Bonded Repair:
Design and Process Considerations

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Introduction

COMMERCIAL AIRCRAFT COMPOSITE REPAIR COMMITTEE ata IATA SAE

- Generally, bonded repairs are not allowed in structurally critical applications
  - Reliance on bonds for flight safety generally disallowed
- One reason is strength performance scatter resulting from the somewhat limited precision inherent to bonded repair design, analysis, and processing
- A second is the absence of a means of verifying bond strength in the finished product
- This presentation provides thoughts on ways to enhance precision [of process control]

Introduction

- Any scenario for process control must be evaluated for reliability of success (probability must be assessed)
- This reliability must be demonstrated through mechanical testing the product from a LARGE volume of bondment process cycles
- Have started this process at *SPIRIT* in support of one of our products, and have tested scarf joint strengths from approximately 200 bondment process cycles
  - Many different mechanics
  - Many different cure thermal profiles
  - Fresh and Old Material
  - Many different resulting NDI scan quality results
- Have learned there are nuances to be considered in selecting a joint geometry for process reliability testing
  - Joint shape and edge proximity (breathing during cure)

Introduction

- This presentation is focused on bonded joints
  - Discussion topics
    1. Regulations / Requirements
    2. Design and analysis
       a) Joint type comparisons
       b) Parametric trends
    3. Surface preparation
       a) Geometry creation
       b) Pre-bond surface cleanliness
       c) Pre-bond substrate moisture content
    4. Laminate patch preparation
       a) Precision ply cutting
    5. Post-bond cure state assessment

FAR Regulations

- **Design Requirements**
- **14 CFR 23.305 / 25.305 Strength and Deformation**
  - *Support limit loads without detrimental permanent deformation*
  - *Support ultimate loads without failure for at least 3 seconds*
- **14 CFR 25.571 Damage Tolerance and Fatigue Evaluation of Structure**
  - *Evaluation of strength, detail design, and fabrication must show*
    - *Catastrophic failure due to fatigue, corrosion, manufacturing defects, or accidental damage, will be avoided*
    - *Capability to successfully complete a flight during which likely structural damage occurs*
      - *[Impact, lightning (25.581), etc…]*
      - *Damaged structure able to withstand the static loads (considered as ultimate loads) which are reasonably expected*
  - *Each evaluation must…*
    - *[Include] typical loading spectra, temperatures, and humidities*
    - *[Be based on] analysis, supported by test evidence*
    - *[Make the assumption that] structure contains an initial flaw of the maximum probable size that could exist as a result of manufacturing or service-induced damage*

FAR Regulations

- Design Requirements (cont'd)
- 14 CFR 23.573 Damage tolerance and fatigue evaluation of structure

(a) Composite Airframe Structure

– For any bonded joint, the failure of which would result in catastrophic loss of the airplane, the limit load capacity must be substantiated by one of the following

1. Maximum disbonds of each bonded joint consistent with the capability to withstand the loads in paragraph (a)(3) of this section must be determined by analysis, tests, or both. Disbonds of each bonded joint greater than this must be prevented by design features
2. Proof testing must be conducted on each production article
3. Repeatable and reliable non-destructive inspection techniques must be established that ensure the strength of each joint

FAR Regulations

- **Design Requirements (cont'd)**

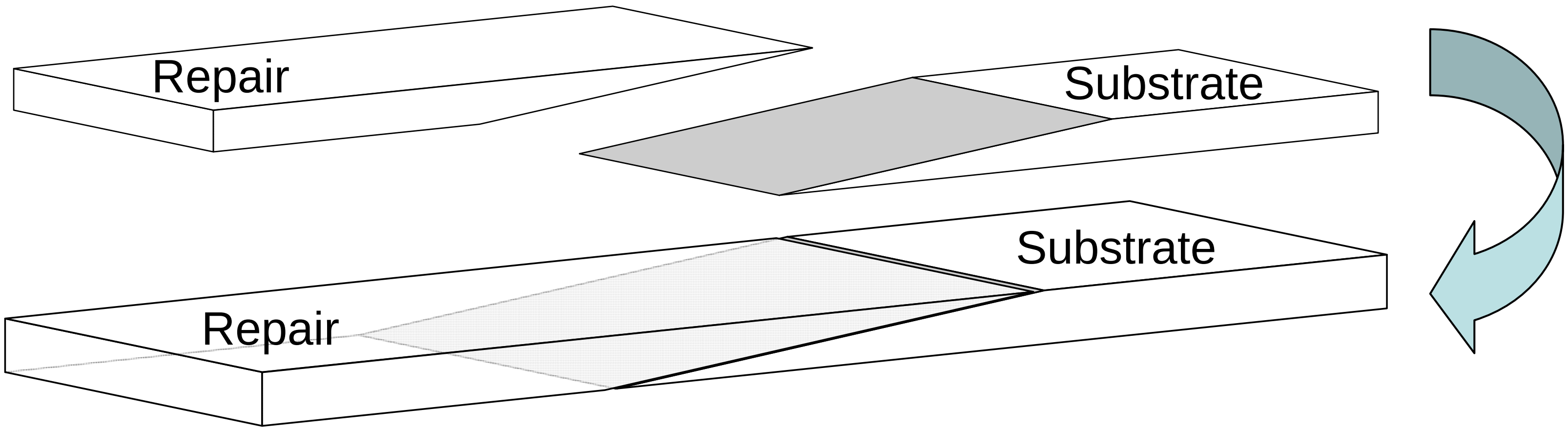
14 CFR 23.573 Damage tolerance and fatigue evaluation of structure

(a) Composite Airframe Structure

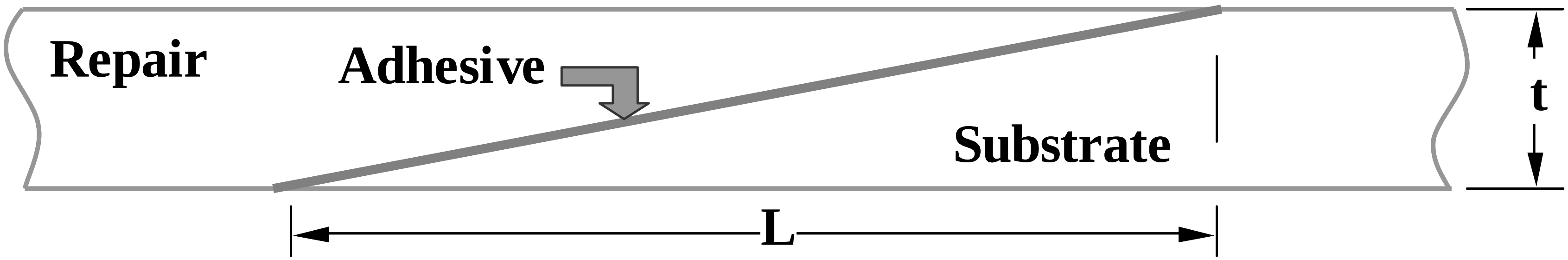
- Demonstrate by tests, or by analysis supported by tests, structure capable of carrying ultimate load with damage up to the threshold of detectability considering the inspection procedures employed
- Growth rate or no-growth of damage from fatigue, corrosion, manufacturing flaws or impact damage, under repeated loads expected in service, must be established by tests or analysis supported by tests
- Requirements on residual strength with damage
  1. Critical limit flight loads with the combined effects of normal operating pressure and expected external aerodynamic pressures
  2. The expected external aerodynamic pressures in 1g flight combined with a cabin differential pressure equal to 1.1 times the normal operating differential pressure without any other load

Joint Geometries
Basic Definitions: "Scarf Joint"

- **"Scarf Lap Joint"** (joint without load eccentricity)

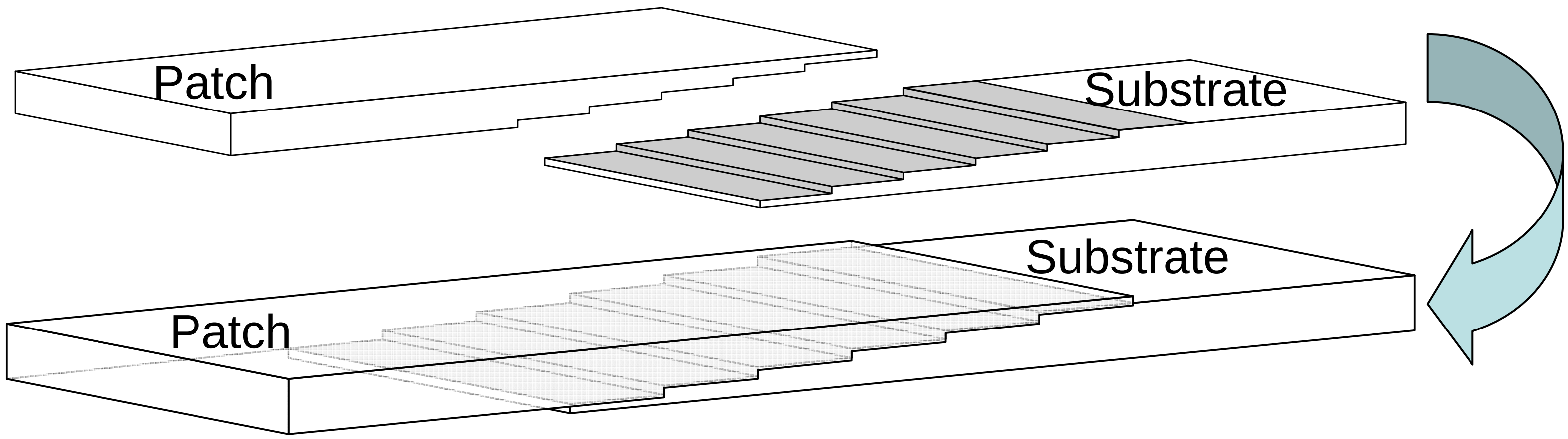


- **"Scarf Rate" = L / t**

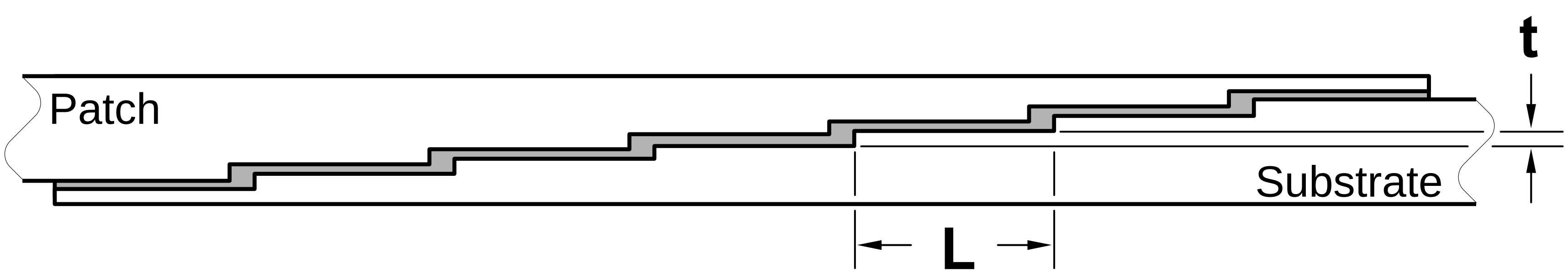


Joint Geometries
Basic Definitions: "Step Joint"

- **"Step Lap Joint"** (joint ^{w}/moderate load eccentricity)

