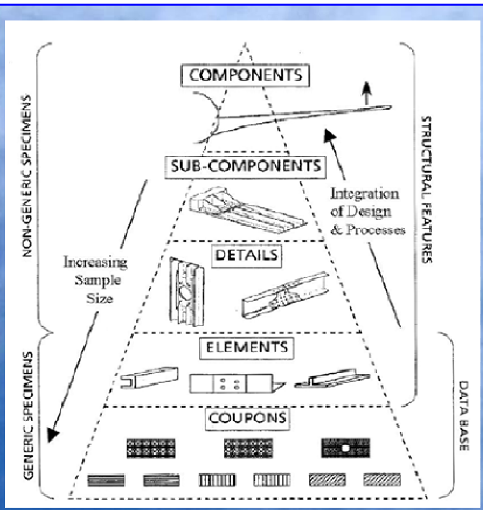
Perspectives on the Complexity of Structural Substantiation, Including Non-standard Damaging Events and Repair



Presented at: ***Spring 2009 Commercial Aircraft Composite Repair Committee***
June 5 ~ Tokyo, Japan

Presented by: ***Michael Borgman (CACRC Co-Chair)***
MD Borgman Consulting
mborgman@niar.wichita.edu
m.borgman@vzw.blackberry.net
+1-316-644-4687

Scope Limit of Current Discussion

- **Scope of discussion herein limited to composite repair substantiation**
  - **Objective is to promote discussion on strategies to advance standardization of repair substantiation approaches**

- **Substantiation of new aircraft composite designs was covered well in previous workshop presentation titled:**
  - *"Design Substantiation for New Applications of Composite Airframe Structures", D. Polland*

Side Note on Records Keeping

Regardless of whether standardization is adopted, it must become standard practice to document all repair activities in component maintenance records

- **Provides means of assessing component "cumulative airworthiness"**
- **Provides information in support of future maintenance damage disposition and repair activities preformed on same part**

Dicussion Outline

1. Complexities of bond strength
2. Concerns in composite repair
3. Repair airworthiness requirements
4. Repeated loadings / fatigue effects
5. Manufacturing defects
6. Environmental effects
7. Cure anomaly effects
8. In-service damage effects
9. Substantiation requirements

Complexities of Predicting Bond Strength

- Predicting static strength of composite repairs is complex task (shear, peel, and fracture phenomena)
  - Local bond stresses function of ply schedule
  - Pristine scarf joint static strength tests may not reveal true bond strength
    - Repeated loading can reduce bond strength
    - Service induced moisture saturation prior to bonding can reduce bond strength (even after dry cycle)
    - Surface contaminants can reduce bond strength
    - Cure cycle anomalies can reduce repair strength
    - Service induced damage to scarf joint reduces bond strength
  - Accounting for core effects is muti-faceted
    - Positive pressure internal to honeycomb and manufacturing defects related to core facing bond are complex
- In substantiation testing of repair schemes, these phenomena (among others) must be evaluated

Concerns Related to Composite Repair

- Safety concerns of particular relevance to safe composite repairs
  - Repair material compatibility with parent material and manufacturing control
    - Repair material (patch) compatibility with substrate material
    - Adhesive compatibility with substrate and repair laminate materials
    - Bond line thickness
  - Laminate “environmental age”
    - Moisture content, molecular response to saturation, sometimes not possible to mitigate influence of service induced moisture condition prior to bonding repair
  - Bond surface preparation
  - Cure thermal management
  - Composite machining
    - Can inflict collateral damage during material removal
    - Geometric accuracy (such as scarf rate in substrate and and/or poor patch fit-up)
  - Fasteners & installation techniques
  - Restoration of protective surface layers
    - Ultraviolet exposure protection
    - Lightning strike protection
  - Repair process controls (in-process inspection & req’d inspection points)
  - Procedures for quality verification of finished repair
  - Response to manufacturing defect or damage and/or in-service damage
  - Repeated loadings
  - Adequate emulation of rebuild practices with OEM specification

Airworthiness Requirements: Composite Repair
(req's on repair are same as req's on original design)

