Composite Bonded Joints Analysis, Data, and Substantiation

- Industry Directions and Technical Issues -

FAA Composite Bonded Joints Workshop
Seattle, WA   June 16-18, 2004

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NSE COMPOSITES

Introduction

- **D.M. Hoyt**, NSE Composites
  - *NSE since 1995, Boeing 777 before*
  - *US Army/Bell Helicopter*
  - *Boeing CAI, AIM-C program, and 7E7*
  - *Wind industry - blade root joints*
  - *Actively working to implement fracture technologies, quasi-static and fatigue growth*

Most experience is in commercial transport but also active in applied R&D

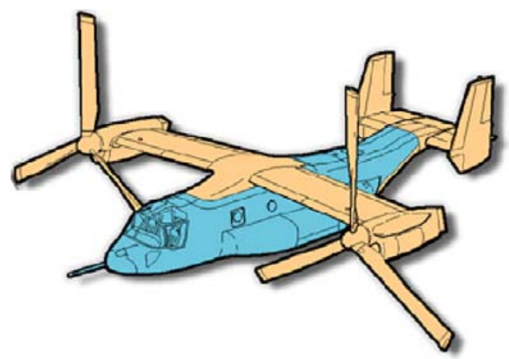
- **Steve Ward**, SW Composites
  - *SWC since 1999*
  - *Boeing 777, Composites Methods and Allowables group*
  - *Active in Mil-Handbook-17 since 1996*
  - *Currently involved in composite material control, design allowables, repair design and analysis*

Applications and Focus

Workshop Primary Objective: *"Collect & document technical details that need to be addressed for bonded structures, including critical safety issues and certification considerations"*

- Range of Applications
  - *No focus on specific applications.*
  - *Many different types of bonded structures.*
  - *Wide range of configurations and loading.*

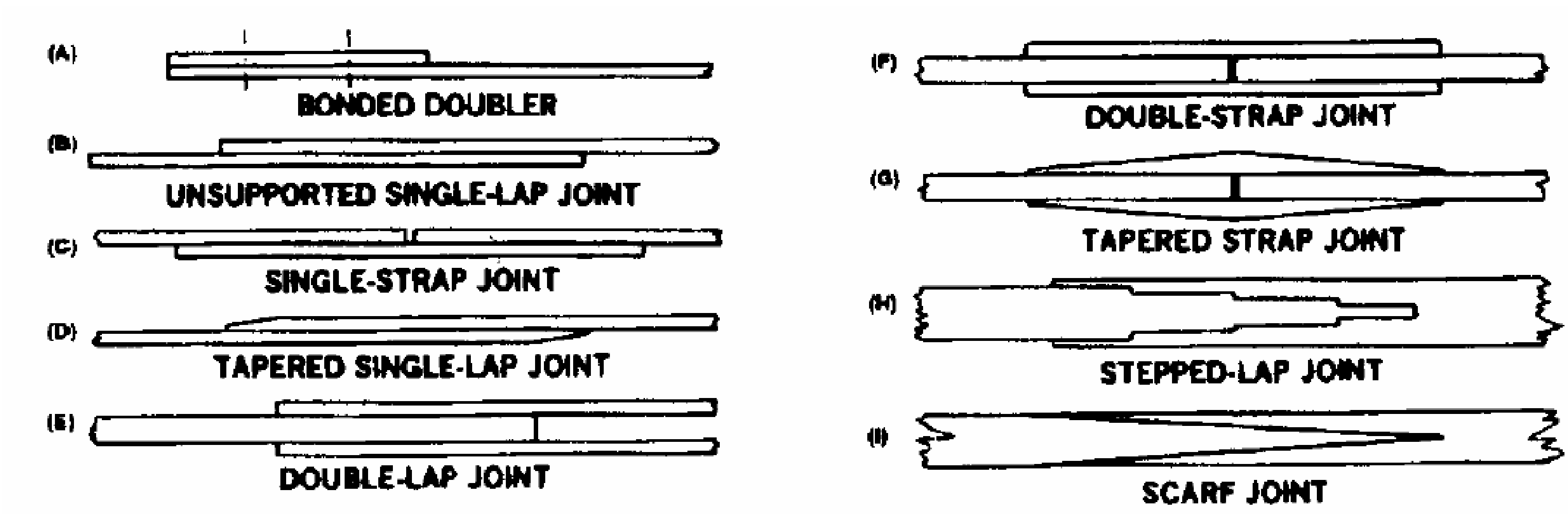
- Focus
  - *Analysis and data needs for range of applications.*
  - *Highlight the need for a range of tools in the industry "toolbox".*
  - *Address the technical issues of each.*



Lap Joints

- Lap joints with primarily uni-axial, in-plane loading are often the focus of bonded joint analysis methods and allowables testing.

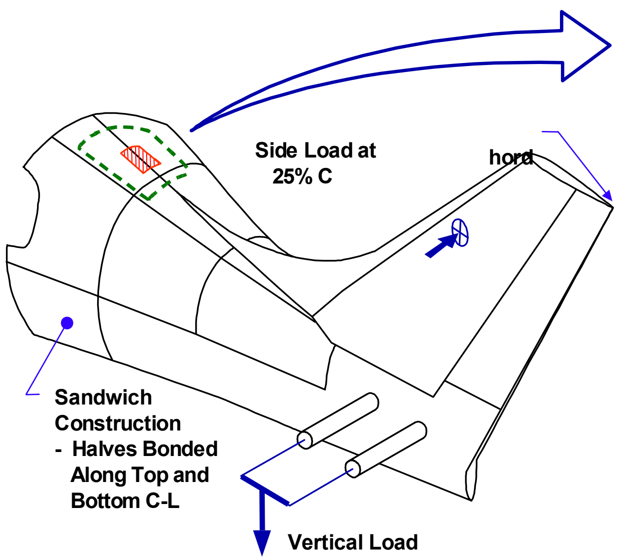
"Bonded Joints"

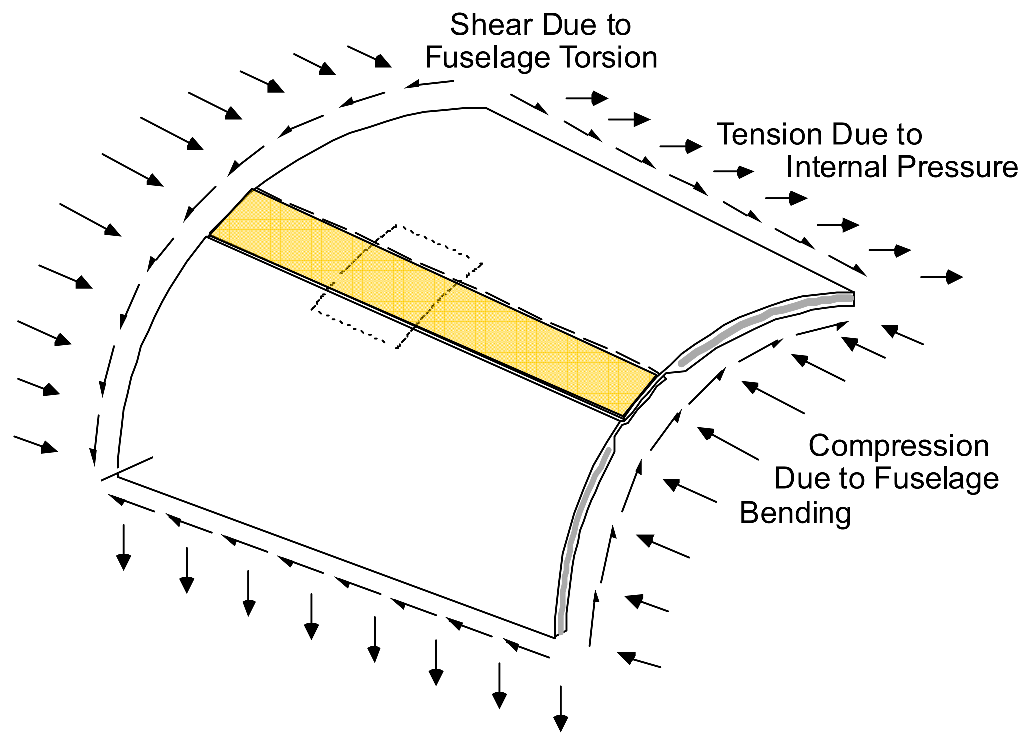


General Aviation Bonded Joints

- Sandwich structure with solid laminate edgebands at bonded joint.
- Loading can be multi-axial
- High load transfer, low loads

High in-plane load transfer, multi-axial loading but “low” loads.



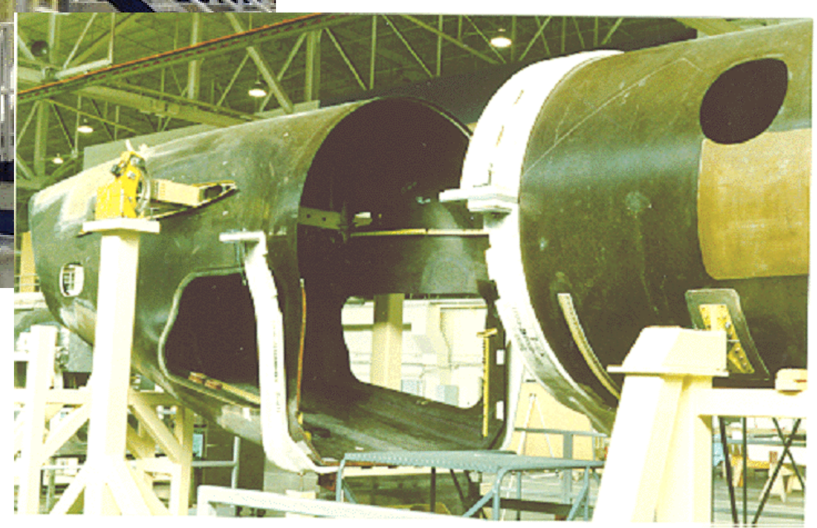


General Aviation Bonded Joints

- Continuous sandwich structure with a few major bonded-bolted joints

Structures with large-area continuous bonded facesheets may have different analysis and data needs.

