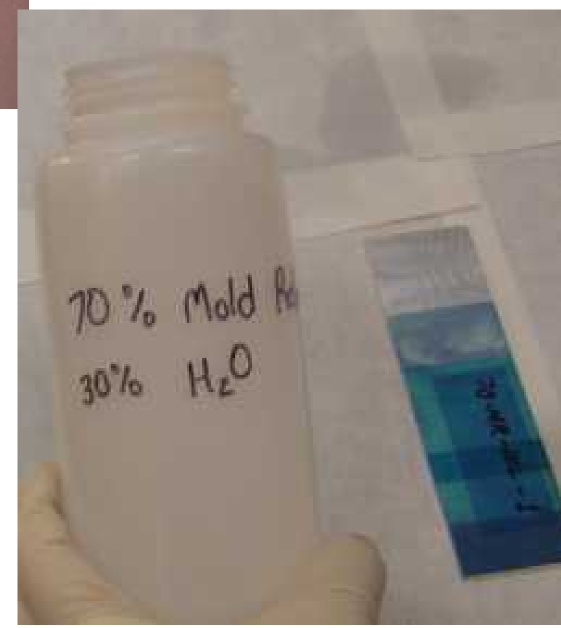
ElectRelease – apply electric field to "unzip" bond line in a controlled fashion

AANC Weak Bond Specimen Production



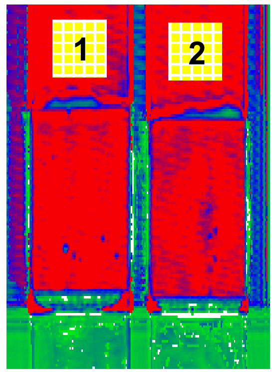






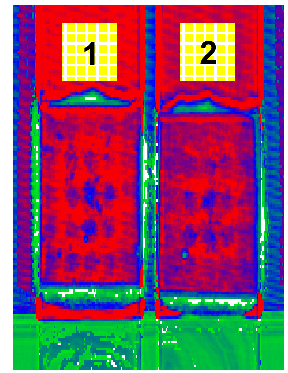
TTU of Weak Bond Specimens Show Trends

Pristine - Best

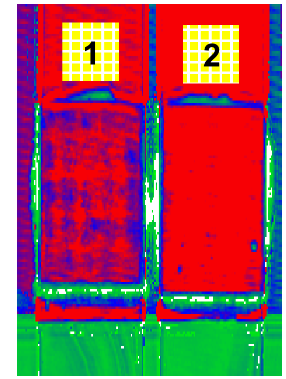


70% MR Dilution

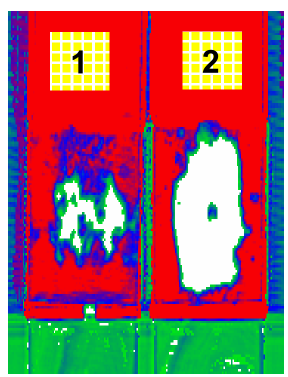
30% MR Dilution



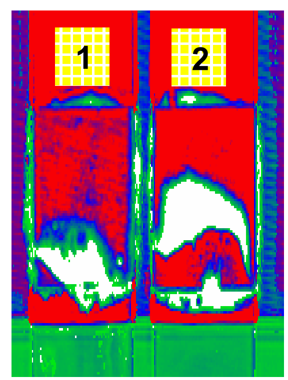
33% MR Screen



66% MR Screen

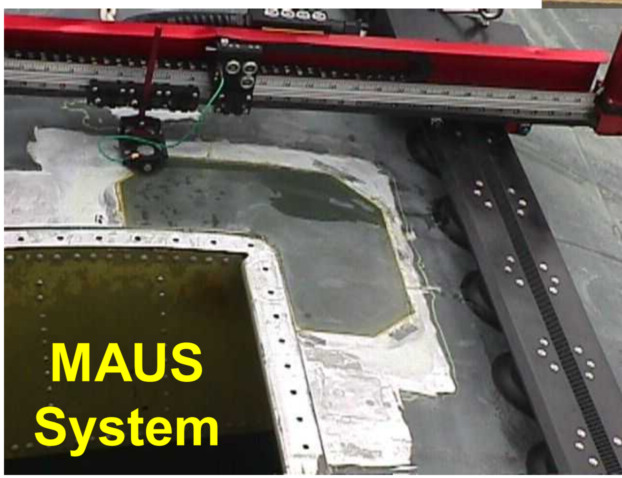


Room Temp.