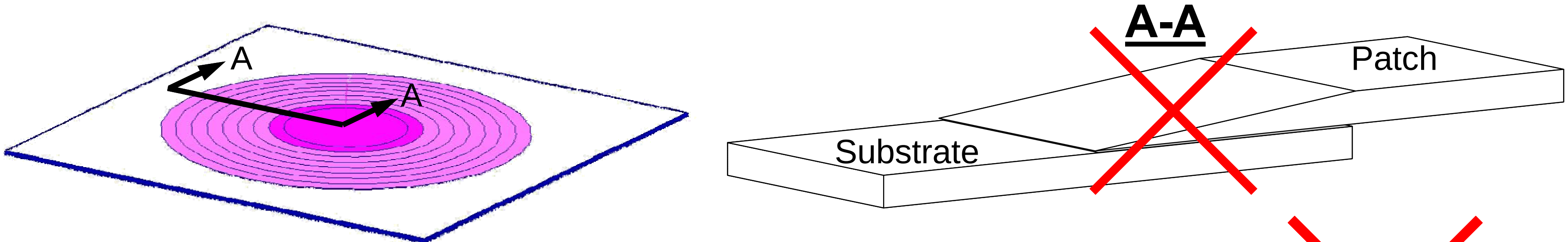


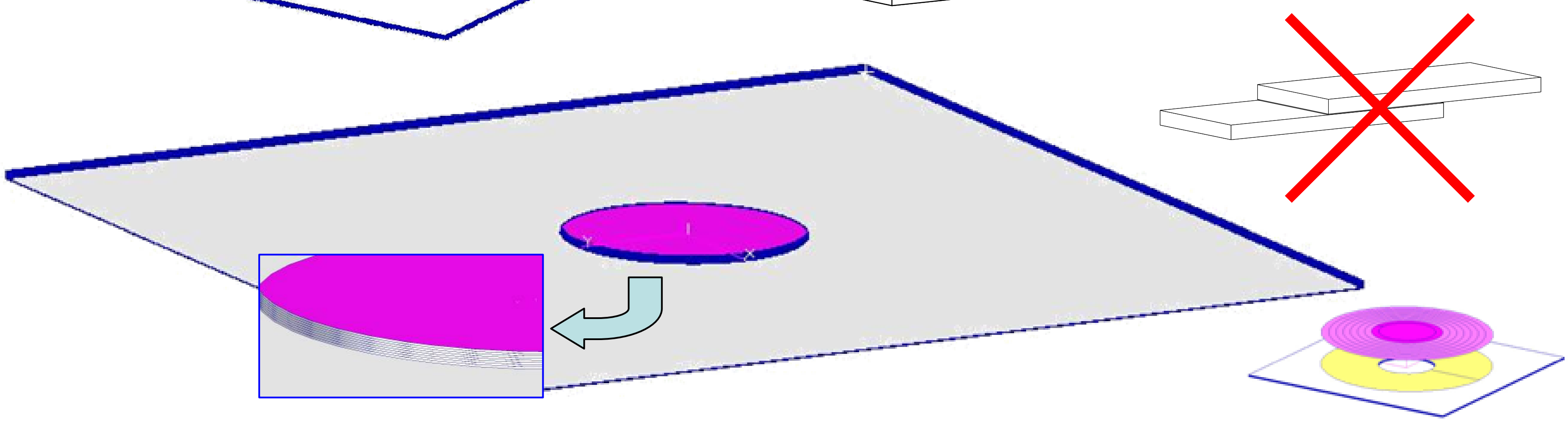
- **"Step Rate" = L / t = "Per Ply Overlap" / "Ply Thickness"**



Joint Geometries
Basic Definitions: Poor Joint Details

- **Poor design details = "square cut" edges on damage removal and/or patch**
  - Large bond stress riser at square edge





Design Preface
"Achilles Heel" Of Bonding

- Cannot verify bond strength via post-cure inspection
- In practice, rigorous control of materials and processes is approach used to ensure bond strength in final product
- Post-cure NDI can identify some quality problems
  - Porosity, delamination, inclusion, non-bond
- However, "kissing bond" may not be found, and…
- Fundamentally, the bond strength is unknown
- As a result…

The structural integrity of any bond can be questioned

Design Preface

“Achilles Heel” Of Bonding

- **Absence of “*NDI bond strength guarantee*” limits scope of bonded repair applications**
- **These limits <u>ARE necessary</u> for today’s level of technology (if can’t <u>prove</u> it’s good, then must assume it’s not)**

∴ In response, the repair design philosophy is…

Continued safe flight <u>with repair completely failed</u>

- **Ultimate load capability restored by presence of repair**
- **However, safe flight (limit) is not dependent on repair**

Analysis Preface

Historic Perspective

- Analysis not generally performed on bonded repair joints
- Instead, substantiation data is developed for specific joint geometry (point design data)
- The substantiated joint is then used without analysis
- Substantiated joint generally chosen such that ultimate failure occurs in adherends not in adhesive bond-line
- Damage tolerance analysis not generally performed
- “Point design” repair data approach has worked well for existing relatively simple composites architectures
- Next generation composite airframe structures are more complicated architecture with more complex loading
- Broader array of point design data will be required to cover the breadth of potential application needs
- May be impractical

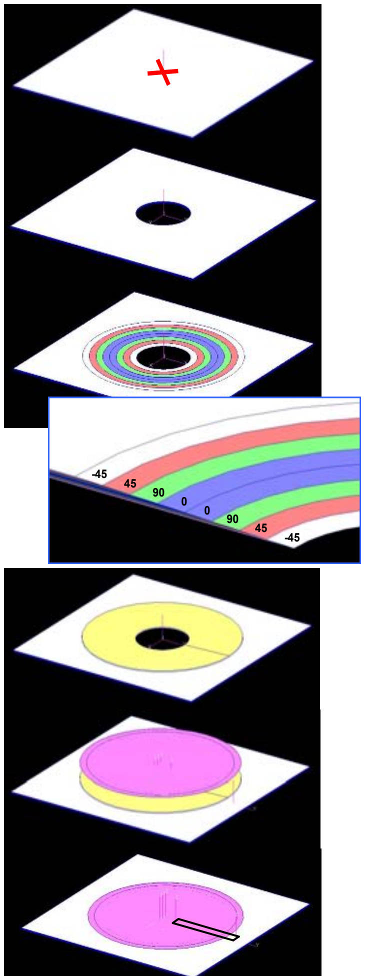
Analysis Preface (continued)

Approach Shift For Today's Materials

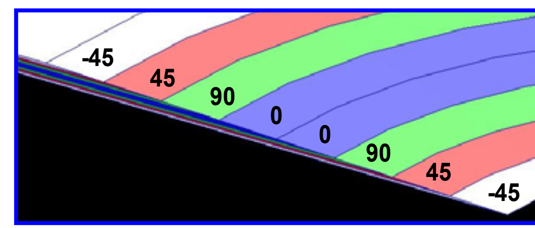
- **Today's very strong adherend laminates sometimes require joint geometries with large joint overlaps (to fail adherends instead of adhesive bond)**
- **These large overlaps can sometimes significantly complicate repair geometry by impinging on surrounding structural details**
- **"Good" bonded joints display relatively repeatable failure stresses (peel/shear)**
- *From structural integrity perspective need predictable, repeatable, failure mode plus understanding of joint static strength, durability, and damage tolerance*
- *If sufficient data is created and if analysis method can be developed and proven effective ~ "Is design for bond failure" a reasonable option to consider?*

Repair Process Steps

- **General steps in bonded scarf repair** (flush repair shown)



1. **Design and analyze repair**
2. **Damage removal**
3. **Prepare substrate repair geometry**
   - **Scarf joint shown but other joint types exist**
4. **Create patch (ply map)**
5. **Clean surface**
6. **Apply adhesive**
7. **Lay-up patch**
8. **Cure and inspect**



Repair "Joint" Analysis

Repair "Joint" Analysis

Taper Region Stiffness Decay

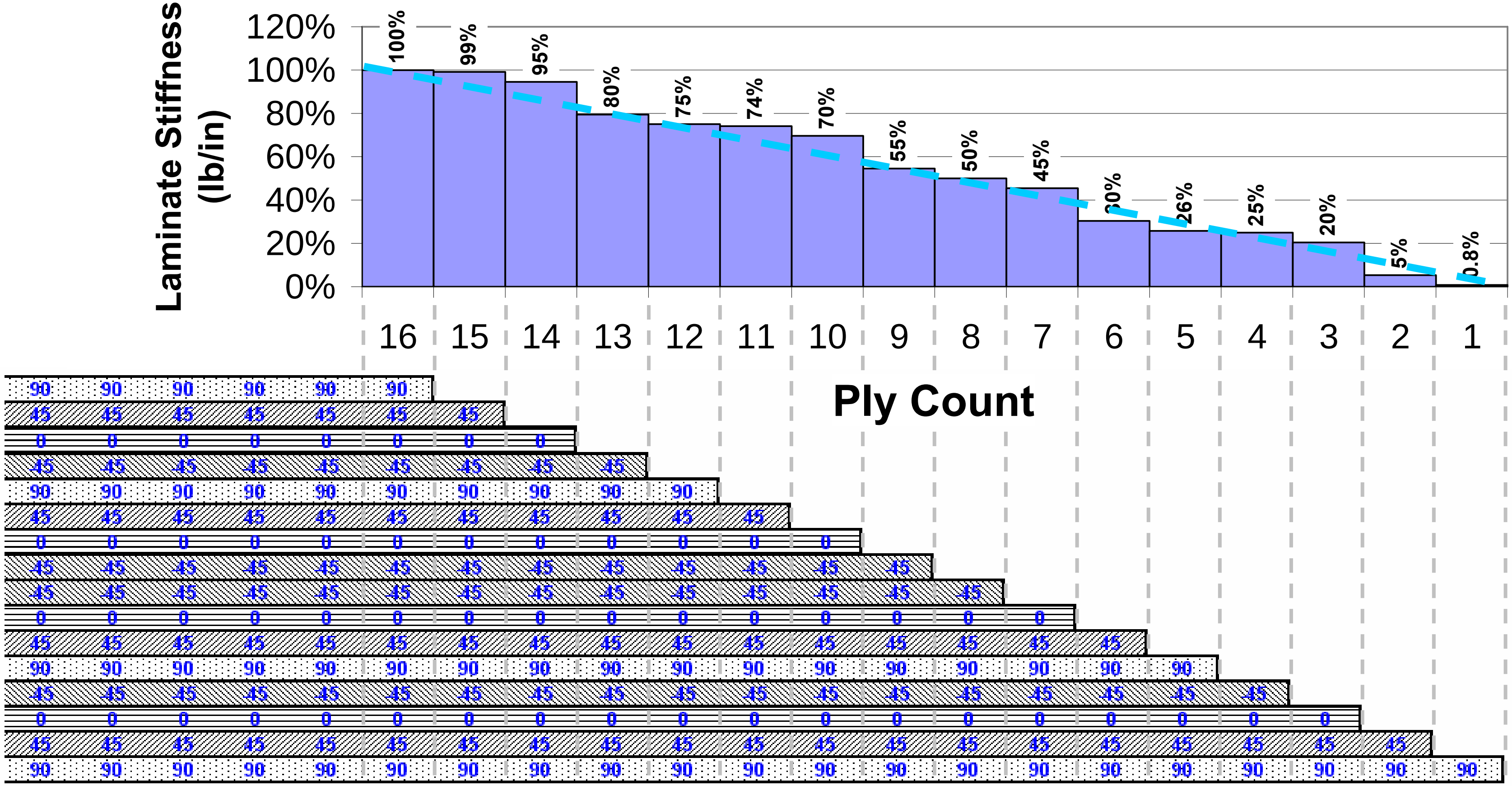
- Laminate stiffness decays in non-linear fashion in joint step or scarf (taper) region

- Linear stiffness variation only present if all plies same stiffness (i.e., uni-directional laminate)
- Analysis methods which neglect laminate stacking sequence cannot predict stress/strain distribution

Analysis Preface (continued)