Raytheon Premier I

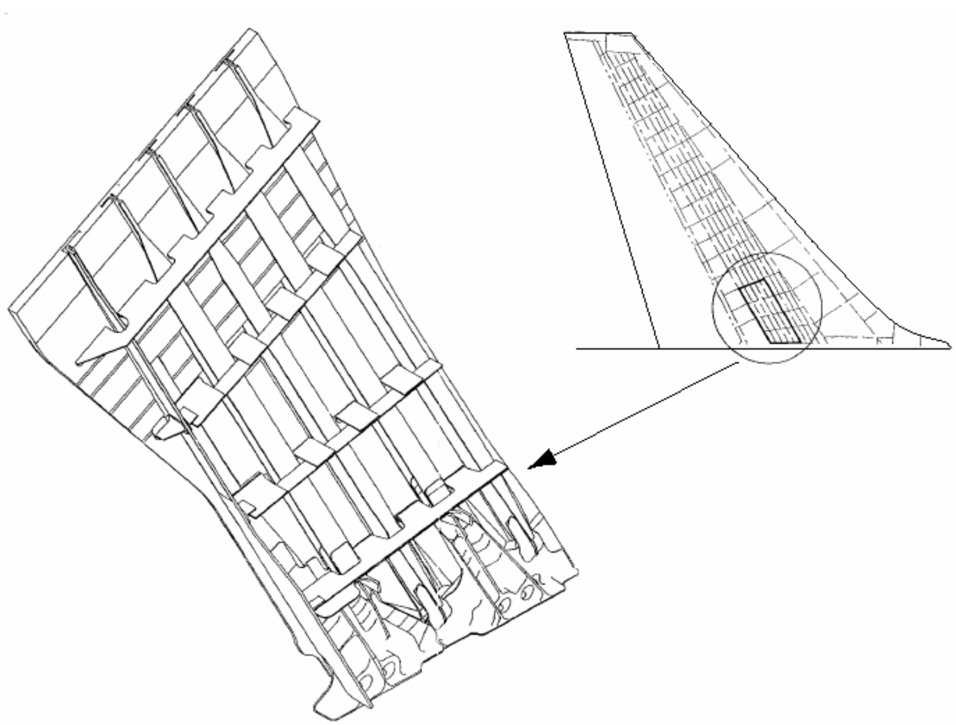


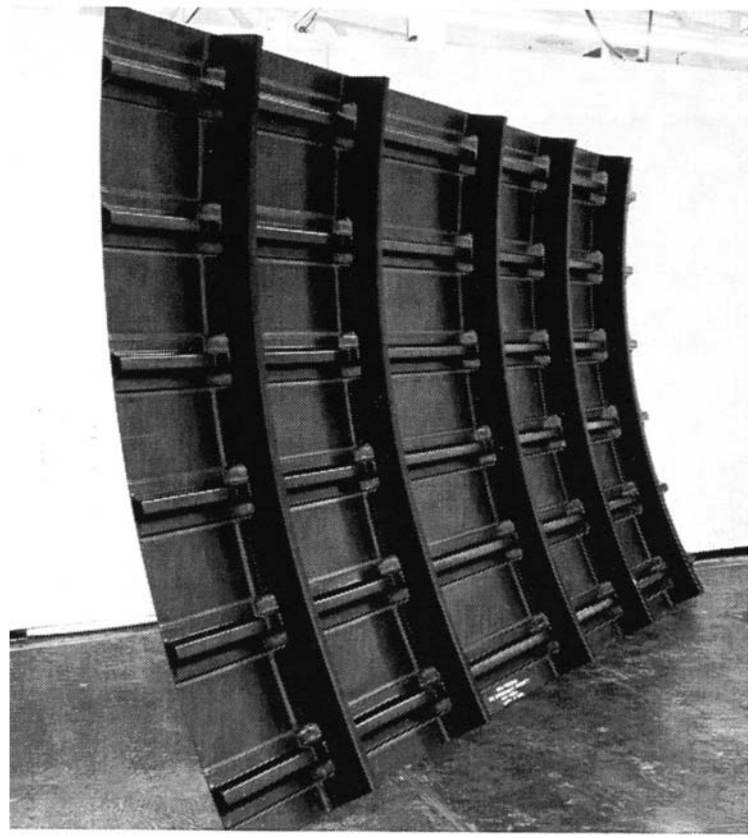
Reference to Ric Abbott presentation to Mil-17, October, 1999

Commercial Transport Bonded Joints

- Typically no bonded joints in high load transfer configurations
- Integrally stiffened structure

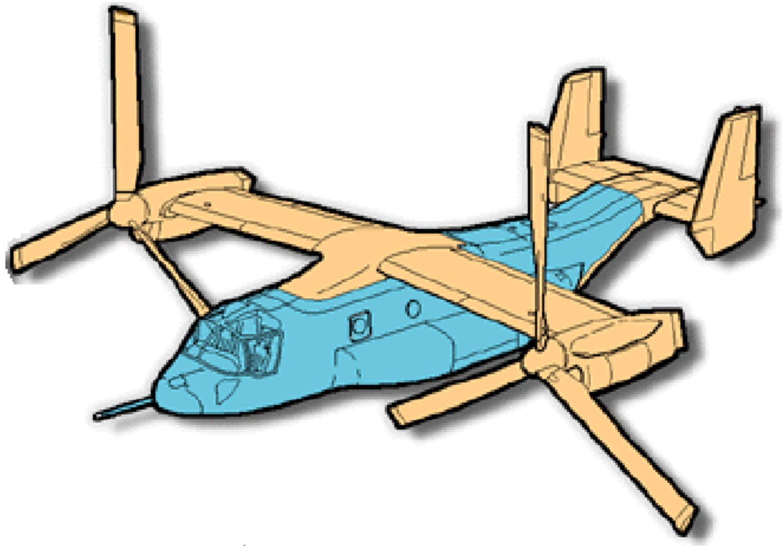
Integrally stiffened structure - high loads, low in-plane load transfer.



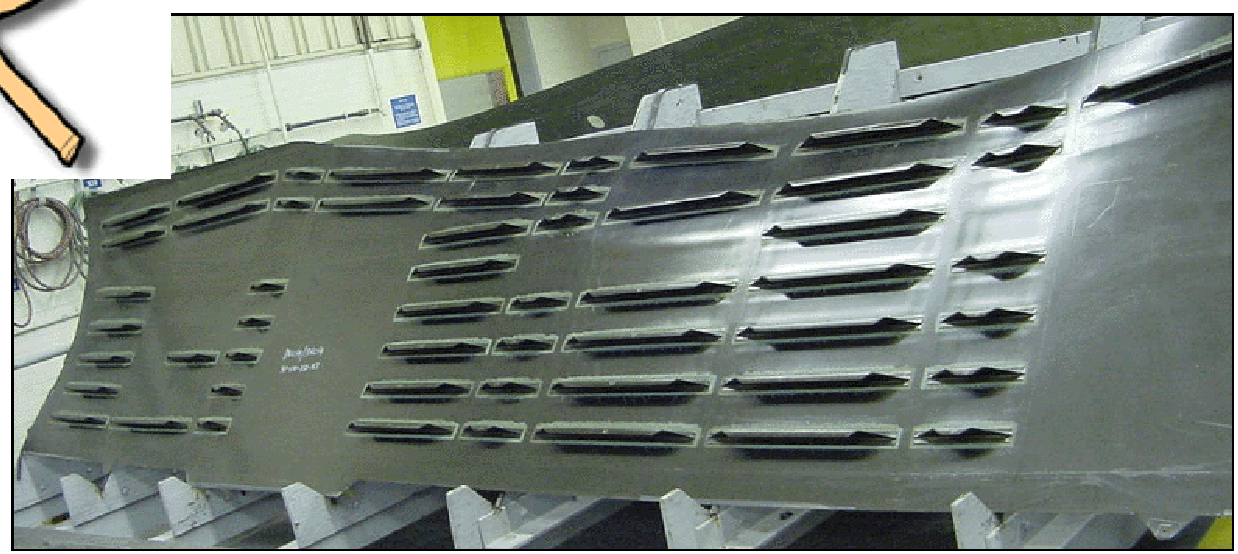


Rotorcraft Bonded Joints

- Fuselage often has thin skins with co-cured stiffeners
- Post-buckling behavior generates severe stresses on the bondline between skin and stiffeners. Pressure loads also load bondline.



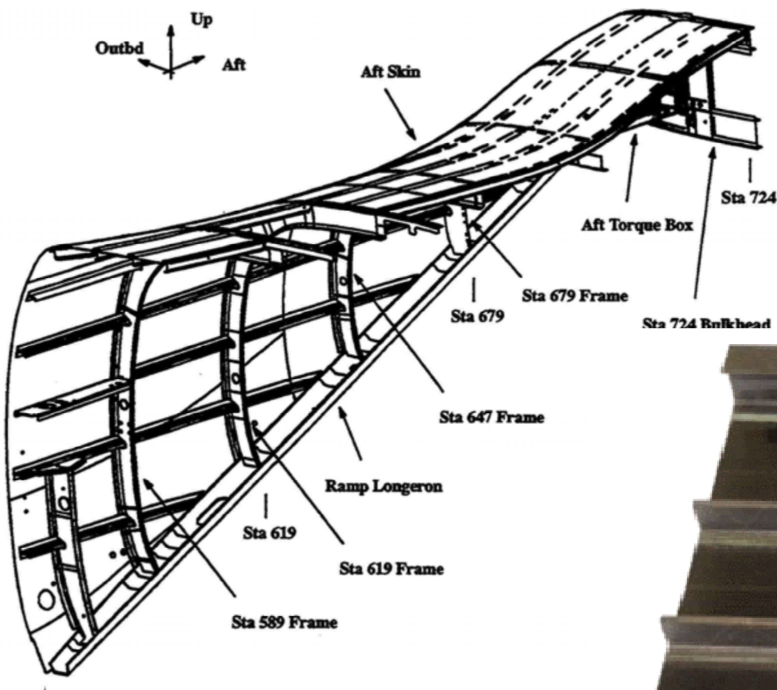
Integrally stiffened structure with out-of-plane loads.



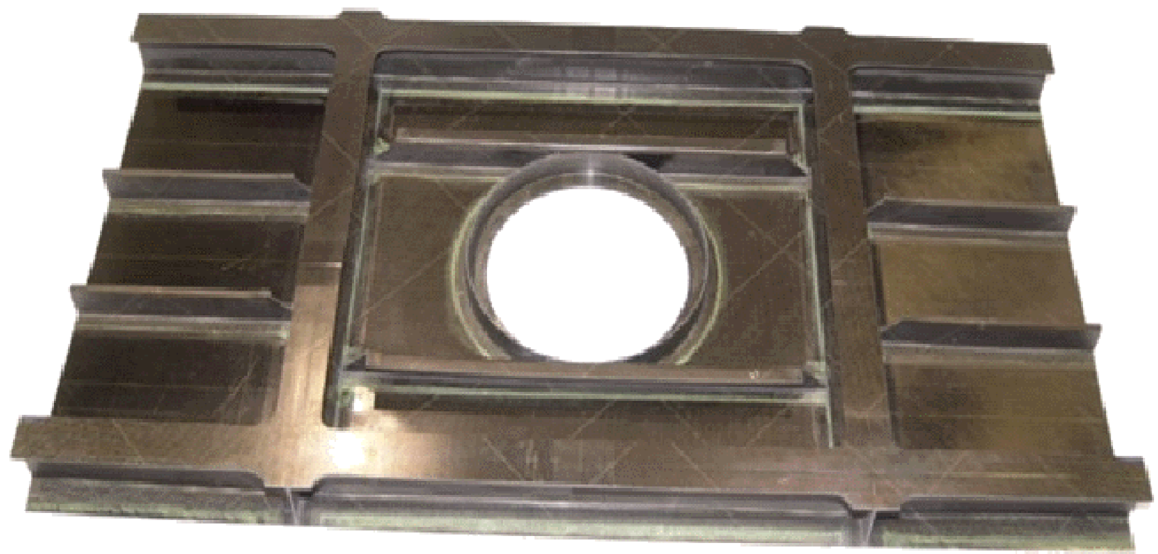
Reference: Minguet, Pierre, presentation to ASTM/FAA Workshop on Fracture Mechanics for Composites, SLC, March 2004

Integrated Composite Structures

- Drive to reduce manufacturing costs leading to highly integrated structures
- One-piece co-cured skin/frames/longerons



Is a co-cured structure with no adhesive be a “bonded joint”?