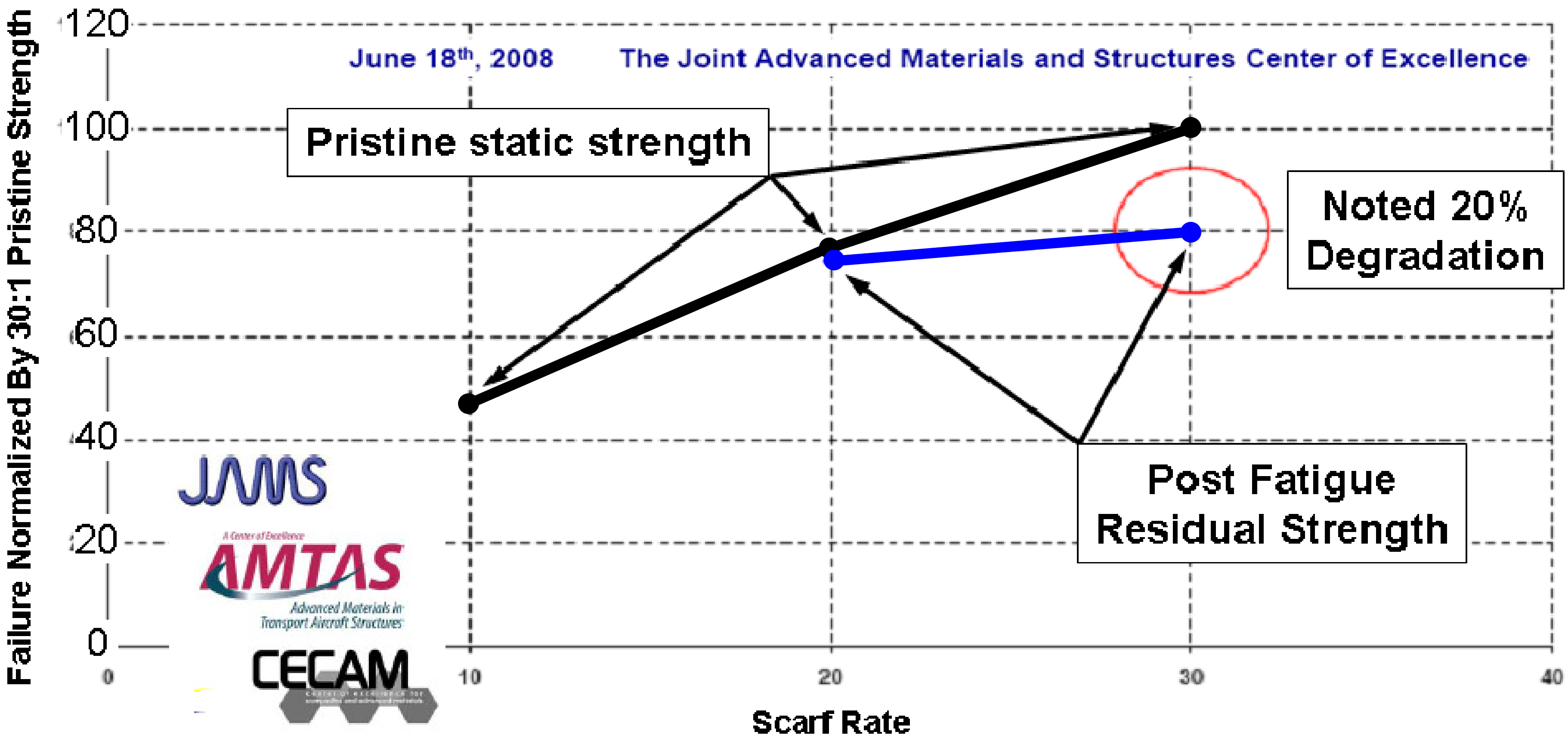
- **Demonstrate structure can…**
  - Sustain ultimate load for at least 3 seconds
  - Sustain limit load without detrimental deformation
  - Sustain repeated loading without significant degradation
  - Resist catastrophic failure due to…
    - fatigue, corrosion, manufacturing defects, or accidental damage
  - Successfully complete flight during which likely structural damage occurs
    - Damaged structure must withstand expected "get home" loads
  - Evaluations must include…
    - Load spectra and environment (temperatures and humidity's)
    - Must also assume existence of flaw of maximum probable size as result of manufacturing and/or service-induced damage
- **Target result: *test evidence supporting analysis methods***

Repeated Loadings / Fatigue (must be accounted for in substantiation testing)