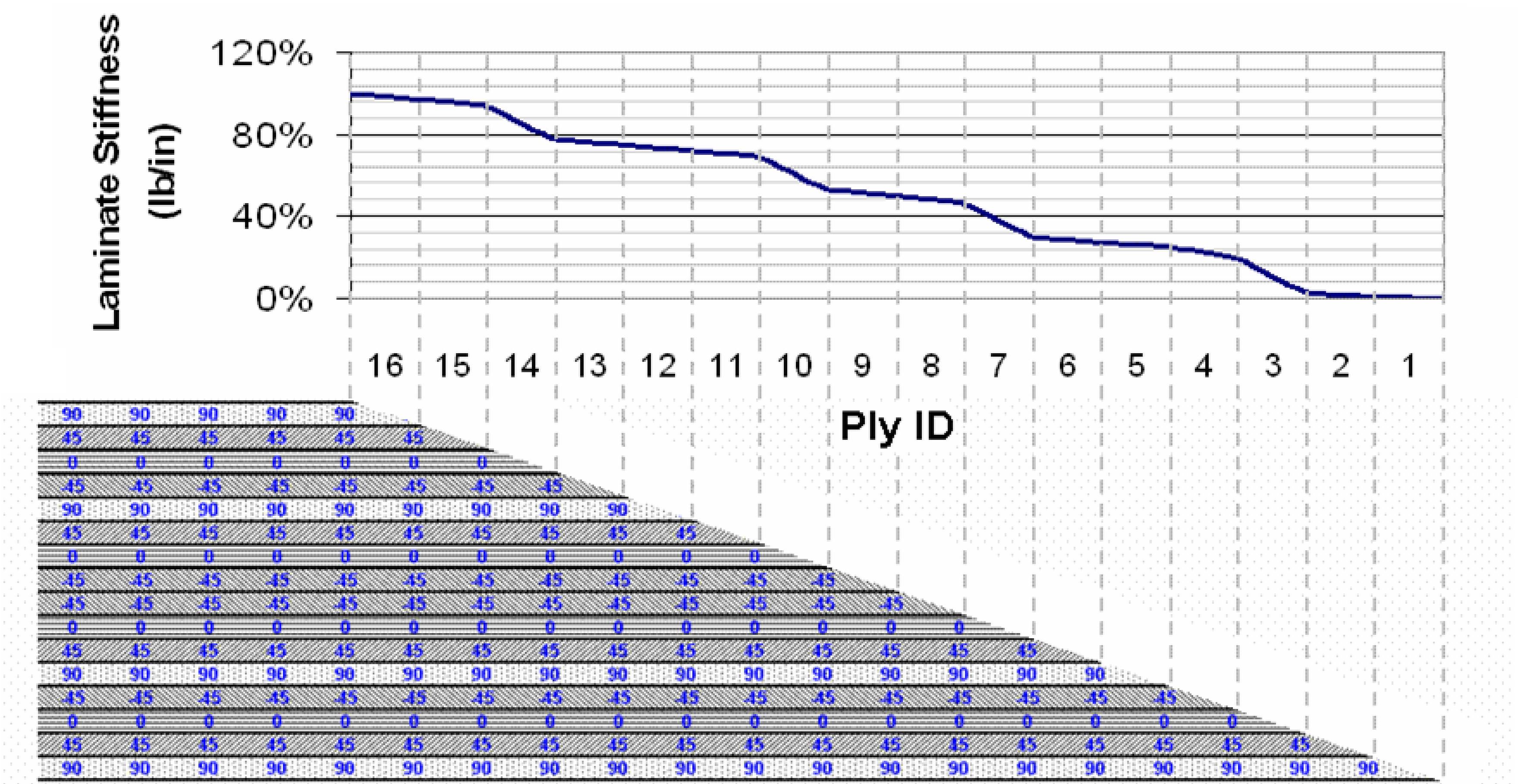
Taper Region Stiffness Decay

- Consider [90/45/0/-45/90/45/0/-45]$_s$ “all tape” laminate (25/50/25)
  - Non-linear stiffness decay as “Step” taper is traversed



Analysis Preface (continued)
Taper Region Stiffness Decay

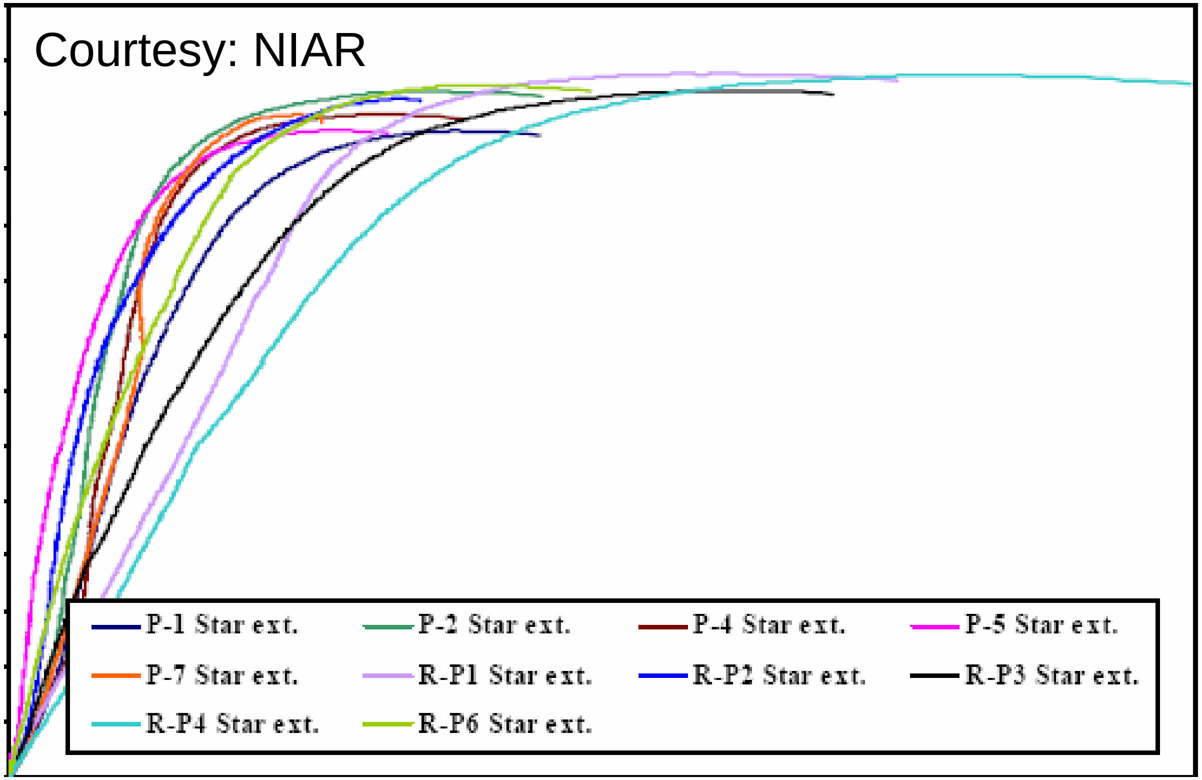
- **Tapered “Scarf” joint displays similar behavior**
  - Non-linear stiffness decay as “Scarf” taper is traversed



Analysis Preface (continued)

Adhesive Elastic-Plastic Behavior

- Epoxy Displays Elastic-Plastic Deformation
  - However, Behavior May Not Be Reliably Repeatable
  - Treating As Purely Elastic Sometimes Appropriate



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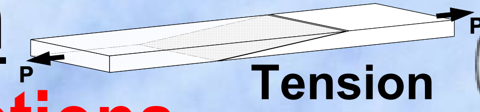
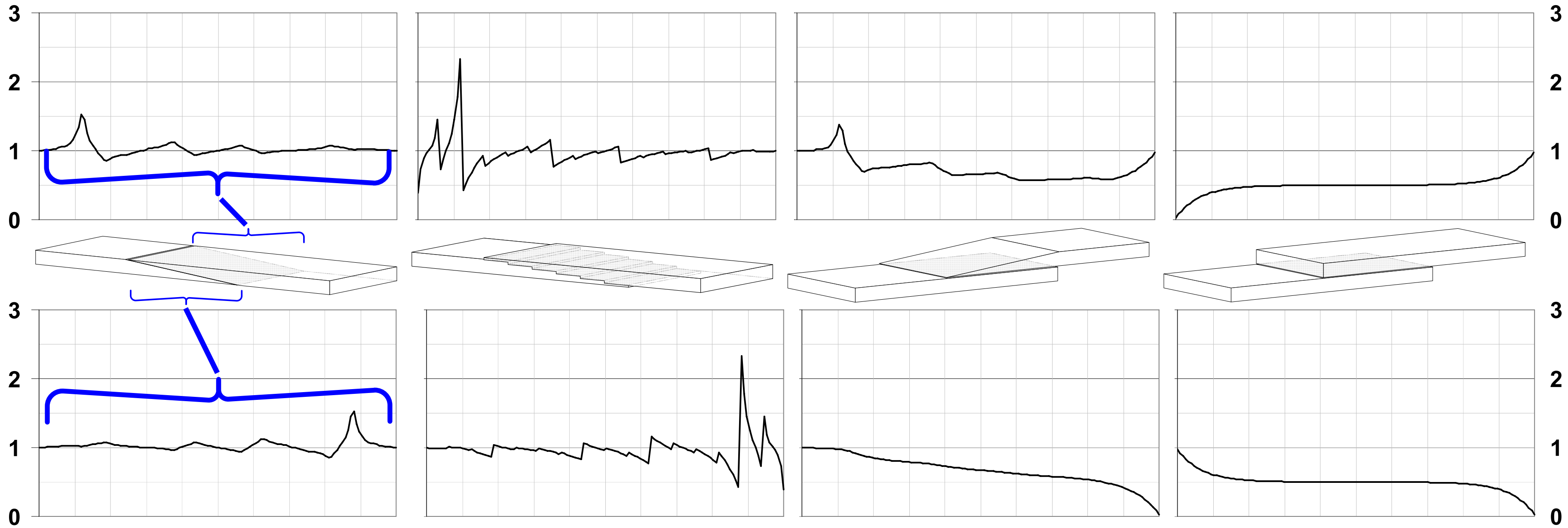
Analysis and Design

Joint Selection Considerations

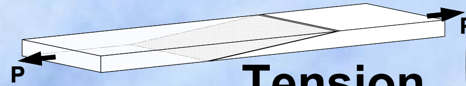


- Adherend strain profile divided by far-field strain
  - Common adherends in all $[90/45/0/-45/90/45/0/-45]_s$
    - Step lap yields highest far-field strain multiplier
      - Adherend max strain ≈ 250% far-field strain
        - » Applies to specific configuration analyzed only