BOEING Philadelphia

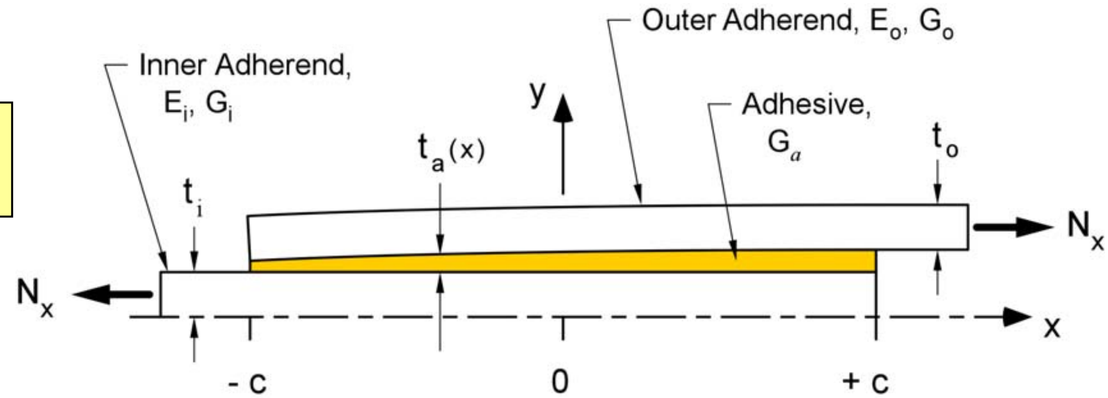
PHANTOM WORKS™

Reference: Minguet, Pierre, presentation to ASTM/FAA Workshop on Fracture Mechanics for Composites, SLC, March 2004

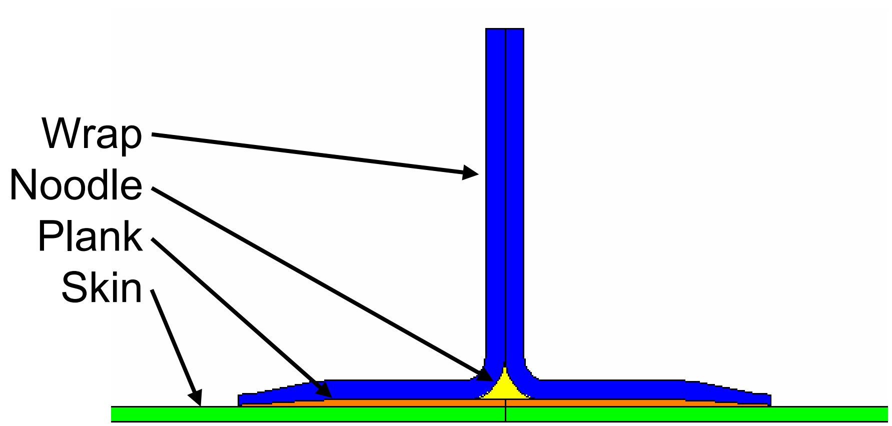
Bondline Thickness Range

- Bondline thickness
  - *General Aviation - paste adhesive up to 0.20"*
  - *Commercial/military film adhesive 0.007" , cobonded, co-cured (possibly no adhesive)*

General Aviation bonded joint with **thick adhesive**.



Recent T-joint model with **no adhesive.**



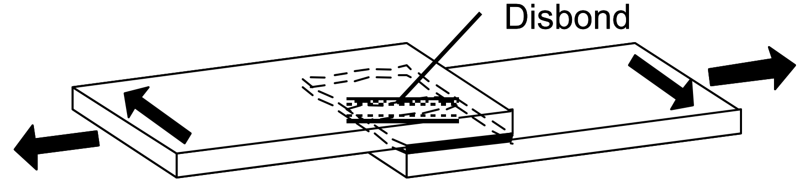
T-Joint Model

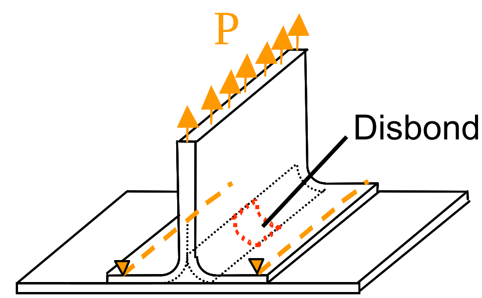
Overview - Analysis, Data, and Substantiation

- Design/Flaw Criteria
  - *Certification requirements*
  - *Flaws, damage, NDI threshold*
- Analysis Methods
  - *Closed-form eqns, A4EI, 2D vs. 3D, FEA*
  - *Failure criteria*
  - *Fracture, VCCT*
  - *Durability, damage tolerance*
- Design Data and Allowables
  - *Material properties for analysis*
  - *Design allowables, statistics*
- Substantiation
  - *Validate design, manufacturing processes, analysis methods*
  - *Satisfy certification requirements*
- Summary of Issues
  - *Safety critical items*
  - *Open issues, need for guidelines, R&D*

Design/Flaw Criteria

- Criteria drive analysis, data needs, and testing.
  - *Certification plan is based on agreed criteria*
- Likely and unlikely damage threats.
- Acceptable (or undetectable) manufacturing flaws.
- Potential process variations over time.





- In large-scale integrated composite bonded structure, flaws and damage may not be readily detectible.
- Typical 'metals' indicators not there. (e.g., missing bolts, through cracks)

⇒ **Set design criteria accordingly**

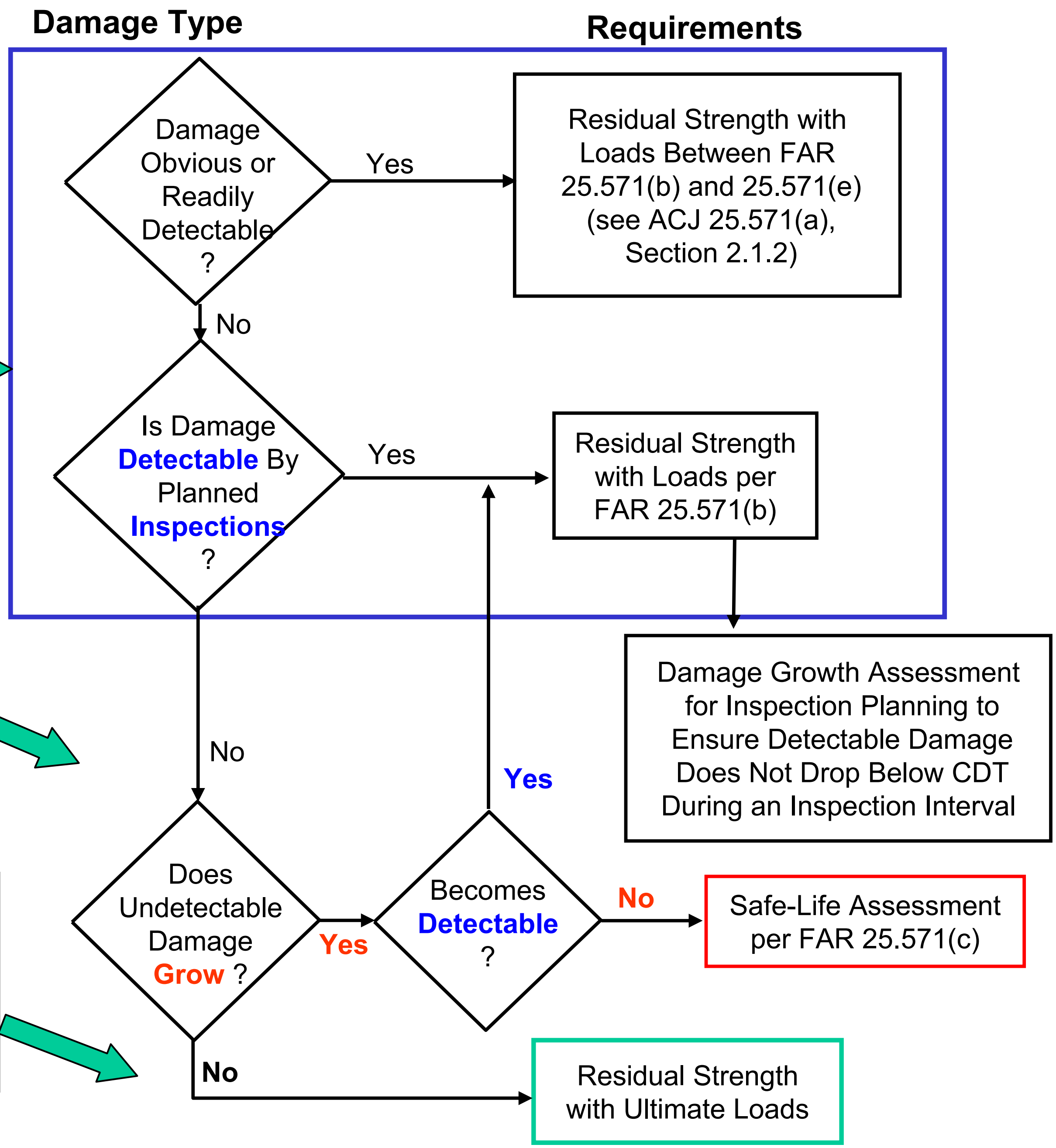
Regulatory Perspective

For Composites, Damage Tolerance focus is on residual strength - not damage growth (Blue Box)

Inspections generally by visual "Surveillance"

No detrimental damage growth allowed (typical), Safe Life not used. (Red Block)

Initial flaws (e.g. disbonds) and BVID considered an Ultimate Load criteria (Green Block)



Design/Flaw Criteria - Examples

Commercial Transport Bonded Skin/Stringer

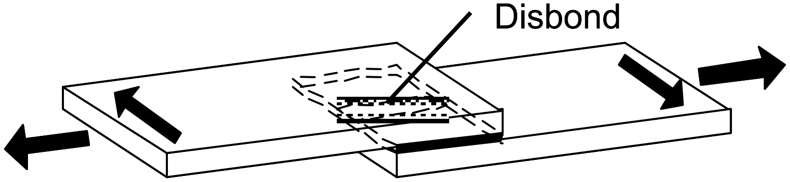
- *Initial flaws - BVID rogue flaw (covered by 0.25 inch OHC),*
  - 0.50 by 0.50 inch disbond,
  - 0.25 inch by "any length" disbond
- *Visible Impact - size (CAI) at chosen energy (includes delam/disbond in stringer)*
- *Large damage - 1 stringer/1 rib bay (covers for debonded stringer?)*

Good for Ultimate Load (initial flaws)

Good for Limit Load or "get home" loads (visible impact and large damage)

Anything that takes structure below Ultimate capability must be **rare**. (or readily detectible)

Design/Flaw Criteria - Issues



- Damage tolerance issues
  - *integrally related to probability of detecting damage-- but lack of related service history*
  - *lack of traditional flaw and damage indicators (bolts, cracks)*
  - *lack of economically feasible in-service NDI*

- Design issues
  - *How big of damage (debond) size must structure be good for?*
  - *At what size does the "no growth" assumption break down (growth at operating loads occurs)?*
  - *When to design with redundant features?*
  - *Experience is thin relative to metals - difficult to ID bad details*

- Repair size limits for primary structure
  - *in-service process control and reliability*
  - *in-service inspection capability*
  - *how does redundant philosophy hold up in repair?*

Appropriate to use criteria to deal with large area process failures?