- **Composites have reputation for being insensitive to fatigue**
- **This generally only applies to pristine laminate material acted on by in-plane load**
  - **Fatigue sensitivity may result from likely manufacturing defect or damage**
  - **Adhesive is not inherently fatigue resistant**
  - **Composite bolted joints not inherently fatigue resistant**
    - **Analysis methods must accurately capture individual fastener loads to assess joint capability**
    - **Bearing strength repeated load sensitivities must be understood to predict joint strength**
    - **Hole tolerances must comply with configuration tested in developing allowables database**

Evidence of Scarf Joint Fatigue Sensitivity

- Test results ***suggest*** potential scarf joint fatigue sensitivity (not conclusive but can't dismiss)

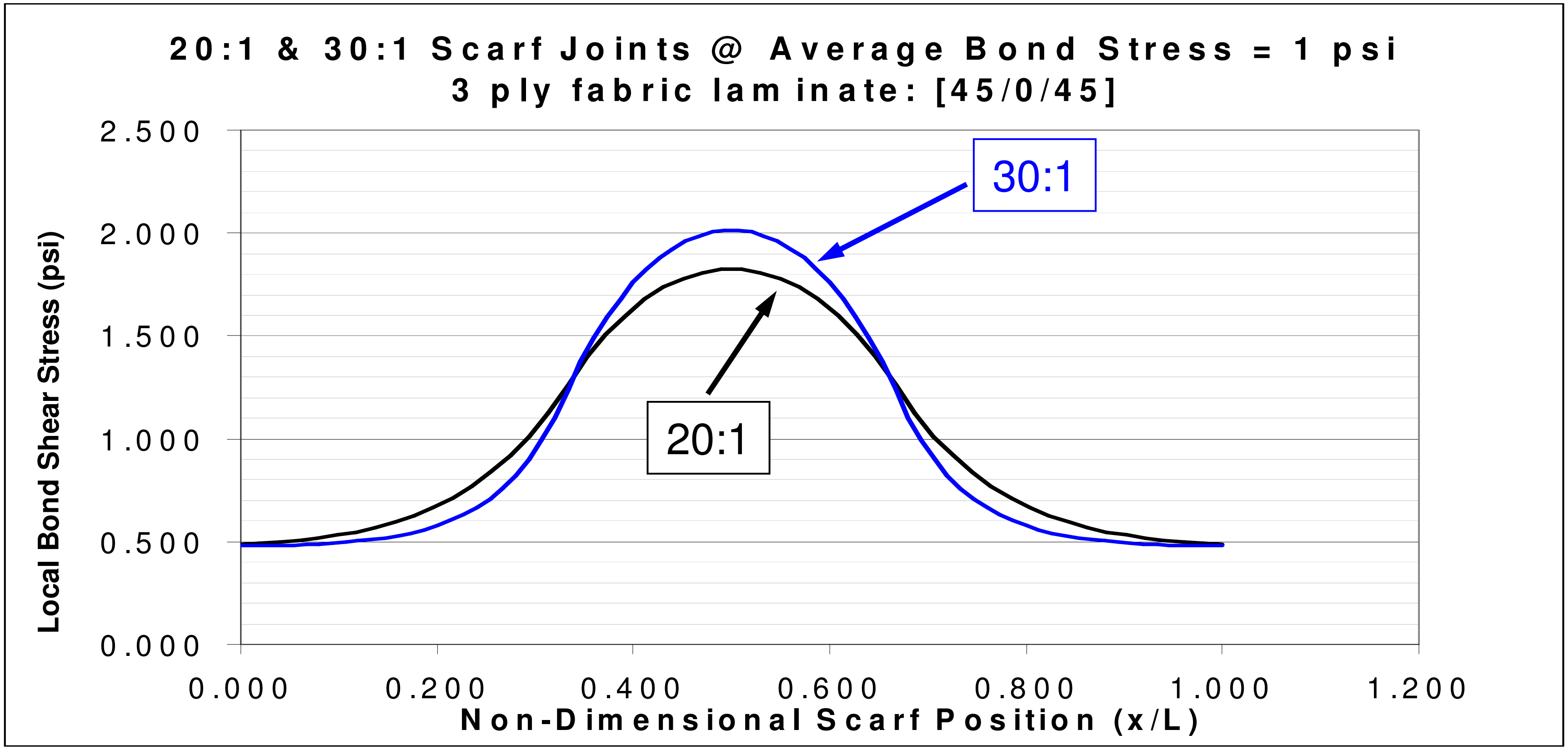


Potential Explanation for Evidenced Scarf Joint Fatigue Sensitivity

- **Shear stress distribution different in 30:1 versus 20:1**

30:1 - Peak bond stress ≈ 2.0 x average bond shear stress

20:1 - Peak bond stress ≈ 1.8 x average shear



Manufacturing Defects

- **Manufacturing defects/damage in repairs can include**
  - **Weak bond** **(no NDI method exists to verify bond strength)**
    - **Contaminants of concern include**
      - **Pre-bond moisture saturation effects**
      - **Chemical contamination**
      - **Perspiration and human factors**
  - **Cure anomalies**
    - **Can effect bond and/or repair laminate strengths**
  - **Fiber mis-orientation**
  - **Scarf joint BVID**
  - **Inaccurate joint geometry**
  - **Inaccurate patch fit-up**