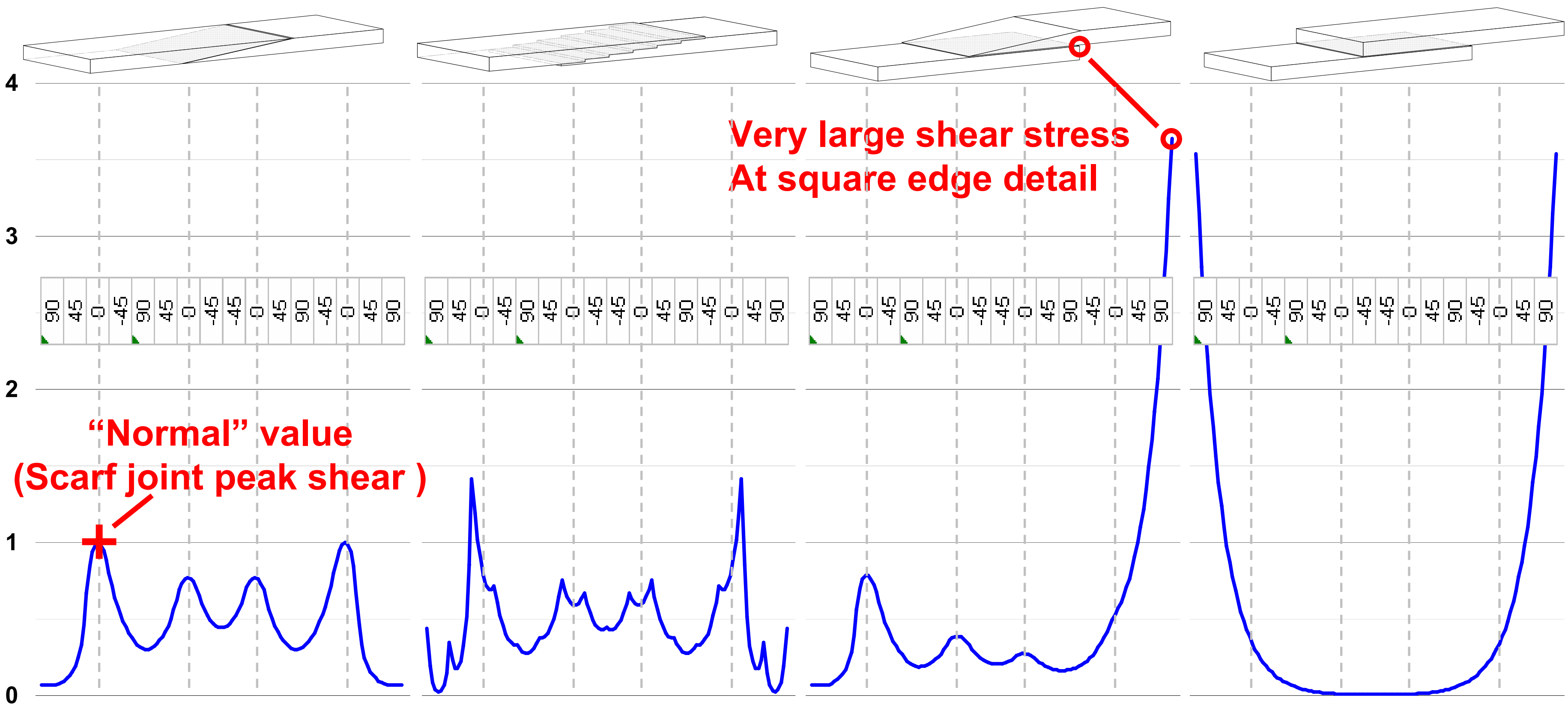


Analysis and Design

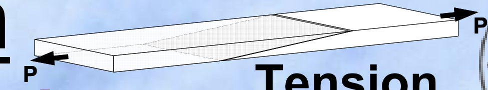
Joint Selection Considerations



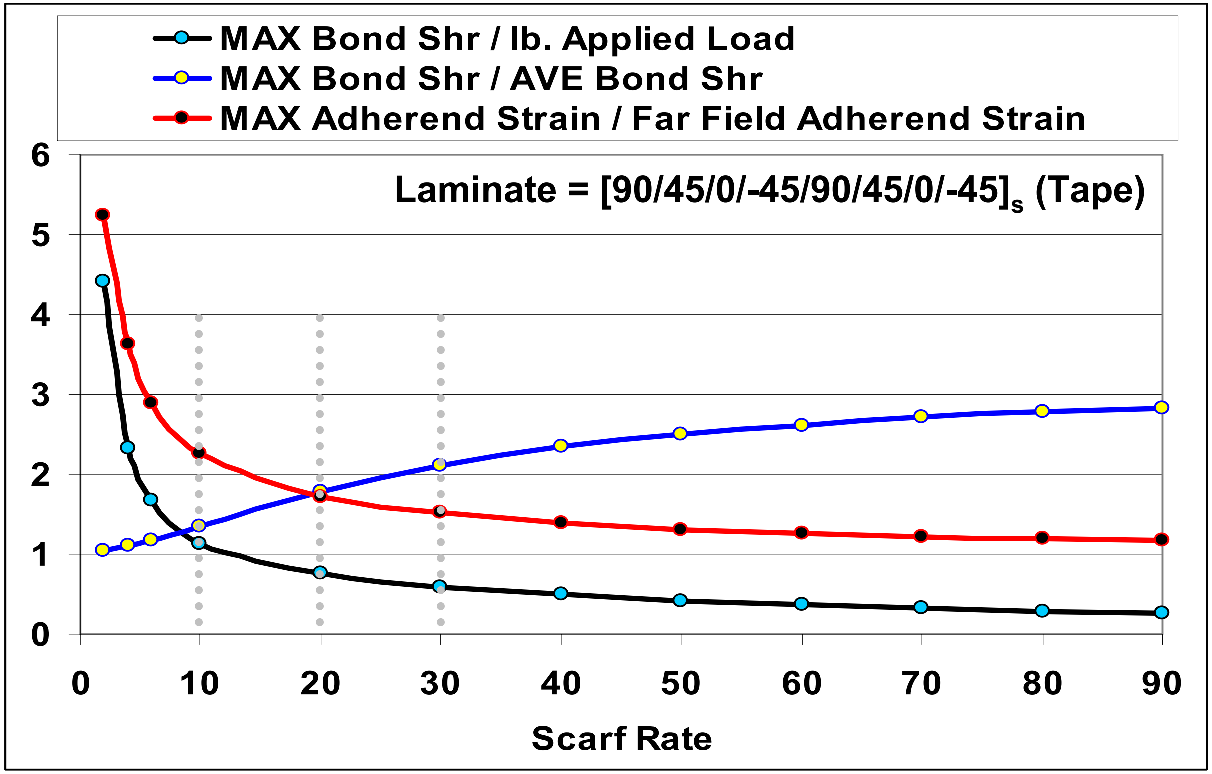
- **Bond shear stress profile at equal load** (normalized)
  - Same adherends in each case shown: laminate = [90/45/0/-45/90/45/0/-45]$_s$
  - Neglecting plasticity effects, stress 50% higher in step, 350% higher in square

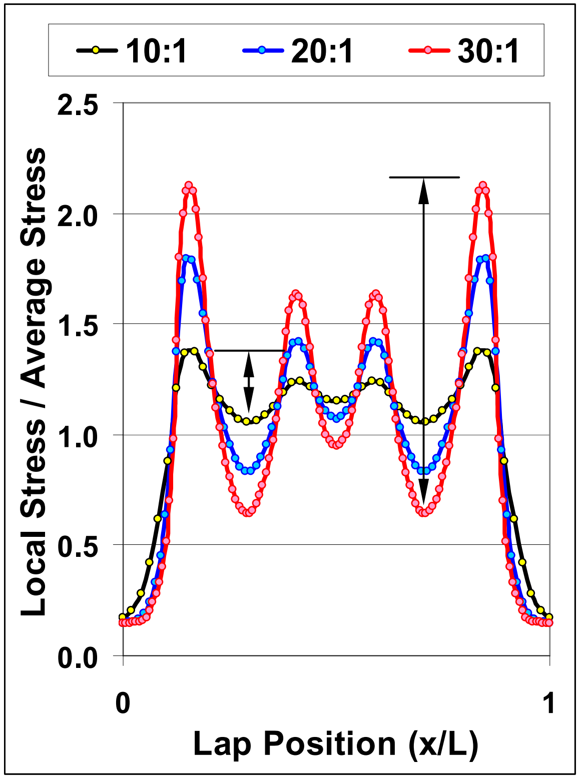


Scarf Parametric Observations



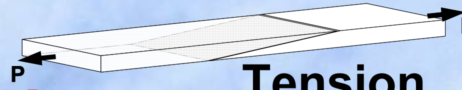
- Scarf rate effects
  - "Lion's share" of benefit to adherends occurs prior to increase to 20:1
  - Bond shear stress "peak to valley" amplitude increases with increasing length
    - Yields surprising fatigue behavior (fatigue sensitivity manifests sooner in longer lap)



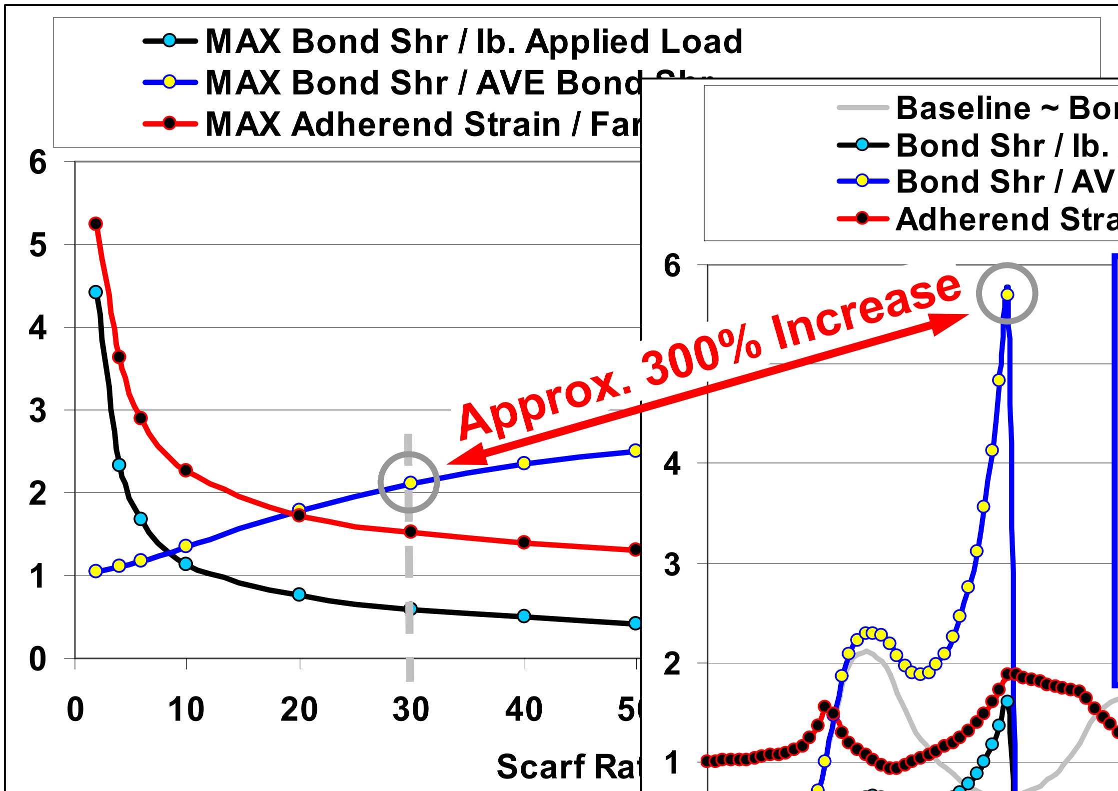


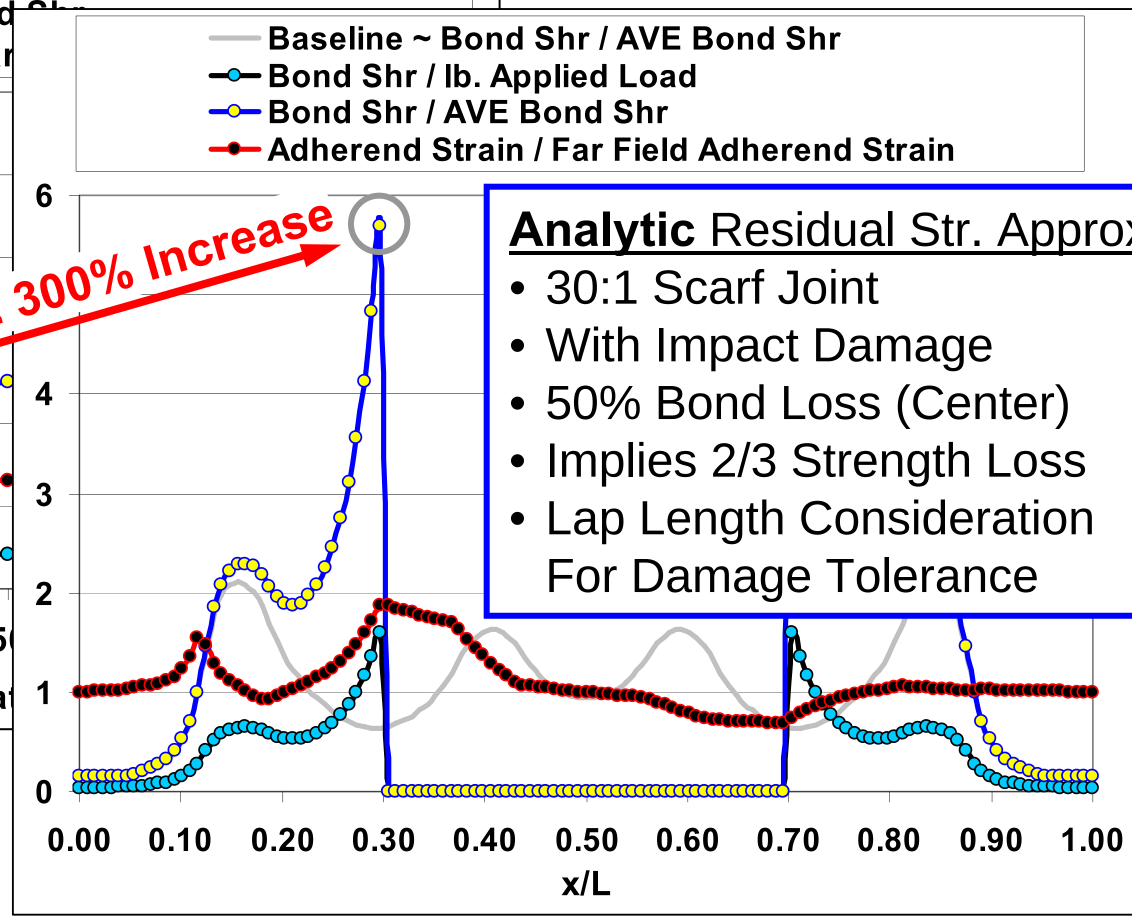
Analysis and Design

Scarf Parametric Observations



- Scarf rate effects & damage tolerance considerations



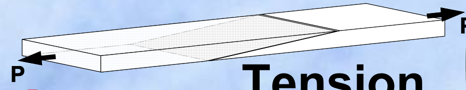


Analytic Residual Str. Approx
- 30:1 Scarf Joint
- With Impact Damage
- 50% Bond Loss (Center)
- Implies 2/3 Strength Loss
- Lap Length Consideration For Damage Tolerance