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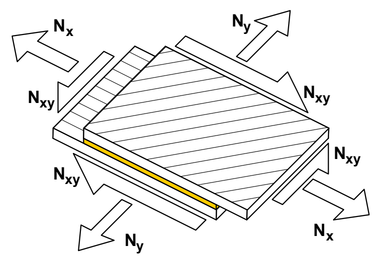
Analysis Methods for Composite Bonded Joints

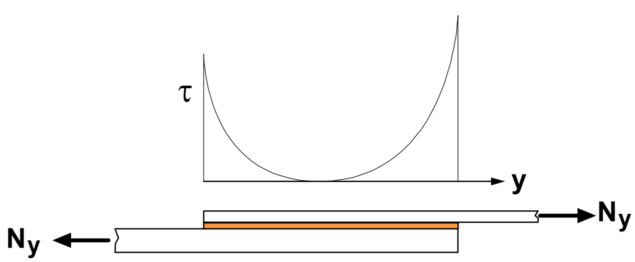
Overview of range of methods and objectives of analysis

Stress-based methods

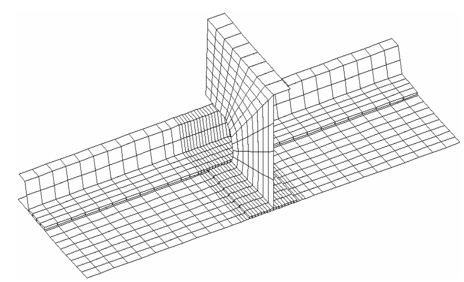


Fracture-based methods

- Average stress cutoff (P/A Closed-form linear (Volkerson, etc..)
- Closed-form non-linear (Hart-Smith/A4EI, etc..)
- 2D and 3D FEM, StressCheck
- Stress failure criteria



- FEM/VCCT (I/F elements)
- Closed-form (CTE, SUBLAM, etc..)
- Fracture failure criteria



Stress-Based Analysis

Average Stress

- Average stress cutoff (P/A), e.g., 500 psi
- True joint strength is insensitive to bond area

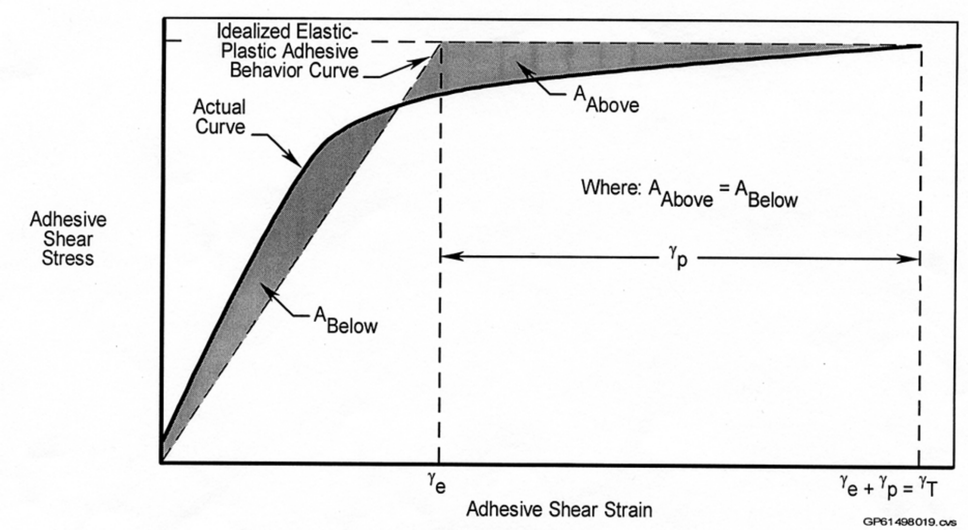
Closed-form Linear

- Volkerson (1938) established non-uniform load transfer
- Extended and modified by many others (Goland-Reissner, Oplinger, others)

Closed-form Non-Linear

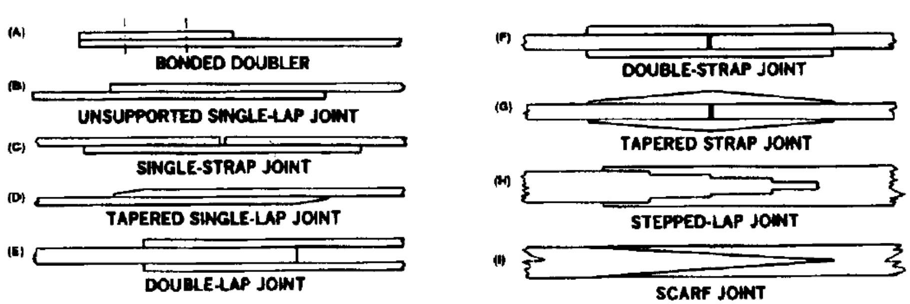
- Hart-Smith, A4EI, and numerous extensions
- Elastic-plastic adhesive

Non-linear w/elastic-plastic adhesive is industry baseline.



Computer Codes for Analysis of Bonded Joints

Sl. No.	Analysis Code	Agency/Developer (Year)	State-of-stress	Applications
1.	JOINT	A. F. /McDonnell D. (1978)	1-D	Single lap, double lap, scarf and step lap joints
2.	JTSDL/ JTSTP	A. F. / SwRI (1972)	2-D	Single lap, double lap and step lap joints
3.	BOND3/ BOND4	A. F. /U. of Delaware. (1974)	2-D	Single lap joints
4.	BONJO I	A. F. /Lockheed (1972)	2-D	Single and double lap joints
5.	A4EI	A. F. /McDonnell D. (1982)	1-D	Stepped lap and doubler joint repair
6.	PGLUE	Navy/McDonnell D. (1987)	2-D	Bonded joint repair
7.	SAVE	Air Force/AdTech (1996-)	2-D/3-D	2-D/3-D generalized coordinate FE structural analysis using variable-order elements.



Many analysis methods focus on lap joints and doublers.

Reference: Rastogi, N., Bogdanovich, A., Soni, S, "Stress Analysis and Strength Prediction of Adhesively Bonded Composite Joints", AFRL-VA-WP-TR-1998-3027.

Stress-Based Analysis (cont'd)

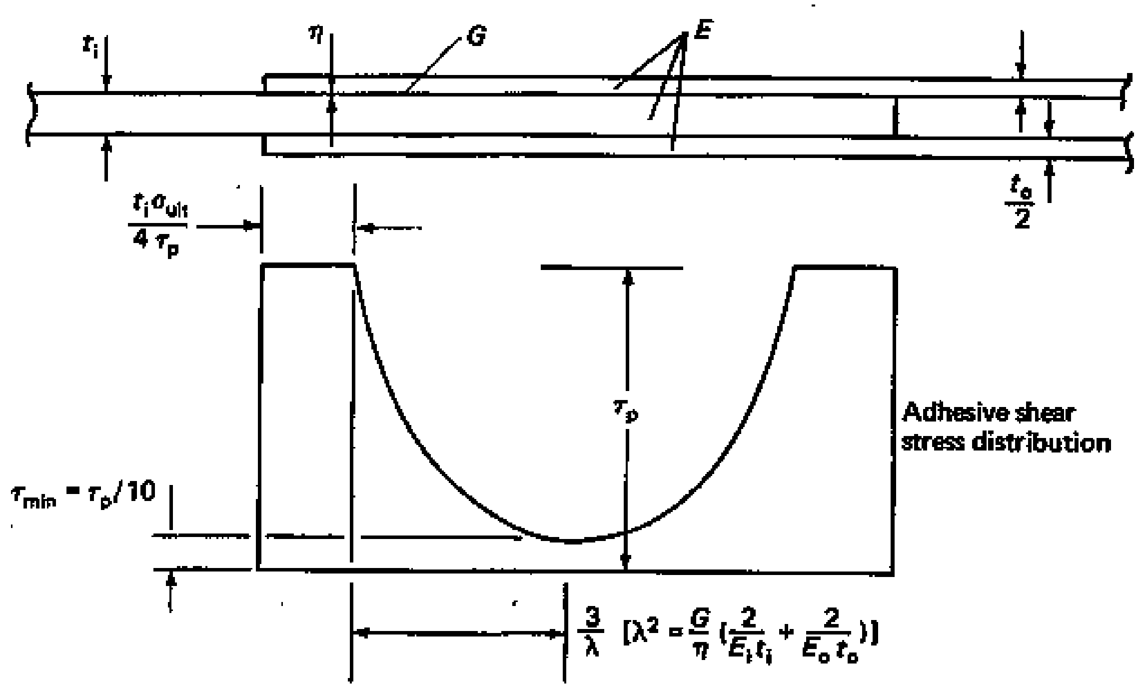
"Rules of Thumb" with elastic-plastic solution used to size joint overlaps.

Use "Rules of Thumb" to Size Overlaps

- *Bond overlap sized based on elastic and plastic lengths*
- *Size bond for up to 50% higher load capability than adherend*
- *Minimum stress target = 10% of adhesive yield stress*
- *Low stress region to avoid creep rupture (adhesive in elastic region "pulls" the joint back after unloading)*
- *Low stress region also increases flaw tolerance*

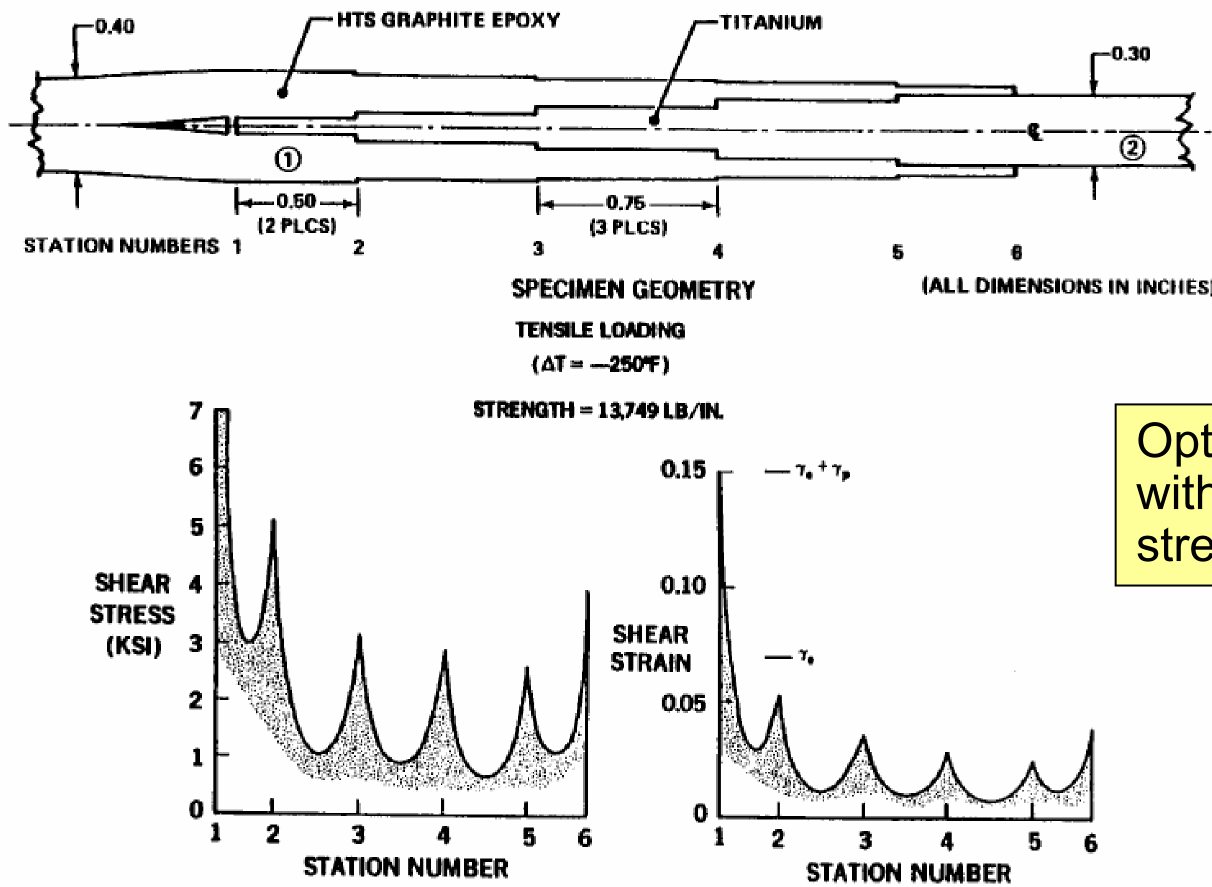
Environmental Conditions

- *Limit to strength based on cold/dry*
- *Required overlap length based on hot/wet*