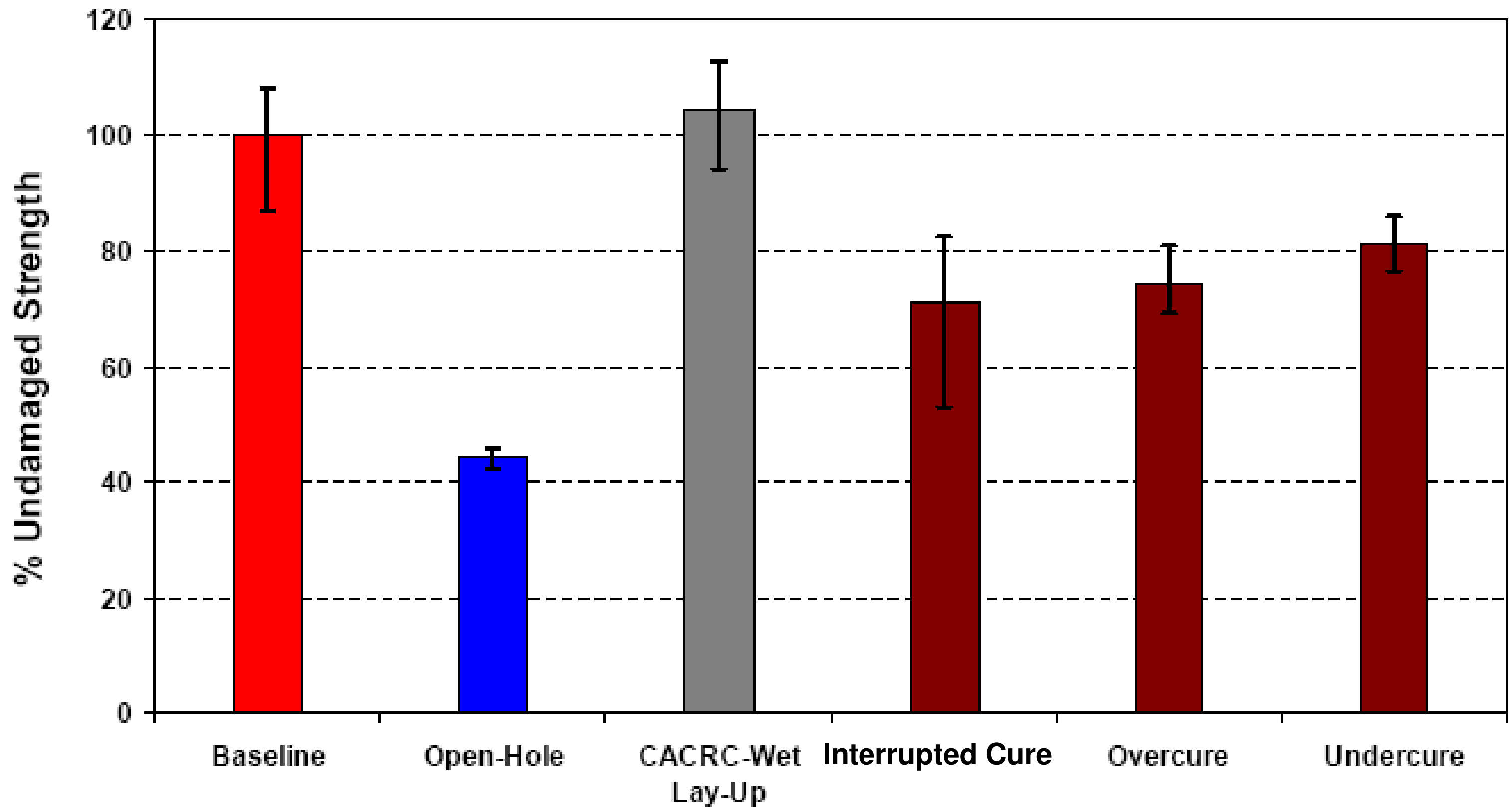
Environmental Effects on Bond Strength

- Substrate laminate moisture saturation can reduce bond strength (even after dry cycle)
  - Literature suggests that epoxies that swell in presence of moisture undergo molecular change
  - Epoxies that do not swell in presence of moisture do not undergo this molecular change
- *Test evidence suggests some laminates exhibit 30% reduction in bond strength as result of this effect
- To successfully predict repair strength, one must have knowledge of laminate response to moisture and subsequent effect on bond strength

*Reference: Joint Advanced Materials and Structures, Test Data Report Out, June 18, 2008