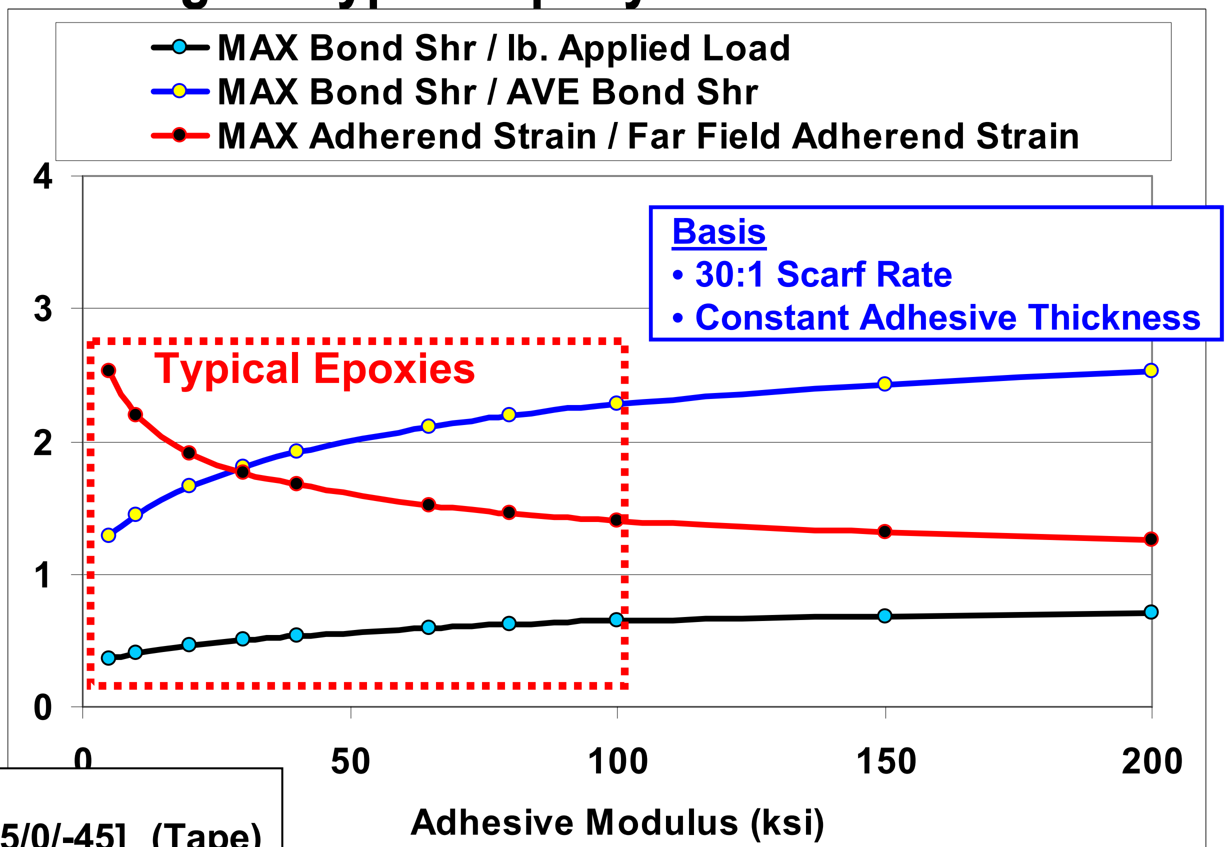
Laminates
$[90/45/0/-45/90/45/0/-45]_s$ (Tape)

Analysis and Design

Scarf Parametric Observations

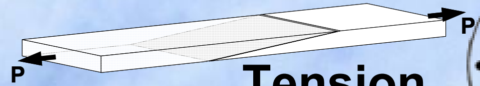


- **Adhesive elastic modulus effects**
  - Significant effect on adherend strain and peak-to-valley shear stress in range of typical epoxy adhesives



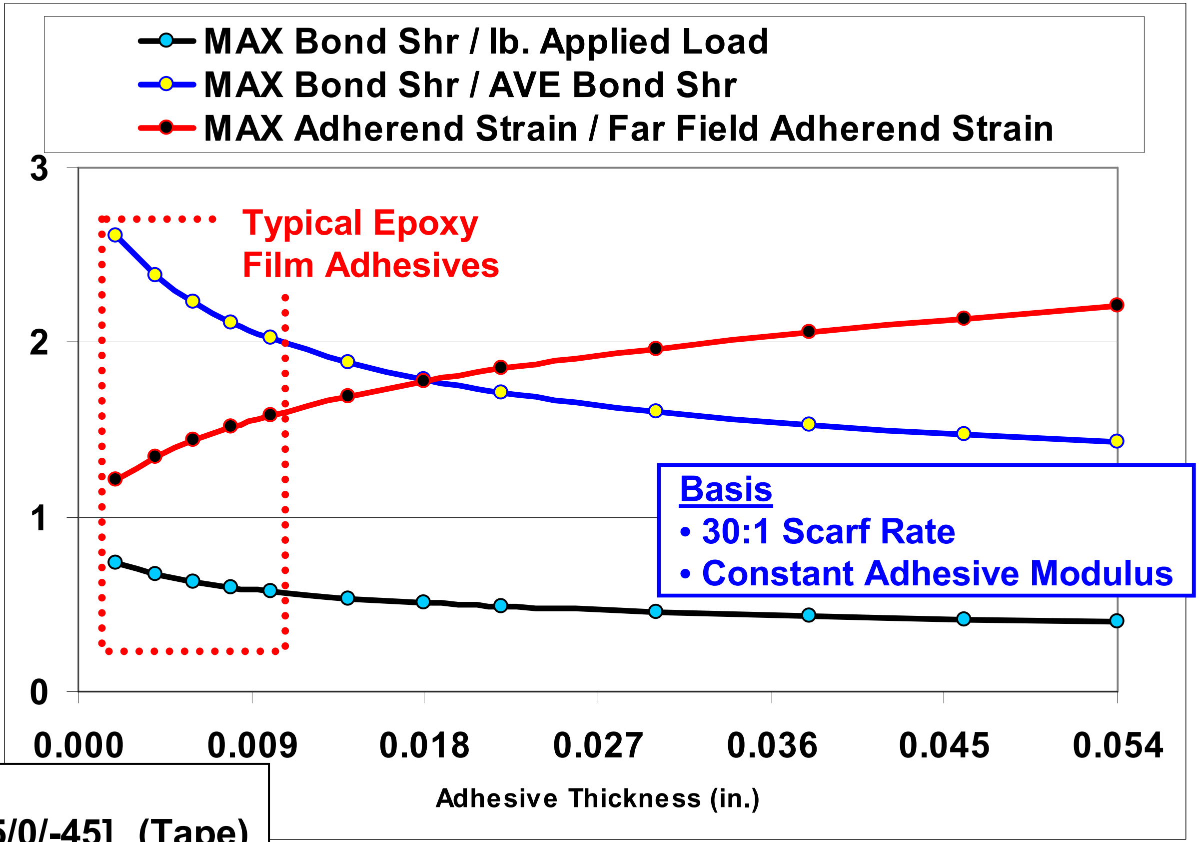
Laminates
$[90/45/0/-45/90/45/0/-45]_s$ (Tape)

Analysis and Design



Scarf Parametric Observations

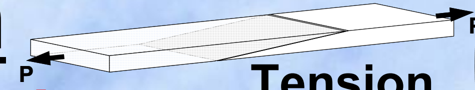
- **Adhesive thickness effects**
  - Significant effect on adherend strain and peak-to-valley shear stress in range of typical epoxy film adhesives (for single ply)



Laminates
[90/45/0/-45/90/45/0/-45]$_s$ (Tape)

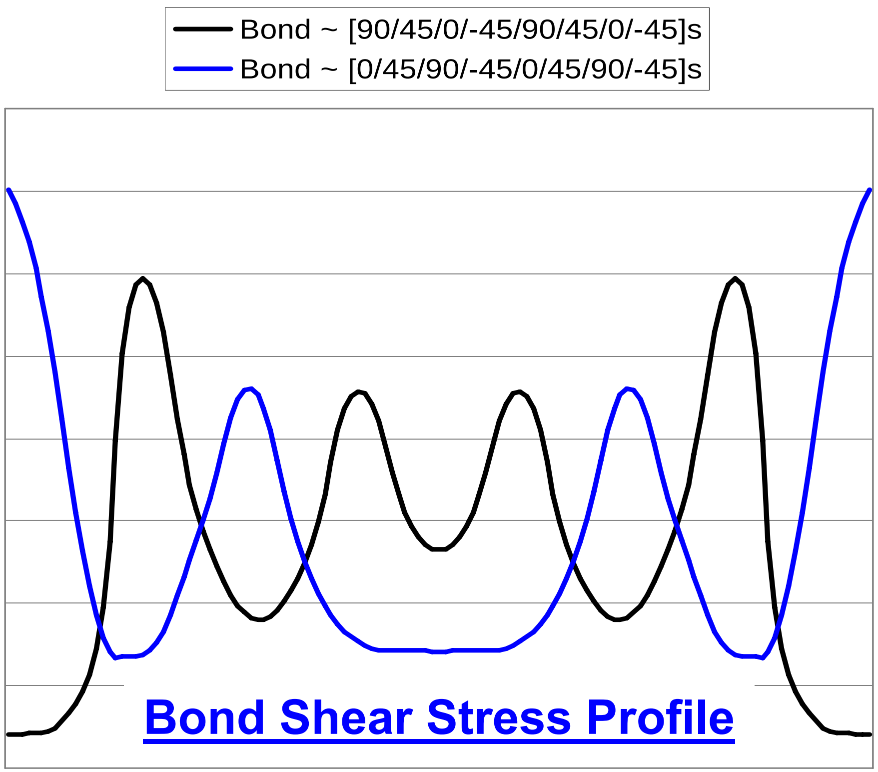
Analysis and Design

Scarf Parametric Observations

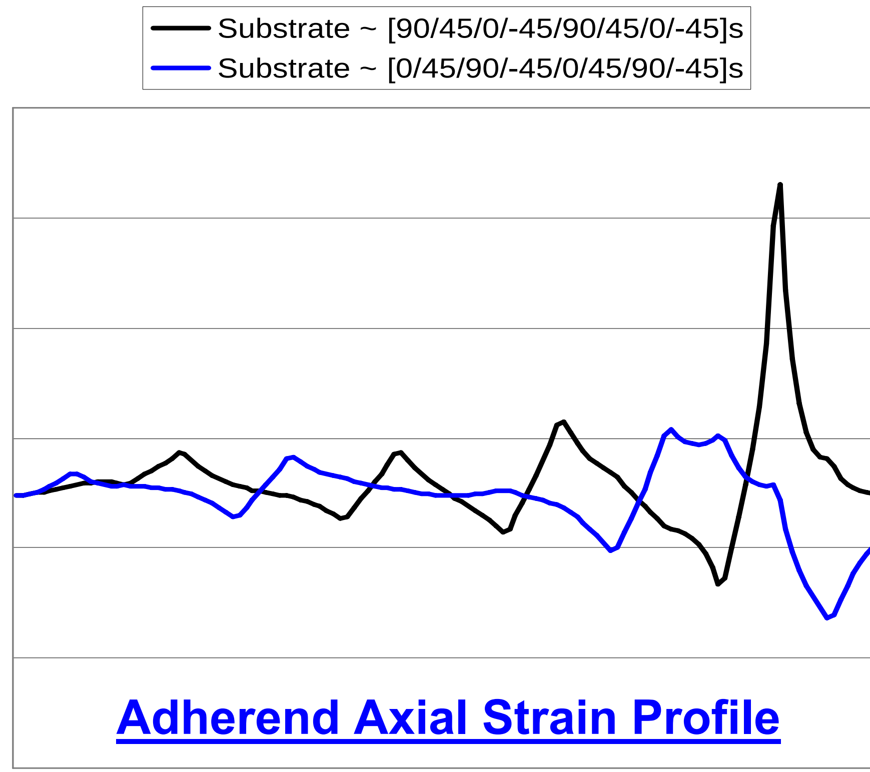


Tension

- **Laminate stacking sequence (16 ply laminates)**
  - Interchange 0º and 90º plies
    - Increased max. bond stress, Decreased max adherend strain