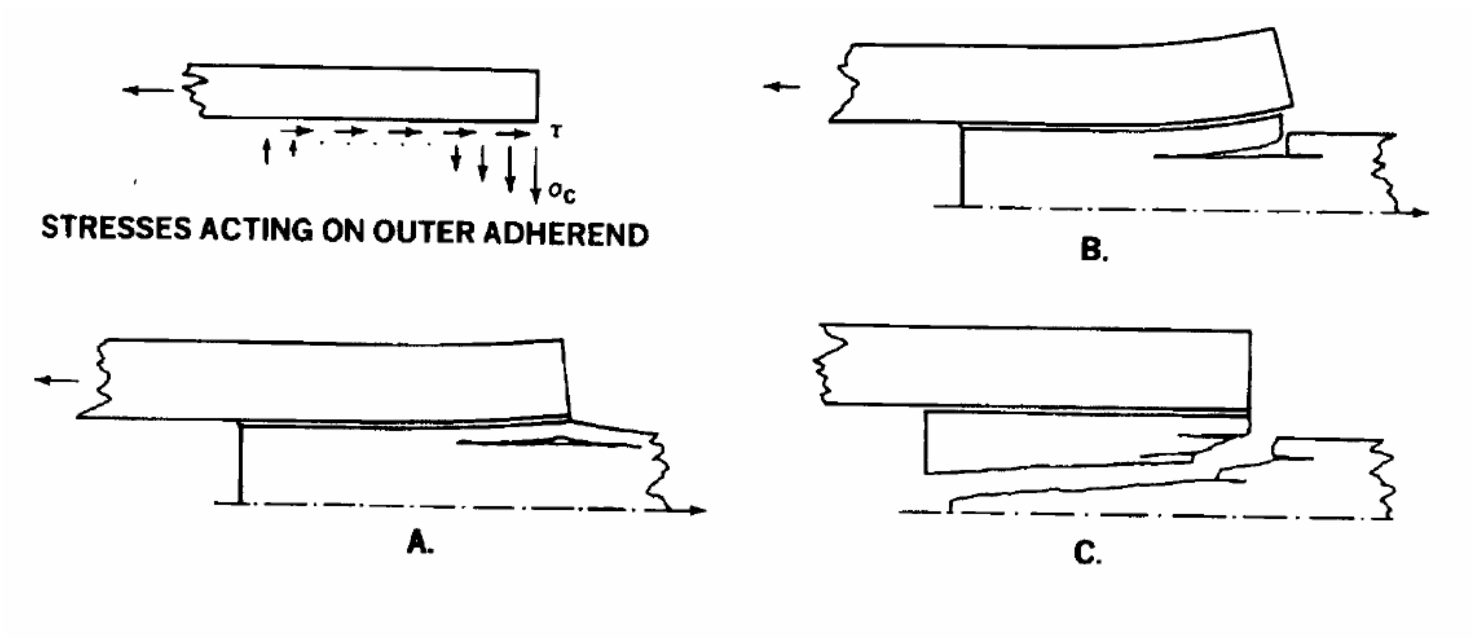
Stress-Based Analysis (cont'd)

Structurally optimized joint based on A4EI-type analysis



Optimized design with minimal peel stresses.

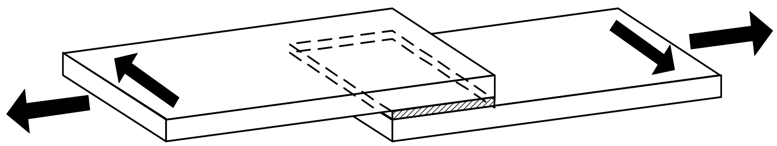
Composite Adherend Failure Modes



What if peel stress is a driver or if adherend failure modes need to be considered?

Static Strength Analysis Roadmap

May need more detailed stress-strain field (including peel) to use with failure criteria.

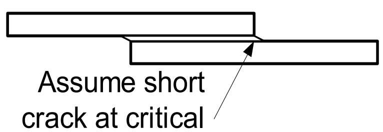


Combined Loading
- shear + axial
- requires linear analysis for easy superposition of load cases

Static Strength Analysis

Adherend Check
- closed form methods
- interlaminar stress check
- simple fracture mechanics analysis
  - small initial flaw
  - calculate G_{onset}

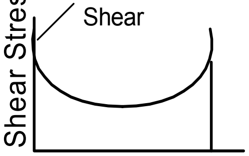
Closed-Form Stress Analysis
- A4EI, UCSB Shear & Multi-axial, etc.
- Linear properties for adherend, elastic/plastic for adhesive



Assume short crack at critical ply interface

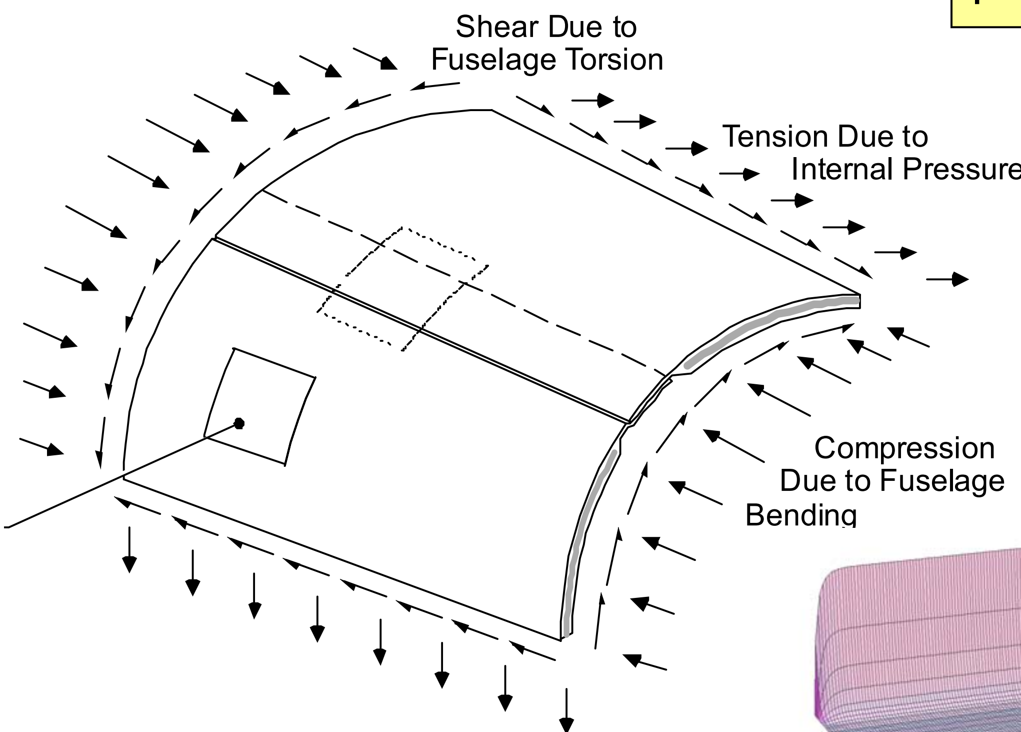
Adhesive Check
- peel stress
- shear + axial stress
- stress interactions
- effective stress design values
- limit peak shear to elastic limit of adhesive

Strength Margins
- Adhesive
- Adherend

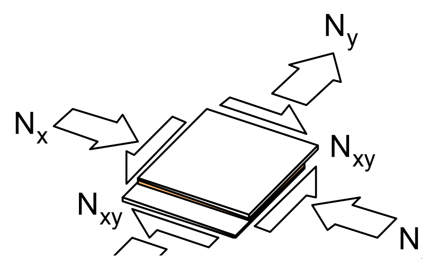


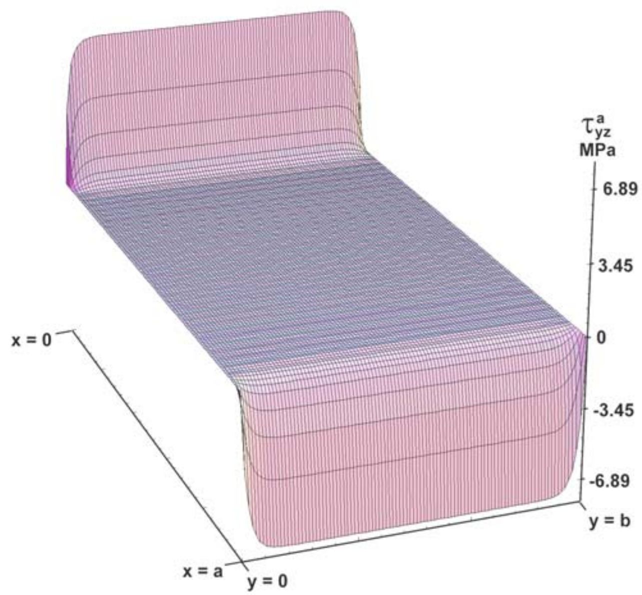
Multi-axial Joint Loading

Closed-form solutions for multi-axial loads can be used produce adhesive shear and peel stress distributions.