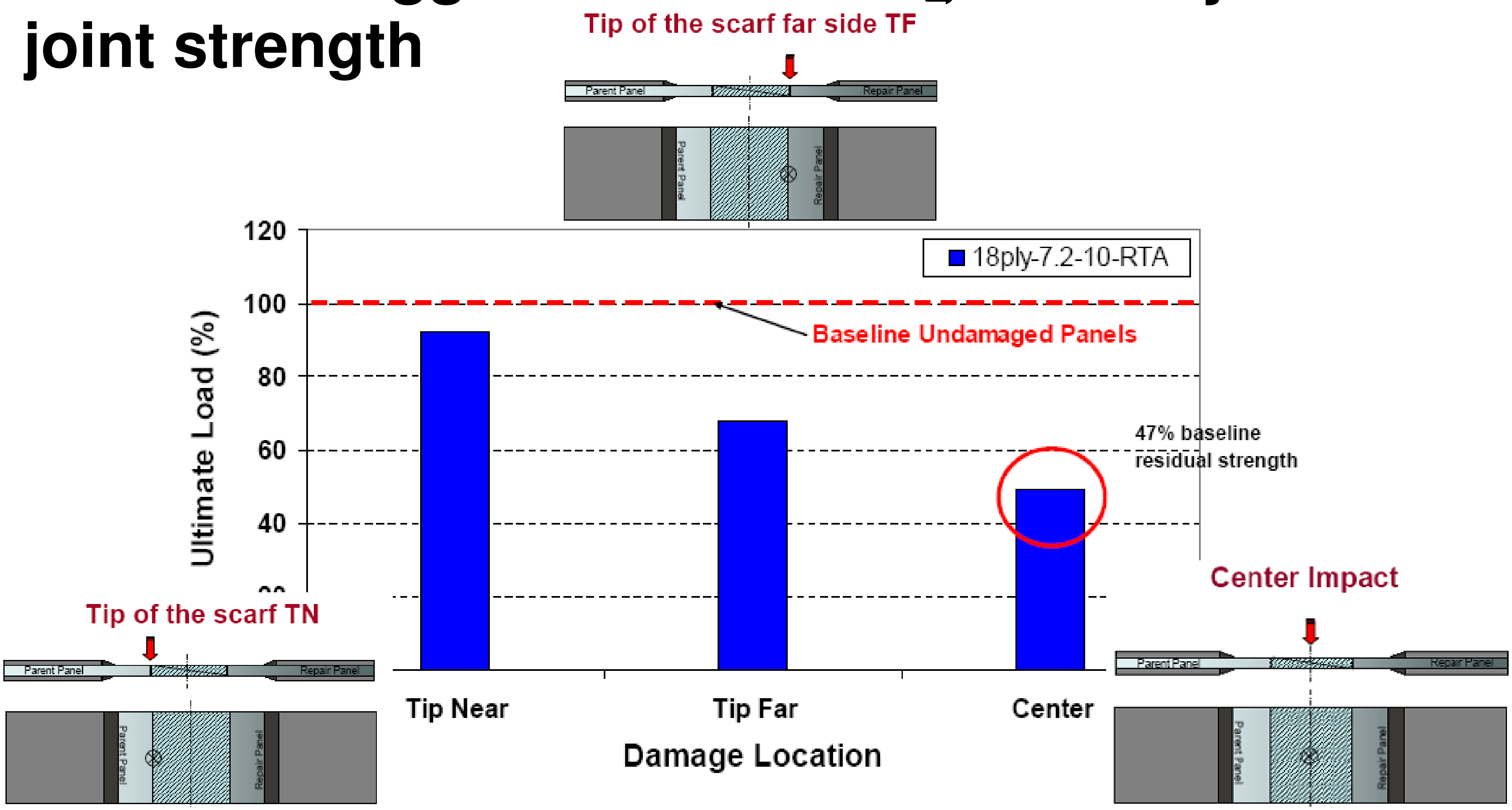
Cure Anomaly Effects on Repair Strength

- Cure error can significantly reduce strength



BVID Effects on Scarf Joint Strength

- Evidence suggest BVID can significantly reduce joint strength



Generic Repair Substantiation Test Requirements

- **In most general case, repair substantiation should include**
  - **Analysis: component analysis and bond stress analysis**
  - **Test Data:**
    - **Characterize process reliability**
    - **Demonstrate repair scheme restores ultimate strength requirement**
    - **Demonstrate limit capability without permanent deformation**
    - **Characterize repair architecture durability (fatigue resistance)**
    - **Characterize damage tolerance of repair architecture**
    - **Characterize damage propagation / evolution behavior**
    - **Characterize damage containment / arrestment behavior**
    - **Characterize effects of likely manufacturing defects**
      - **Must assume presence of defect of maximum probable size**
    - **Characterize environmental effects on strength and durability**

However, for bonded repair…

What is Maximum Probable Defect Size in Bonded Repair?

- Cannot inspect for bond strength, therefore the maximum probable defect size in a bonded repair is ***complete repair failure***
- Therefore, must show capacity for “get home” loads with complete repair failure
- Conclude that bonded repair is size limited
- Magnitude of database required to satisfy substantiation becomes function of load restoration requirement
- In essence is today’s ADL/RDL approach

The following repair substantiation approach should not be construed as conforming with existing guidance or standard policy

Consider Categories of Damage

1) Damage allowed without action for life of aircraft

- **Ultimate capability unaffected for life of aircraft**