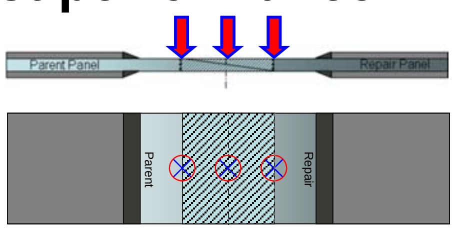
Bond Shear Stress Profile



Adherend Axial Strain Profile

Side Note: Current FAA Work Analysis / Damage Tolerance

- FAA collaborative research in process at NIAR
- Scope: 1) analysis methods development, 2) bond process robustness assessment, and 3) repair damage response
- Four major thrusts
  1. Baseline mechanical performance
     - Static strength / post-fatigue residual strength / durability
  2. Degradation of mechanical performance as result of contaminants on bond surface
  3. Impact damage site [in joint] resulting in greatest performance degradation (i.e., What is critical site?)
  4. Detect-ability of bond surface contaminants
     - Adequate pre-bond surface preparation / cleaning



Process Considerations

Surface Preparation

Surface Preparation

Scarf Grinding Operations

- Damages seldom occur in region with constant laminate thickness
- Ply drops in region effect final taper sand geometry
- Sometimes difficult to anticipate what the final material removal product should look like
- Beneficial to have visualization of final taper sand prior to starting grinding operations
- During initial design, many airframe components modeled as 3-D entities in space and on A ply-by-ply basis
- With appropriate software can generate 3-D simulation of taper sanded region (prior to start)

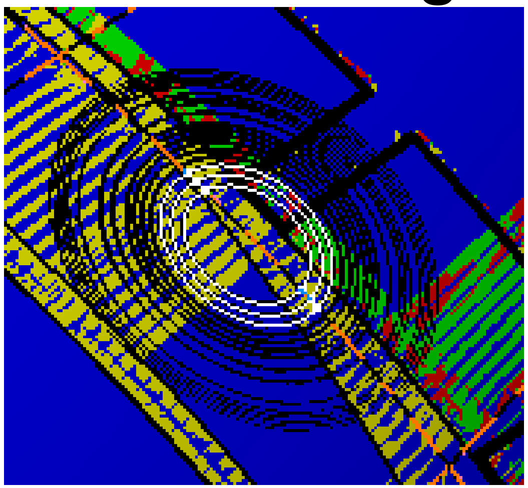
Surface Preparation
Scarf Grinding Operations

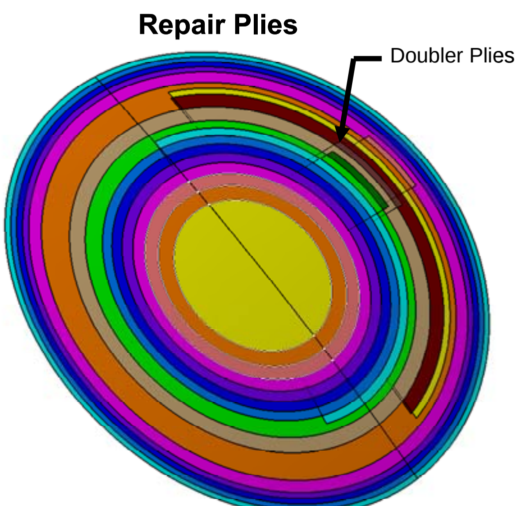
- Three dimensional simulation enhances ability to produce repairs of higher precision
- Provides greater confidence that sanding operation was performed correctly
  - Mechanic visual aid
  - Data for mechanizing major material removal steps using robotic grinding
    - Hand finishing still required
  - Improved records demonstrating that final repair geometry “looked like it was supposed to”

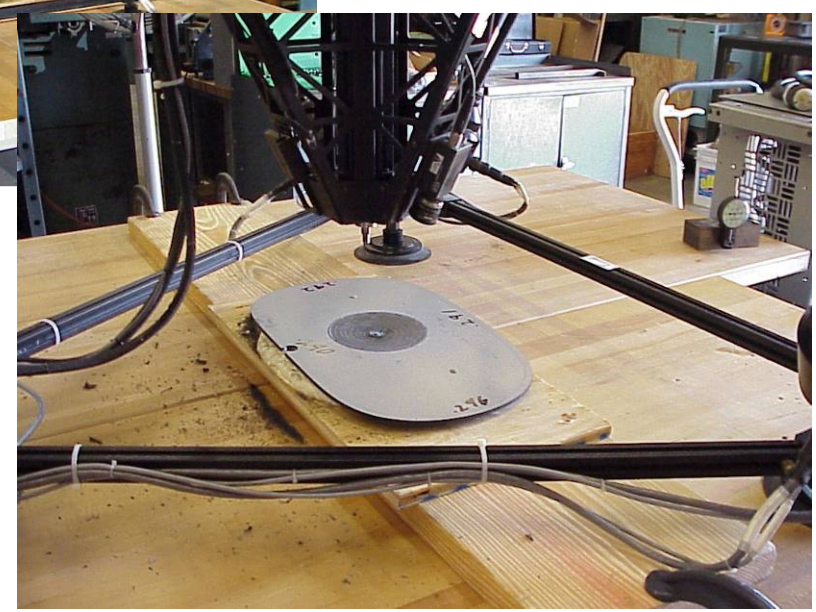
Surface Preparation

Precision Scarf Grinding

- Automated grinding using digital model data





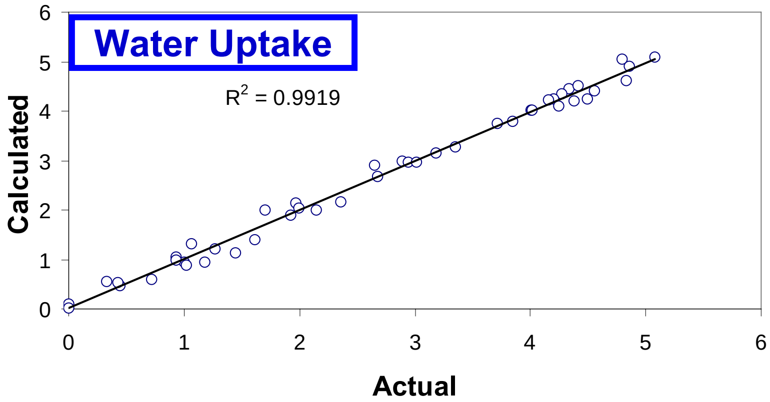


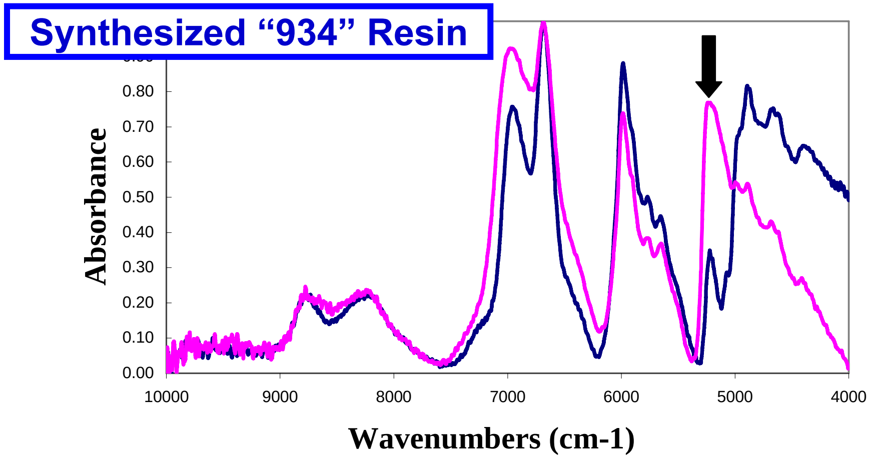
Surface Preparation

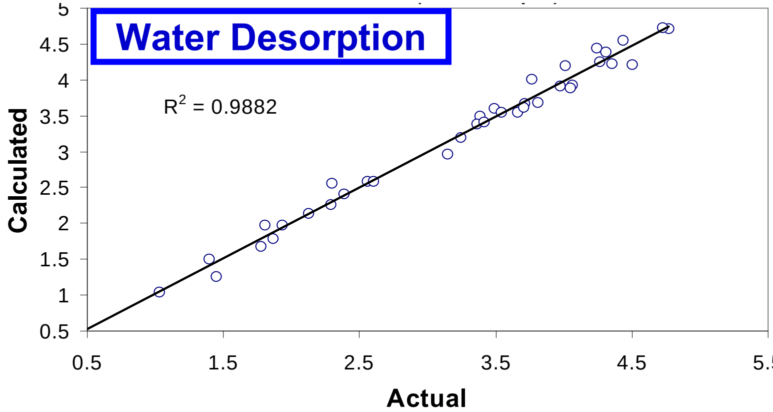
Pre-Bond Surface Inspection

"Compact instrumentation" inspections methods

- Contact angle (surface energy resulting from contaminants)
- Near IR diffuse reflectance spectroscopy (shown)







Courtesy: Wichita State University, Department of Chemistry (FAA Collaboration)

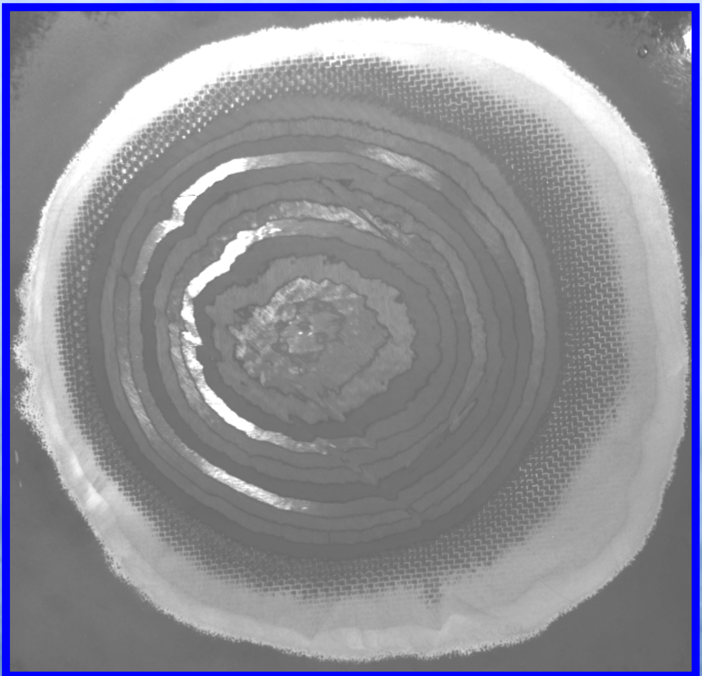
Process Considerations

Laminate Patch Preparation

Process Considerations

Laminate Patch Preparation

- Even in repair scenarios with simple substrate geometry the patch plies seldom have regular, well defined edges
- A ply kit is created by….
  1. Taping clear Mylar over taper sanded region
  2. Hand tracing ply boundaries
  3. Transferring ply definition from Mylar
  4. Hand cutting repair plies with snips
- Final patch fit is marginal at best
- The process is slow, and hand cutting plies difficult to accurately accomplish
- Randomness of patch fit adds to randomness of structural performance