Segment of Joint Loaded by Biaxial Tension/Compression and Shear

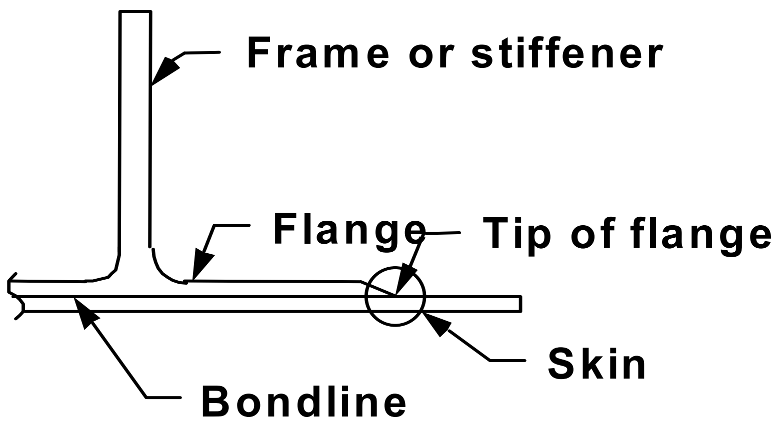


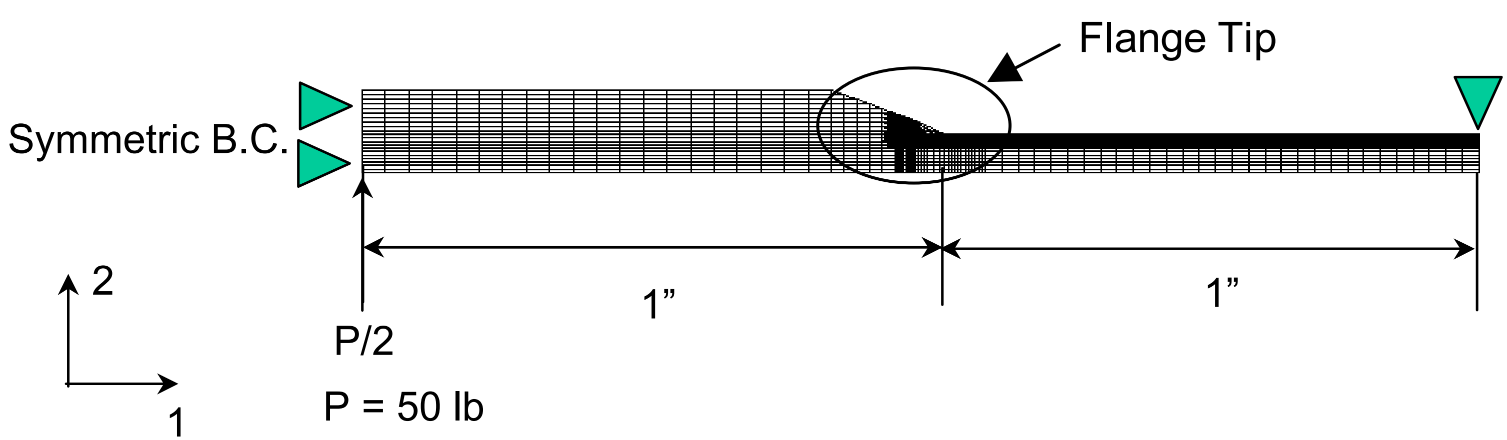


Reference: Hyonny Kim, Purdue University

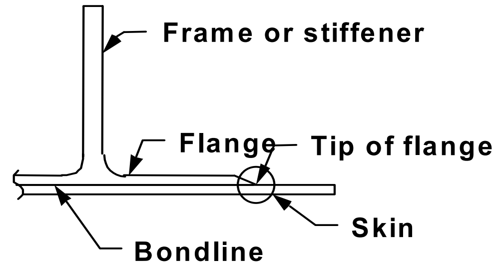
Skin/T-Stiffener FE Model

Local FEM used to assess stress-strain field under generalized loading



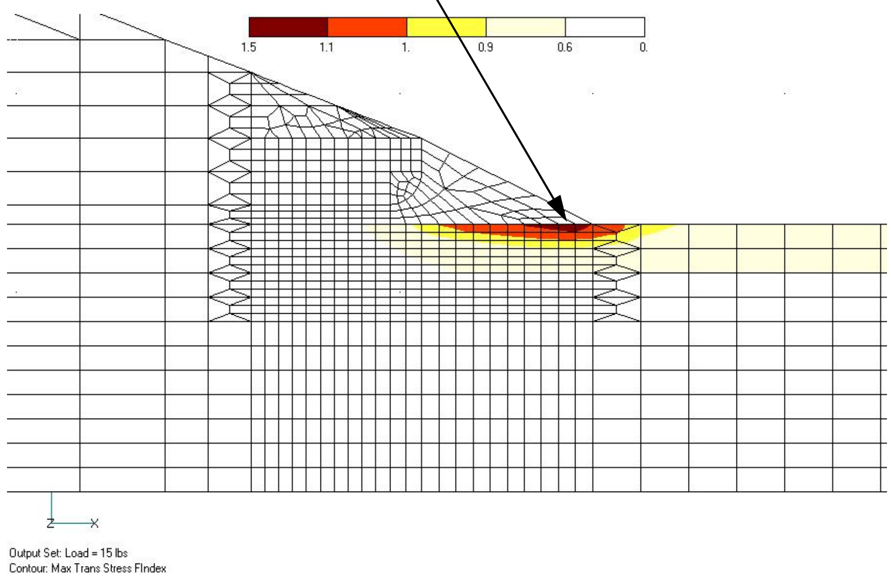


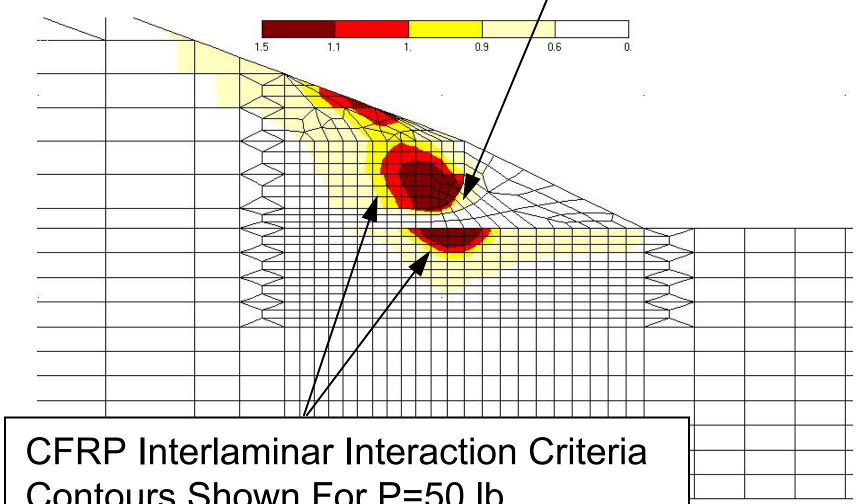
Failure Index Contours



CRITICAL FAILURE INDEX
Matrix Crack in Top 45° Plies
Max Transverse Tensile Stress
Contours Shown For P=30 lb.

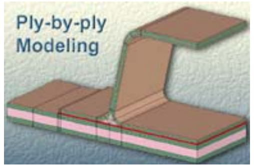
Adhesive VonMises Strain Criteria
Contours Shown For P=50 lb.





CFRP Interlaminar Interaction Criteria
Contours Shown For P=50 lb.

StessCheck - P-method FEA Technology



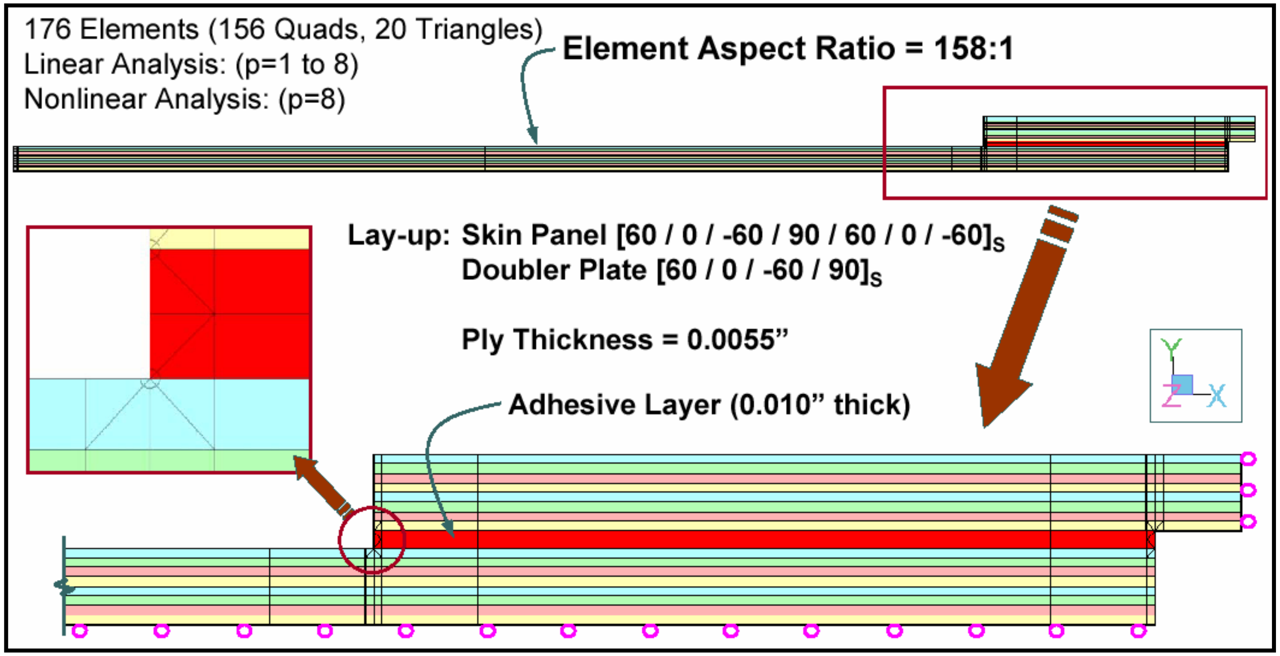
Features for Bonded Joints

- *Can use high aspect ratio elements for single ply modeling.*
- *Nonlinear load step analysis with simultaneous evaluation of multiple failure criteria, including J1 (SIFT)*

Handbook Technology

- *Parametric model libraries for bonded joints*
- *Standardization of design/analysis procedures.*

"Handbook" approach may make FE feasible even for PD work

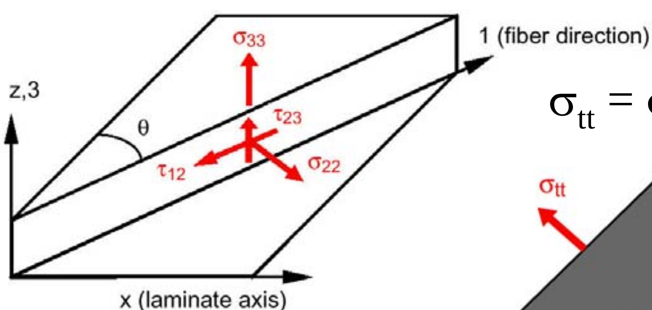


Reference: Forness, S., Presented to Mil-17, October 2003

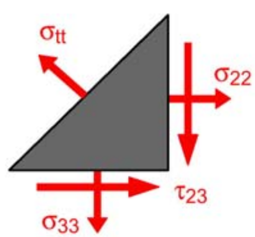
Stress-Based Failure Criteria

Strength prediction only as good as chosen failure criteria

Adhesive	Stress solutions:	Hart-Smith (A4E* series) [3,4] Tsai/Oplinger/Morton [2] UCSB shear and multi-axial bonded joint solutions [5,6] Peel stress analysis (to be determined) 2D and 3D FEA approaches [7-10]
	Failure criteria:	Truncated elastic plastic Point stress Von-Mises Damage zone models [11]
Adherend	Stress solutions:	transverse shear, peel
	Failure criteria:	Max principal transverse (matrix cracking) [10] Interlaminar tension-shear interaction (delamination) Fiber failure



$$\sigma_{tt} = \sigma_{max}$$

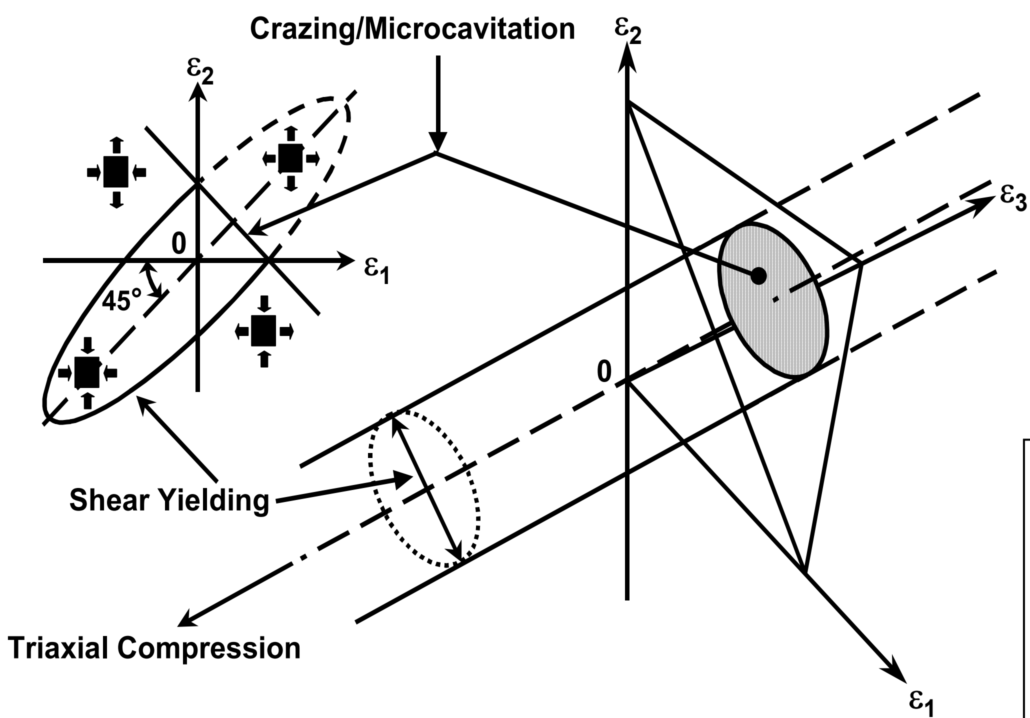


Maximum Principal Transverse Stress

$$\sigma_{max} = \frac{\sigma_{22} + \sigma_{33}}{2} + \sqrt{\frac{(\sigma_{22} - \sigma_{33})^2}{4} + \tau_{23}^2}$$

First Strain Invariant Failure Criterion, J1

- "Strain Invariant Failure Theory" = "SIFT" can be used to effectively predict failure in the first ply of the parent laminate (ref. Navy, Tsai, Alper, Barrett)
- J1 failure criterion valid for various environmental conditions, loading conditions, and surface ply orientations (shown to have a nearly constant critical value over a range of configurations and failure loads).