➔SAFE FLIGHT DAMAGES

2) Damage detected during scheduled inspections

- **Limit capability retained through maintenance interval**

➔ SAFE FLIGHT DAMAGES

3) Damage detected within a few flights

- **Limit capability retained until detected**

➔ SAFE FLIGHT DAMAGES

4) Damage prompting pilot action

- **"Get Home Loads" capable with pilot intervention (manage flight loads)**

➔ FLIGHT ENVELOP LIMITING DAMAGES

5) Damage beyond design validation envelop

➔ **OUT OF SERVICE UNTIL REPAIR APPROACH IS VALIDATED**

Classification of Repairs by Structural Demand

- **Consider repair "*class*" breakdown**
  - **It is conceded that this may not be best class breakdown**

Category of Damage	Substantiation Considerations	Class of Repair	
Category 1: Damage that may go undetected by field inspection methods (detection not required)	Demonstrate reliable service life. Retain ultimate load capability. Used to define retirement.	***Class 1:*** Ultimate capability with repair failed.	**ADL**
Category 2: Damage detected by field inspection	Demonstrate reliable inspection. Retain limit load capability. Used to define maintenance	***Class 2:*** Limit capability with repair failed. Ultimate capability with repair intact.	**RDL**
Category 3: Obvious damage detected within a few flights	Demonstrate quick detection. Retain limit load capability. Used to define operations actions		
Category 4: Discrete source damage and pilot limits flight maneuvers	Define discrete-source events. Retain "Get Home" capability. Used to define operations actions.	***Class 3*** Beyond current **bonded repair** technology state-of-the-art Bolted Repair?	
Category 5: Severe damage created by anomalous ground or flight events	Repair generally beyond design validation (known to operations). May require new substantiation		