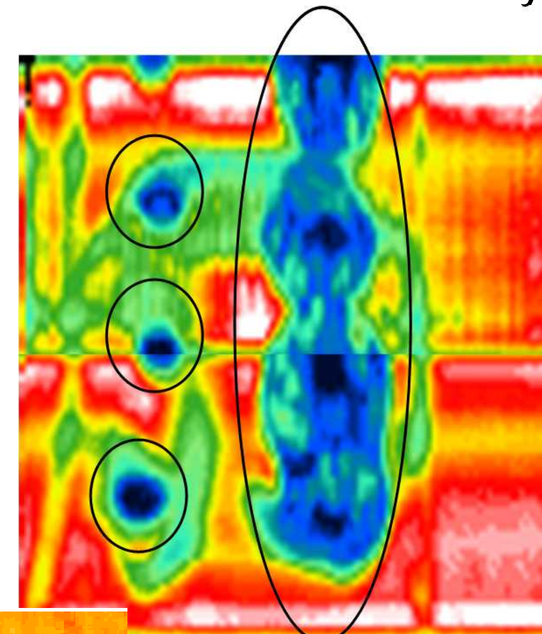


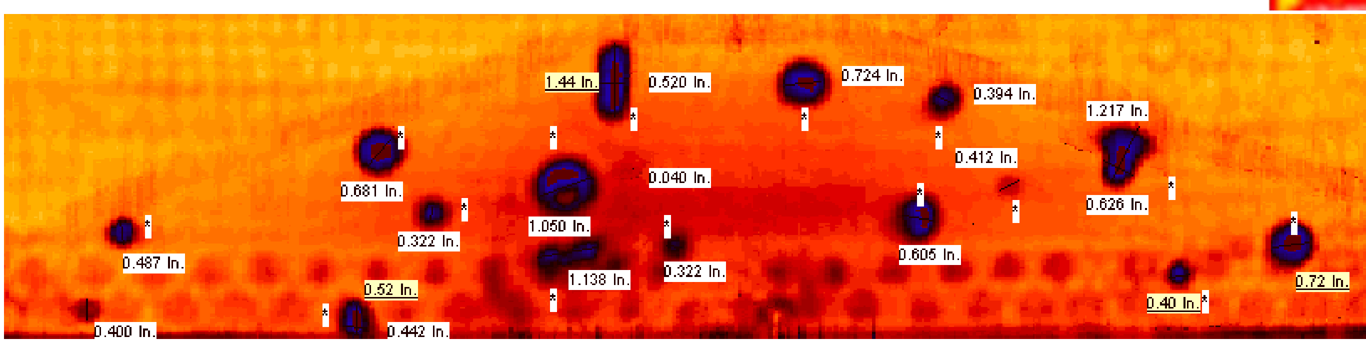
100 MR

Possible Goal - Deployment in Wide Area and C-Scan Inspection Methods



Ultrasonic Wheel Array





MAUS
Image

Conclusions on Weak Bond Assessments

- Make sure that the solution is addressing the correct problem
- Understanding physics of bond integrity is key – select proper interrogation method (what do we exploit)
- One NDI method may not detect all sources of weak bonds
- Several NDI techniques show promise
- Expected low signal-to-noise ratios provide the biggest impediment; optimized excitation is important . . . .
- Ensure that inspection is truly nondestructive

Enhanced Inspection Methods to Characterize Bonded Joints: Moving Beyond Flaw Detection to Quantify Adhesive Strength

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ABSTRACT

The extreme damage tolerance and high strength-to-weight ratio of composites have motivated designers to expand the role of these materials in aircraft structures. With the improvements in various fiber reinforcements and resin systems, developments in manufacturing techniques, and increased knowledge of the material behavior, the next-generation airplanes have a much greater percentage of composite parts including the primary components. The Boeing 787 and Airbus 380 aircraft have vastly increased the use of composites for Principal Structural Elements including the fuselage and wings structures. This emphasis on composite construction has increased the importance of nondestructive inspection (NDI) methods capable of identifying interply delaminations, disbonds in laminate-to-laminate joints, and impact damage. Furthermore, it has also produced a need for NDI methods that can quantify bond strength. Bond deterioration in aging structures and bond strength in original construction are now critical issues that require more than simple flaw detection. While extensive development has been completed to mature the detection of delaminations or fiber fracture flaws in composites, the problem of assessing weak bonds has not been solved by the NDI community. Use of advanced inspection methods to measure the mechanical properties of a bonded joint and associated correlations with post-inspection failure tests have provided some clues regarding the key parameters involved in assessing bond strength. Recent advances in ultrasonic- and thermographic-based inspection methods have shown promise for measuring such properties. Vibrothermography uses the effect of externally-induced vibrations to excite a structure and observe the resulting heat patterns within the material. This approach may be sensitive enough to reveal subtle material differences associated with weak bonds such that the monitored thermal field can be correlated with the strength of the bond (properties of bond material). Similarly, specialized ultrasonic (UT) inspection techniques, including laser UT, guided waves, UT spectroscopy, and resonance methods, can be coupled with unique signal analysis algorithms to accurately characterize the properties of weak interfacial bonds. The generation of sufficient energy input levels to derive bond strength variations, the production of sufficient technique sensitivity to measure such minor, and often nonlinear, response variations, and the difficulty in manufacturing repeatable weak bond specimens are all issues that exacerbate these investigations. This paper will present several ongoing efforts to quantify bond strength and review a number of completed studies that provide a foundation for further evolution in weak bond assessments.