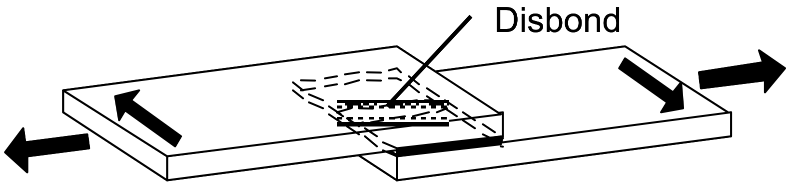
Use preferred failure criterion to predict adherend failures.

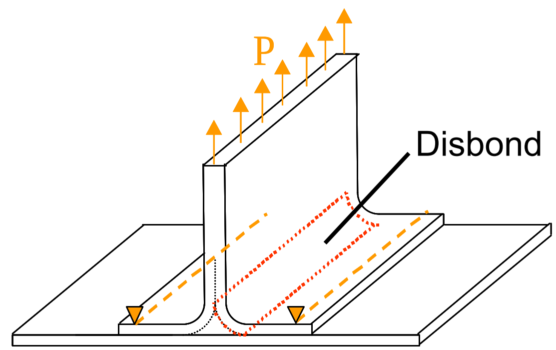
References:

Gosse, Jon H., Christensen, Stephen, "Strain Invariant Failure Criteria For Polymers In Composite Materials", AIAA-2001-1184.

Tsai, H.C., Alper, J., Barrett, D., "Failure Analysis of Composite Joints", AIAA-2000-1428.

Flaws/Disbonds and Out-of-Plane Loading





What if disbonds are present (based on criteria)?

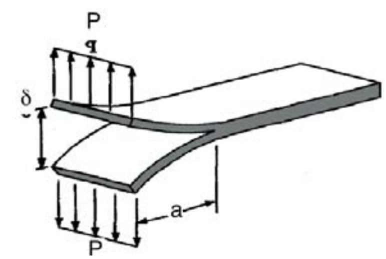
Out-of-plane loads, or complex post-buckled behavior.

Fracture Mechanics

Turn to fracture mechanics to address disbonds and damage growth to failure.

Interlaminar Fracture Mechanics (ILFM)

- Captures physics of long, dominant interlaminar cracks (a.k.a. disbonds or delaminations).
- Stress singularities not an issue
- Potentially handles fatigue delam. growth

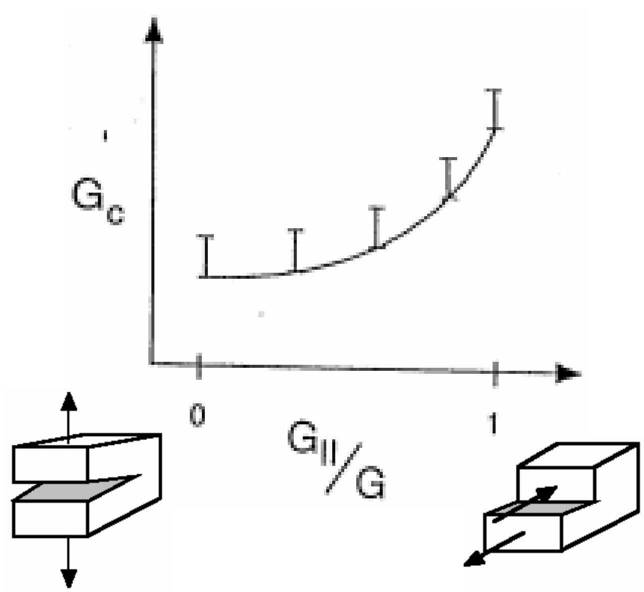


Strain Energy Release Rate (SERR)

- Calculated using Griffith Crack Theory Define SERR
- "Crack driving force", how much energy will be release as delam. or disbond grows

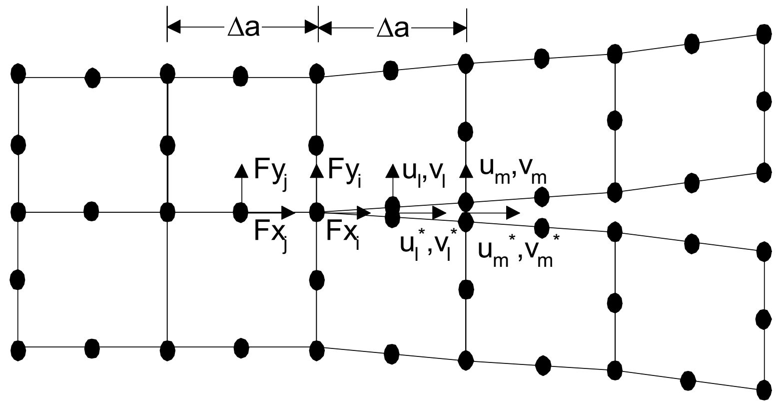
Fracture Toughness Failure Criteria

- Gc values
- Mode mix failure envelopes



Virtual Crack Closure Technique (VCCT)

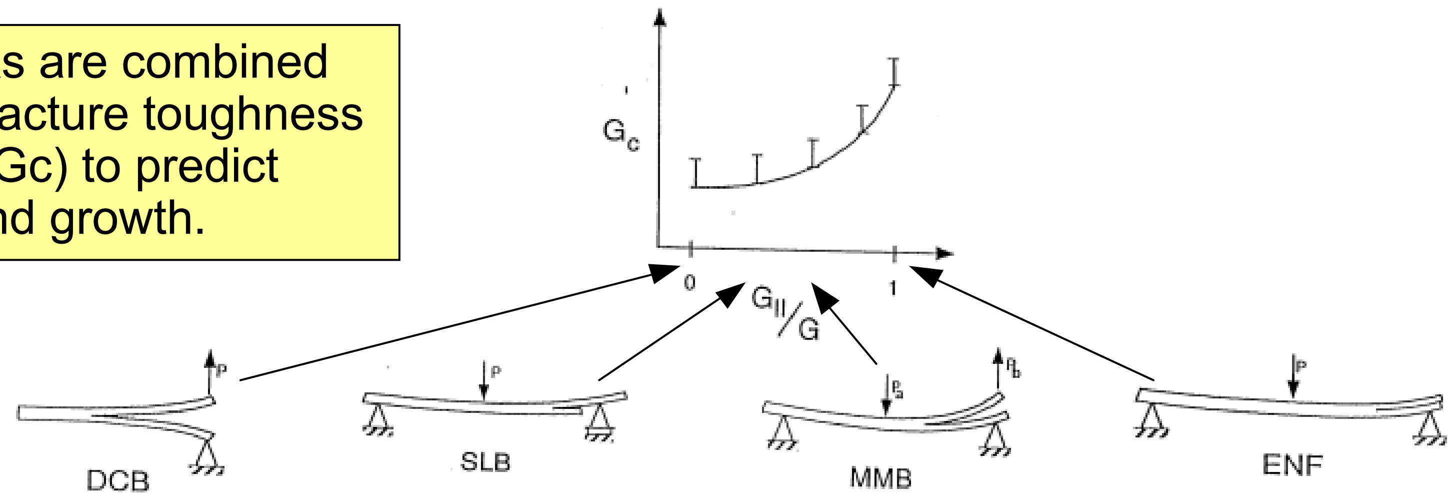
Virtual crack closure technique (VCCT) used to calculate Mode I and II strain energy release rates (SERRs) from 2-D FEM



$$G_I = -\left[Fy_i\left(v_m - v_m^*\right) + Fy_j\left(v_l - v_l^*\right)\right] \Big/ 2\Delta a$$

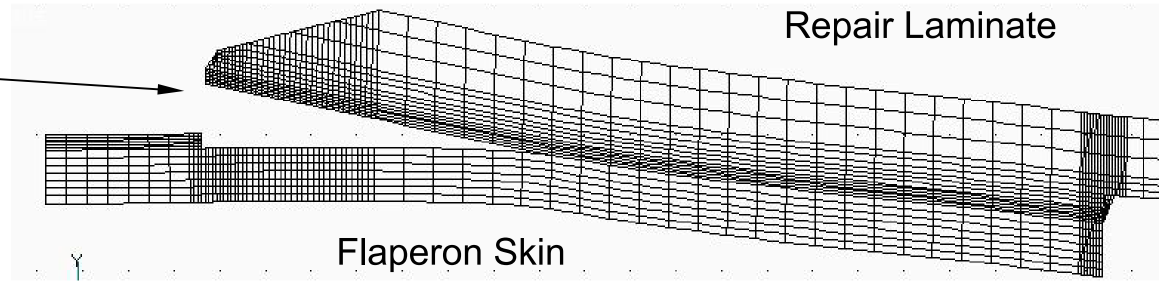
$$G_{II} = -\left[Fx_i\left(u_m - u_m^*\right) + Fx_j\left(u_l - u_l^*\right)\right] \Big/ 2\Delta a$$

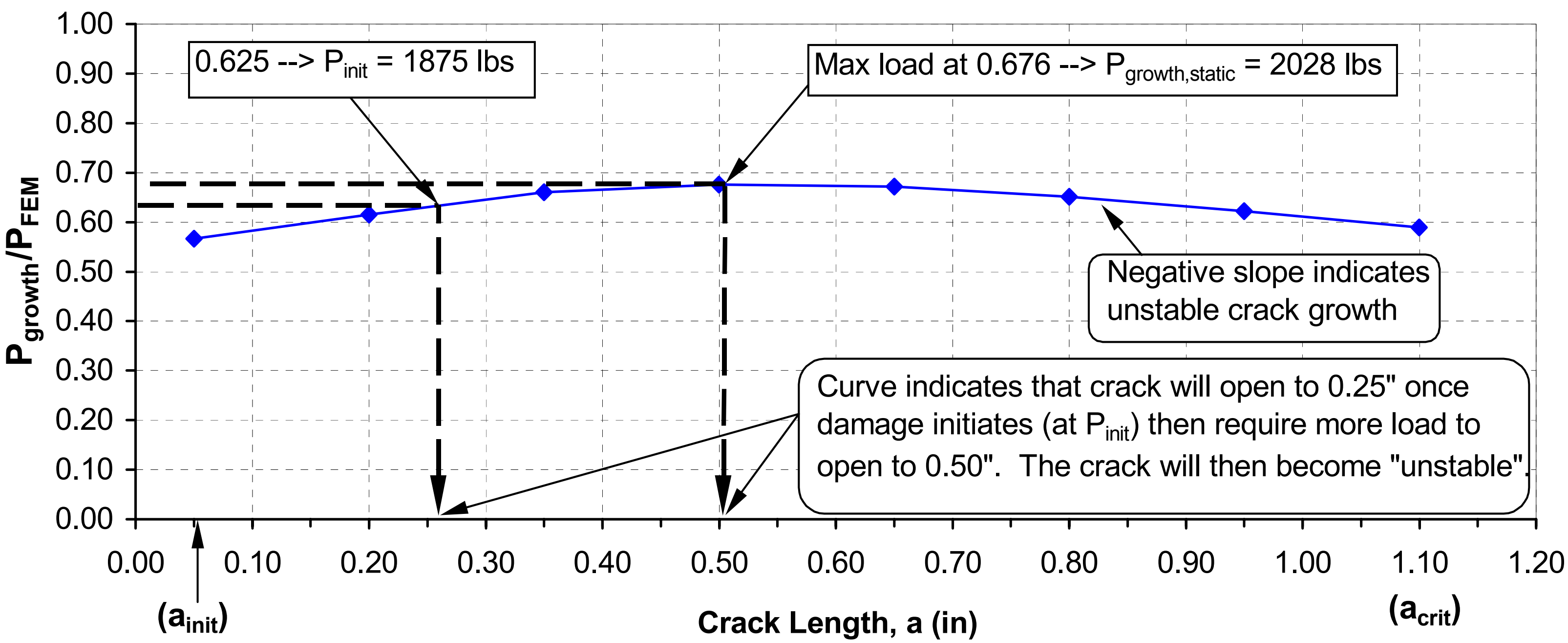
SERRs are combined with fracture toughness data (Gc) to predict disbond growth.