Substantiation of “Class 1” Repair

Class 1 ≡ Ultimate capable with repair failed

- Substantiation approach
  - Analysis
    - Ultimate residual strength & adequate durability ʷ/repair failed
  - Required test evidence (taking into account “environmental age”)
    - Proof that repair process does not degrade parent structure
    - Proof that repair restores original environmental resilience
- Meets FAR Requirements
  - ✓ Limit load can be sustained
  - ✓ Ultimate load can be sustained
  - ✓ Repeated load can be sustained
  - ✓ Damage propagation will not cause catastrophic failure
  - ✓ Catastrophic failure will not occur as result of defect / damage
  - ✓ Successful completion of flight with probable damage

Substantiation of "Class 2" Repair

- Class 2 repairs ≡ Limit capable without repair
  - Substantiation approach
    - Analysis
      - Demonstrate limit load capability w/o perm. def. and appropriate durability with repair failed
      - Demonstrate restoration of ultimate capability with repair intact
    - Required test evidence (taking into account "environmental age")
      - Proof repair process does not degrade substrate structure
      - Proof repair provides strength increment from limit to ultimate (all env's)
      - Proof that failure of repair does not lead to uncontrolled damage propagation
      - Proof repair restores original environmental resilience
  - Meets FAR Requirements
    - ✓ Sustain limit load without permanent deformation
    - ✓ Sustain ultimate load
    - ✓ Damage propagation will not cause catastrophic failure
    - ✓ Successful completion of flight with probable in-flight damage

Substantiation of “Class 3” Bolted Repair

- Class 3 (Bolted Repair)
  - Analysis
    - Patch strength and durability
    - Joint strength and durability (patch and parent)
  - Required test evidence
    - Characterize repair material strength and fatigue resistance
    - Characterize parent material bearing and bearing bypass strength and fatigue behavior
    - Characterize repair (patch) material bearing and bearing bypass strength and fatigue behavior

<u>Component "Rebuild"</u>

- **An additional class of repair might be "*component rebuild through emulation of OEM manufacturing approach*"**
- **If <u>strict compliance</u> with OEM processes can be demonstrated then arguable that original design substantiation covers "rebuild repair"**
  - **Proof of emulation requires**
    - **Demonstration of equivalent raw materials receiving, storage and tracking**
    - **Qualified facilities and personnel**
    - **Appropriate inspection personnel and appropriate inspection points in process**
  - **Only true if original materials and processes are used**

What is Motivation for Class Approach?

- The approach is nothing profound. It only sets stage for standardization of existing repair substantiation approach
- Provides clear bonded repair application limits
  - However, must be closely linked with specified levels of repair skills for maintenance personnel and repair conditions in the field
- Airline operators have expressed desire to have latitude to substantiate substitute materials for bonded repair
  - Class approach potentially minimizes substantiation data requirements as function of repair criticality to flight safety
  - Potentially minimizes magnitude of task (and cost) of substantiating substitute repair materials
- Airline operators have demonstrated that rebuild is necessary option and occurs frequently on components on today's legacy fleet
  - If documented standard approach is put in place then the safety of this practice can be enhanced

Component Classification

- Further flexibility in preforming repairs may be achievable by categorizing components by level of criticality
  - Criticality to aircraft safety
  - Criticality to ground safety (PDA)
- Current PSE, SSE, Major, Minor deemed by some to be inadequate breakdown and may cause bad precedents

Categorization of Composite Parts

(Categorize by criticality to safety/airworthiness)

- ***“I just found another PSE being 'remanufactured' at an MRO with 'Minor Repair' approval during an audit. 'Engineering judgement' would indicate that remanufacture of this part (an engine structure) was reasonable action. However, this is setting a bad precedent. We need to define and control such activities more effectively. The OEMs could help by providing an adequate break-down of structure classification and definition in the SRM (recognizing the problem that such a document could be very long and unmanageable!)”***

Summary

- A paper trail documenting repair history must exist for all composite repairs on a given part
- Many fundamental concerns must be understood and addressed in repair of composite structures
- To predict repair bond strength one must understand influence of service environment including repeated loading, moisture saturation, manufacturing defects, and probable service induced damages
- Airworthiness criteria is same for repaired composite structures as for original design
- Bonds cannot be NDI'd for strength
- Classifying repairs into discreet classes based on category of damage may enhance repair station flexibility and provide increased options for performing composite repairs with materials common to individual qualified repair stations (with appropriate substantiation testing)
- Component rebuild is fact of life and should be regulated through standards, guidance, and policy to ensure strict compliance with OEM materials and processes, and to it is performed only when genuinely appropriate

END

Thank You For Your Attention!