Example of Simple Taper Sand

Process Considerations

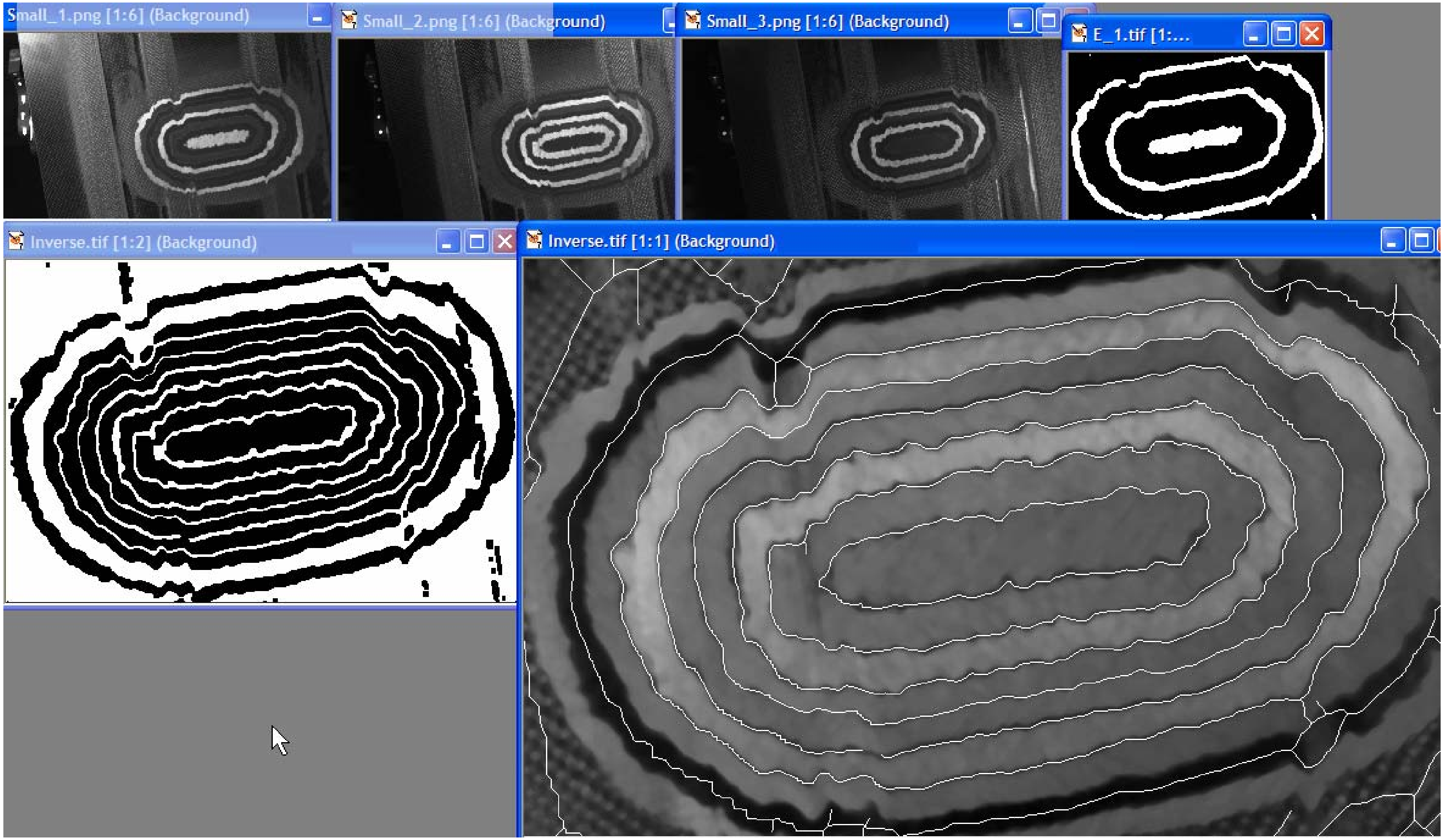
Precision Laminate Patch Preparation

- Structural performance benefit in precision patch “ply kit”
  - Reduce randomness of structural performance
- Digital image processing is candidate technology to accomplish this
- With appropriate lighting, individual ply orientations can be detected using *AFI instrumentation* *(Spirit AeroSystems patent pending)*
- Points of prescribed density can be automatically defined in orientation change demarcation zones
- Splines laid through points to create ply edges
- Feed data to automatic knife for precision cutting
- Feed data to laser projector for patch ply lay-up
- Provides permanent digital record of patch accuracy

Process Considerations

Precision Laminate Patch Preparation

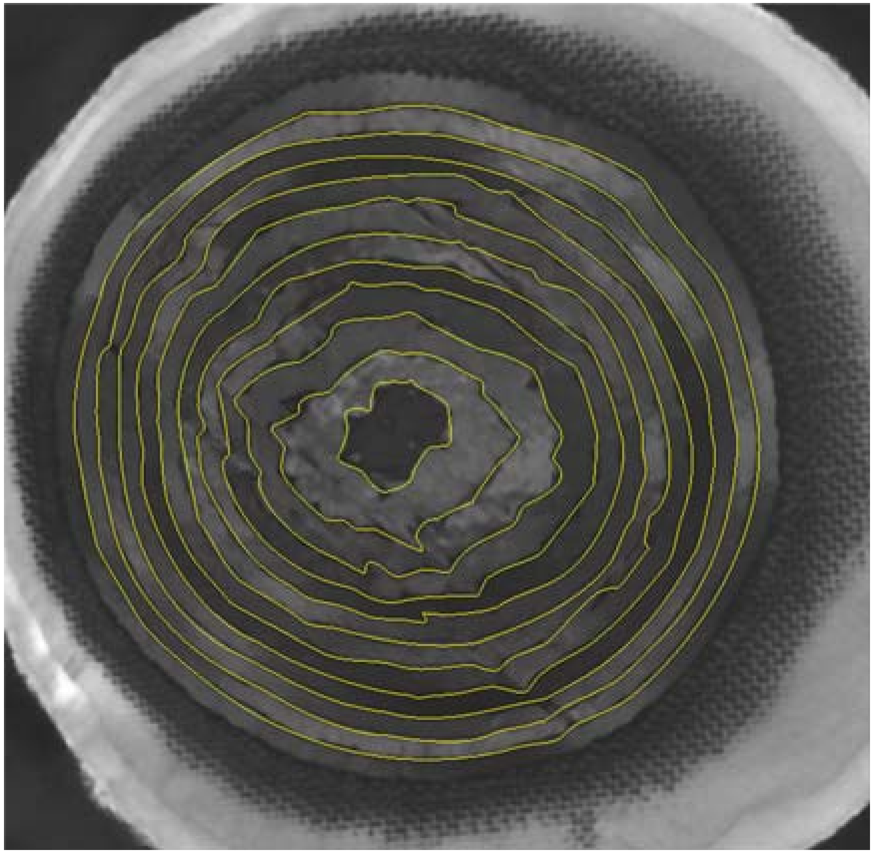
- Variation of lighting accentuates ply orientations

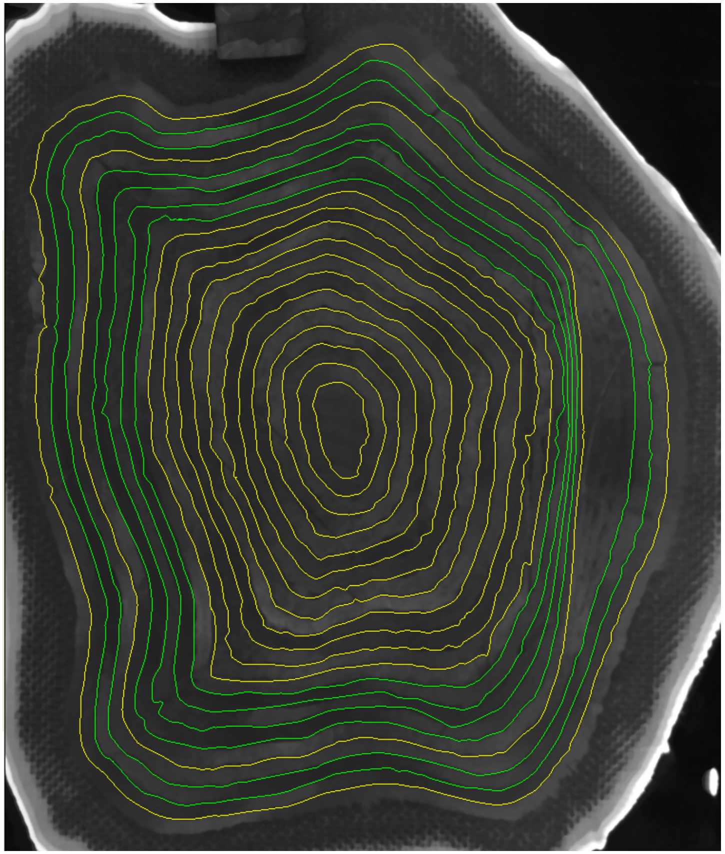


Process Considerations

Precision Laminate Patch Preparation

- Examples: optical edge identification & digitization
  - Production of high precision "patch ply kits" possible





Process Considerations

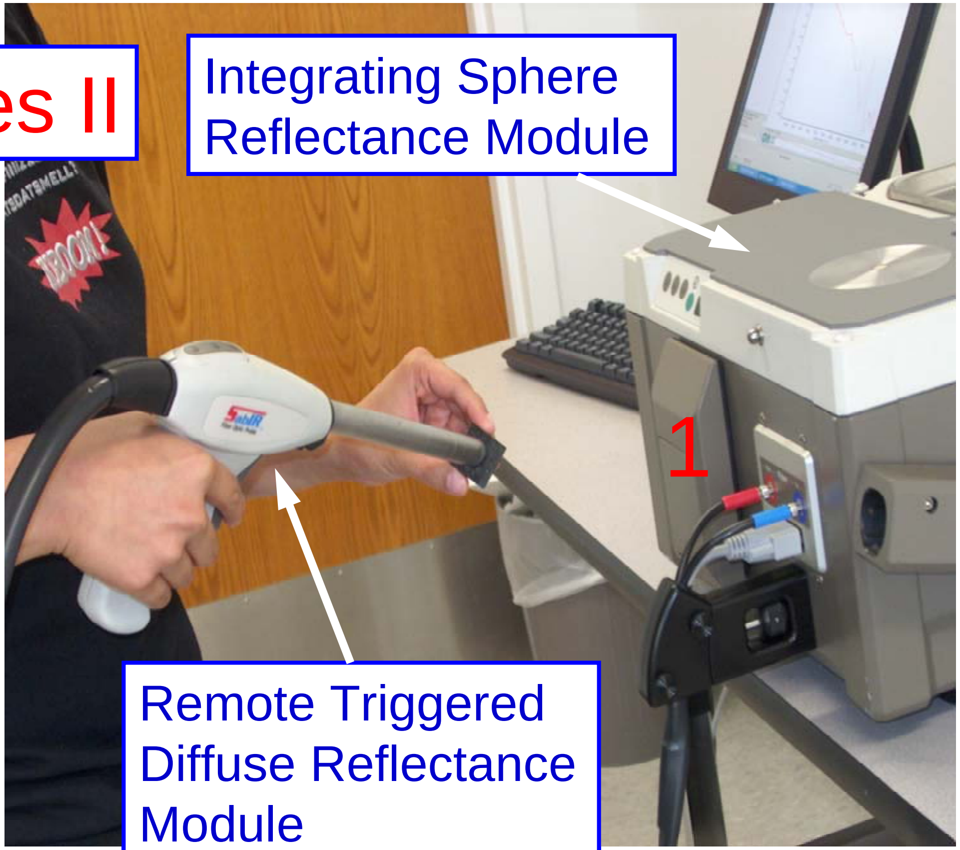
Cure State Verification

Post Bond Cure State

- Resins are uniquely individual with regards to cure response to thermal cycle
  - Some resins achieve an approximately full cure state early in thermal cycle
  - In other resins cure reaction initiates late in cycle
- Repairs frequently cured using heat blankets
  - Heat blankets deliver thermal profile with tolerance band broader than autoclave cure
  - Some areas hotter than others
- **Important to verify full cure**
    - **DOT/FAA/AR-03/74,** Office of Aviation Research, "*Bonded Repair of Aircraft Composite Sandwich Structures*", John S. Tomblin, Lamia Salah, John M. Welch, Michael D. Borgman, 2004
    - *http://www.tc.faa.gov/its/worldpac/techrpt/ar03-74.pdf*

Post Bond Cure State Inspection

- **Hand held diffuse reflectance infrared spectroscopy**
  - **For assessment of cure state by peak amplitude area**

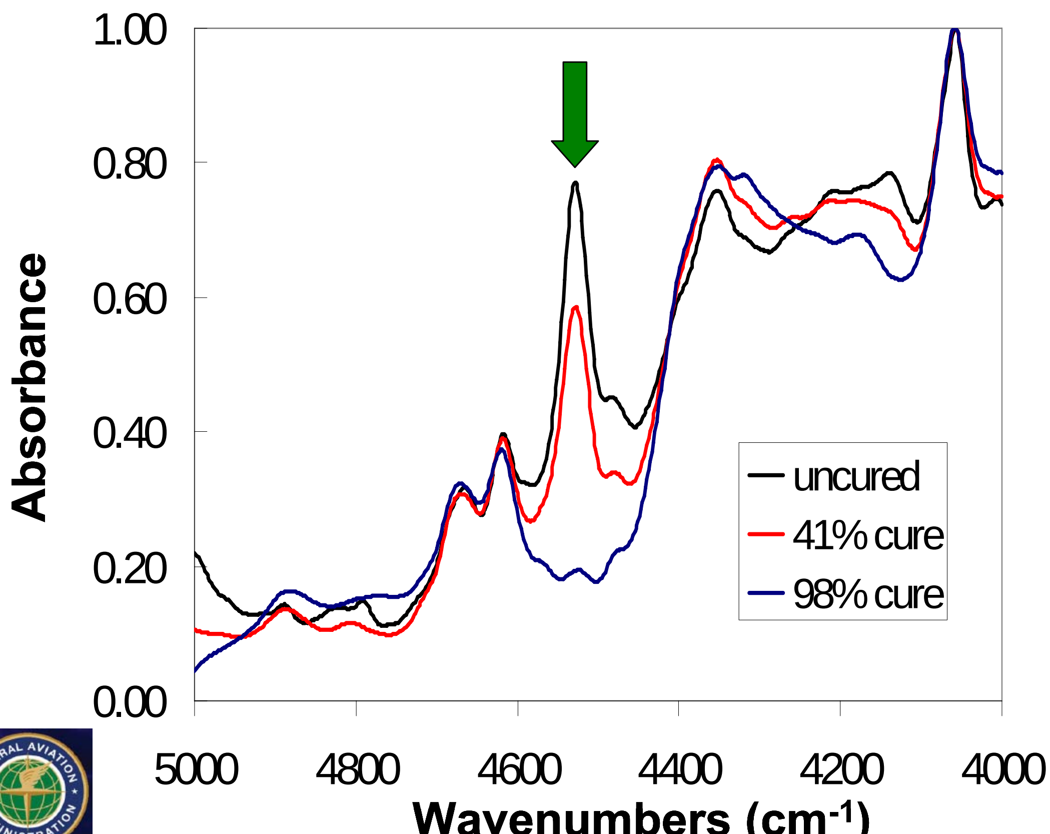


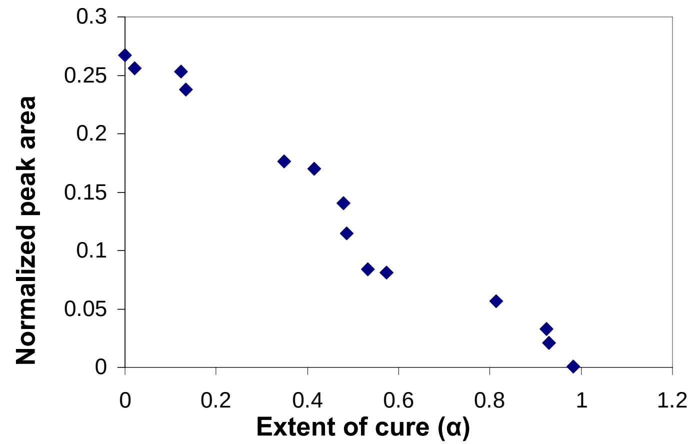
Courtesy: Wichita State University, Department of Chemistry (FAA Collaboration)

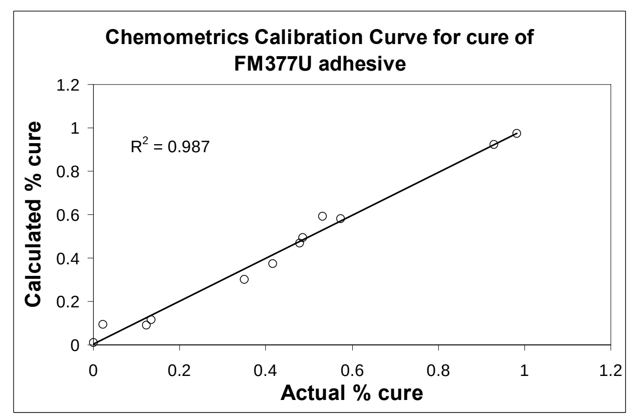
Post Bond Cure State Inspection

- Cure state by diffuse reflectance IR spectroscopy

Curing FM377U adhesive





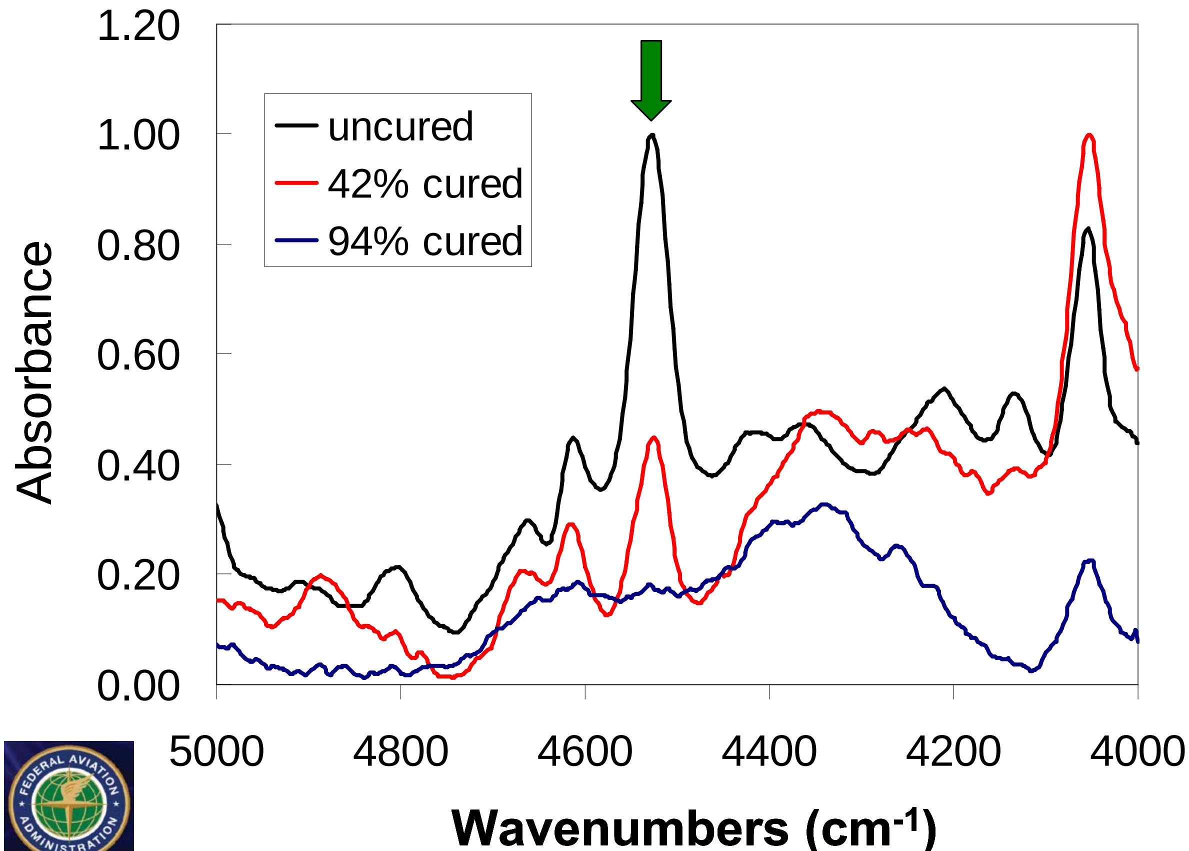


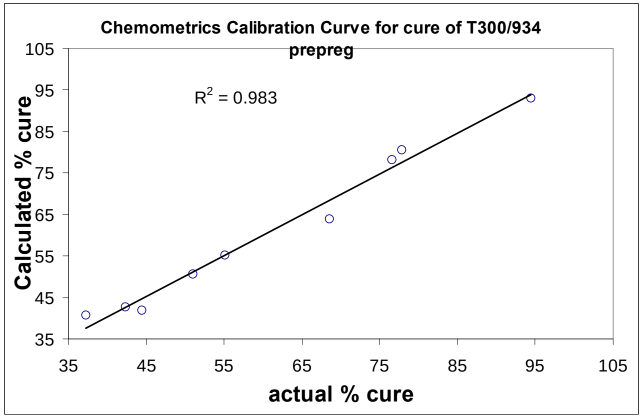
Courtesy: Wichita State University, Department of Chemistry (FAA Collaboration)

Post Bond Cure State Inspection

- **Cure state by diffuse reflectance IR spectroscopy**

Curing T300/934 prepreg





Courtesy: Wichita State University, Department of Chemistry (FAA Collaboration)

Summary of Observations

- For structurally critical bonded repairs to be pursued, absence of NDI method for verifying bond strength creates need for high precision repairs using highly constrained processes performed by highly trained personnel (mechanics and analysts)
  - Proof of statistical reliability only existing alternative for strength guarantee
    - Reliability must be demonstrated in terms of analysis & design, surface preparation, patch "fit" precision, and process validation & records
- Bond-line failure mode may be consideration (or requirement) in lieu of traditional requirement for adherend failure mode
  - Fairly repeatable / predictable mode (given adequate repair precision)
  - However, need A great deal more substantiation data to verify it as reasonable alternative

Summary of Observations

- Joint type strongly impacts peak bond stresses
- Joint geometry parameters must be chosen with care
  - Some parameters are "double edge sword"
  - For example scarf rate can improve static strength but, at the same time, reduce fatigue resistance (increase sensitivity to fatigue)
- Analysis methods must include laminate stacking sequence effects
  - Including stiffness decay in taper region
- Research on performance of damaged scarf joints is needed
  - Propagation characteristics
  - Damage containment feature development and demonstration
- Candidate *precision* repair technologies exist but need maturation
- Moisture detectable by diffuse reflectance near IR spectroscopy
- Cure state detectable by diffuse reflectance near IR spectroscopy

Future

- In any process control scenario reliability of success will have to be proven
- This reliability must be demonstrated through mechanical testing the product from a LARGE volume of bondment process cycles
- I have started this process at SPIRIT in support of one of our products, and have tested scarf joint strengths from approximately 200 bondment process cycles
  - Many different mechanics
  - Many different cure thermal profiles
  - Many different resulting NDI scan quality results
- Have learned there are nuances to be considered in selecting a joint geometry for process reliability testing
  - Joint shape and edge proximity (breathing during cure)

END