Lap Joint Strength Using Fracture Mechanics

Matrix crack in skin at tip of adhesive followed by crack growth between skin plies 2 and 3.

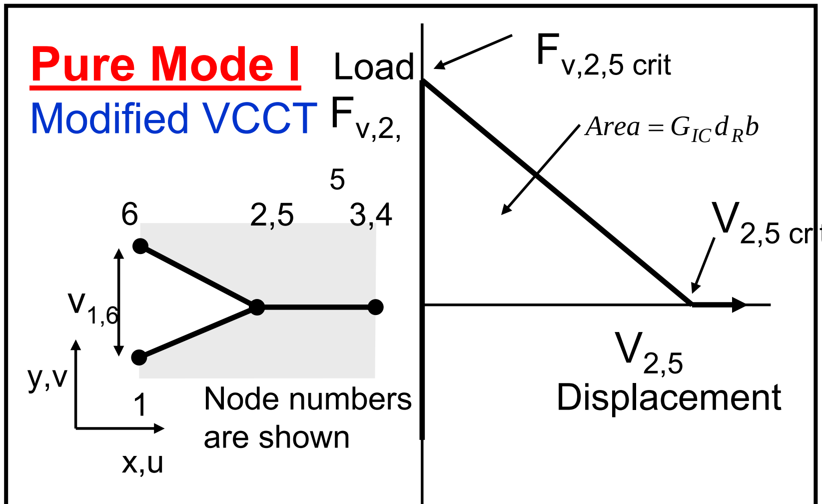




Boeing/ABAQUS Interface Element

I/F elements are an enabling technology for composites.

- Triggers release based on fracture criteria, not stress-based criteria.
- Promising technology to be able to handle delaminations and disbond growth within an FEM.



Nodes 2 and 5 will start to release when :

$$\frac{1}{2}\frac{v_{1,6}F_{v,2,5}}{bd_L} = G_I \ge G_{IC}$$

Mode II treated similarly

where

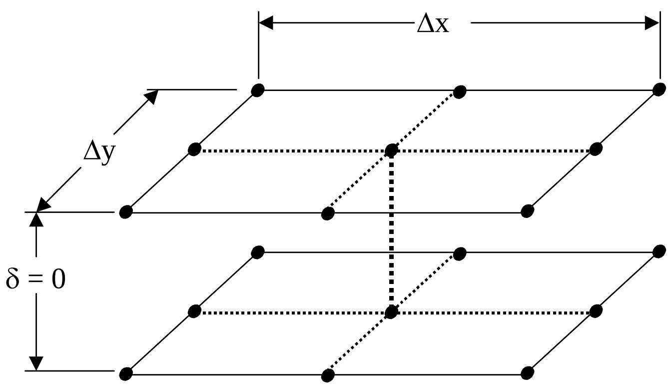
G_I = mode I energy release rate

G_{IC} = Critical mode I energy release rate

b = width

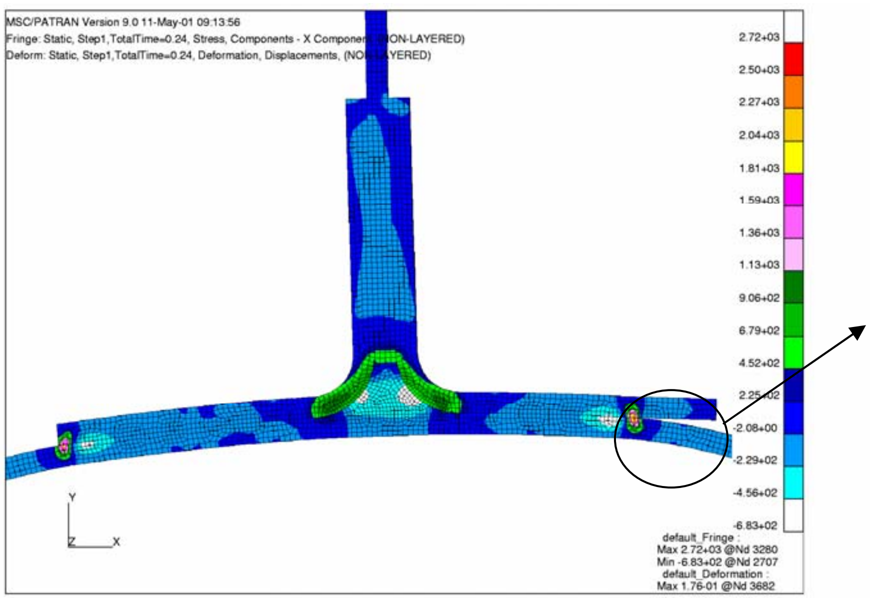
$F_{v,2,5}$ = Vertical force between nodes 2 and 5

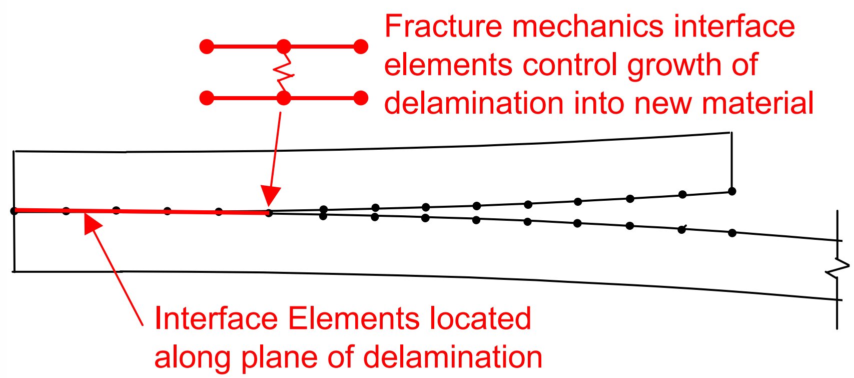
$v_{1,6}$ = Vertical displacement between nodes 1 and 6



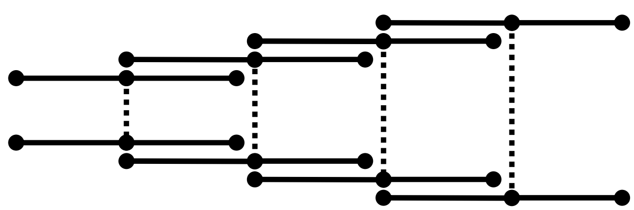
Reference: Mabson, G., Deobald, L., Dopker, B., "Fracture Interface Elements", Presentation to Mil-Hdbk-17, Oct. 28, 2003.

Boeing/ABAQUS Interface Element (cont'd)





Patent pending

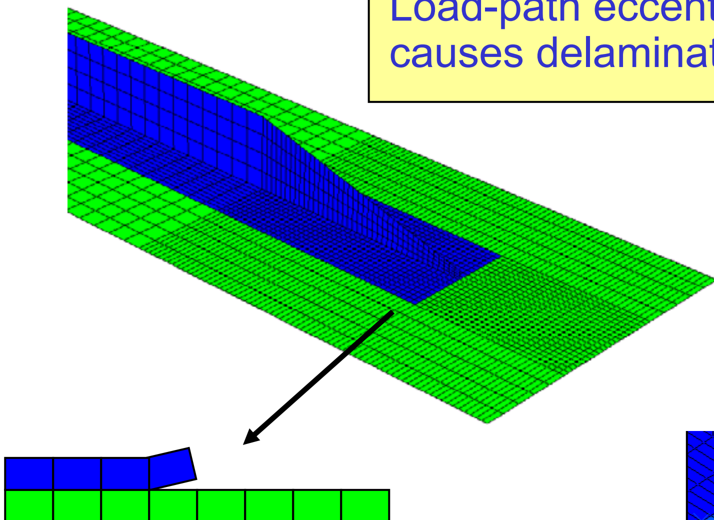


- By using a series of overlapping interface elements, delaminations can be propagated along a path in either direction.
- Direction of propagation is not pre-specified.

Reference: Mabson, G., Deobald, L., Dopker, B., "Fracture Interface Elements", Presentation to Mil-Hdbk-17, Oct. 28, 2003.

Stiffener Runout With Squared Off Flanges

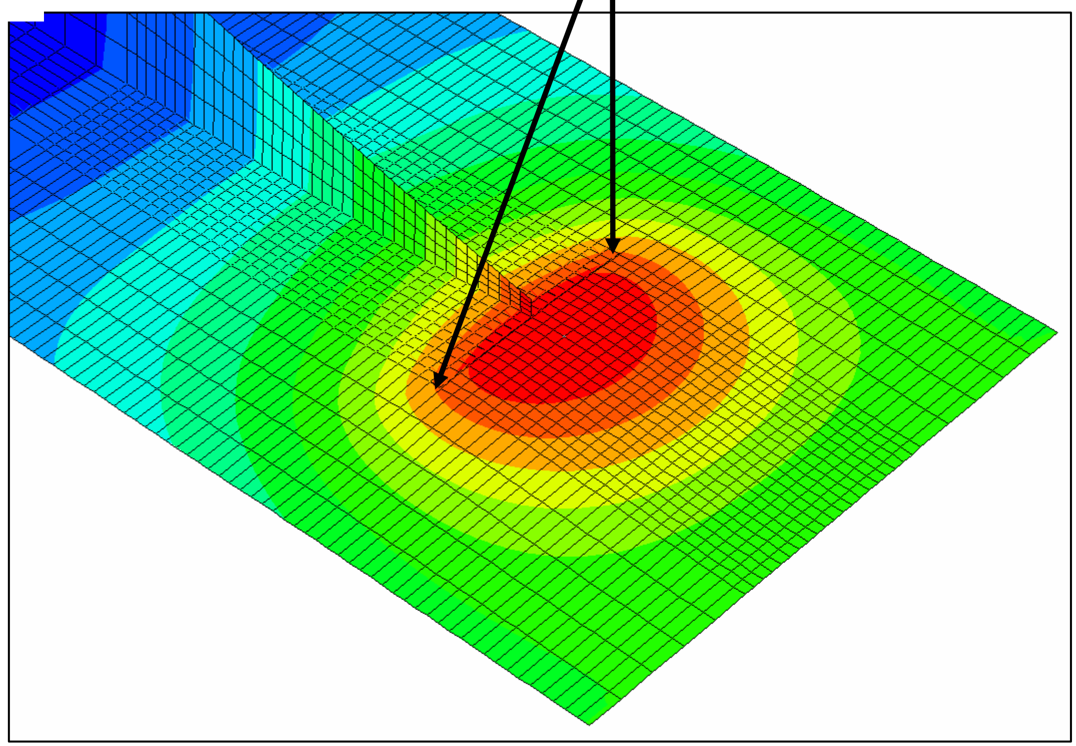
Load-path eccentricity causes delamination



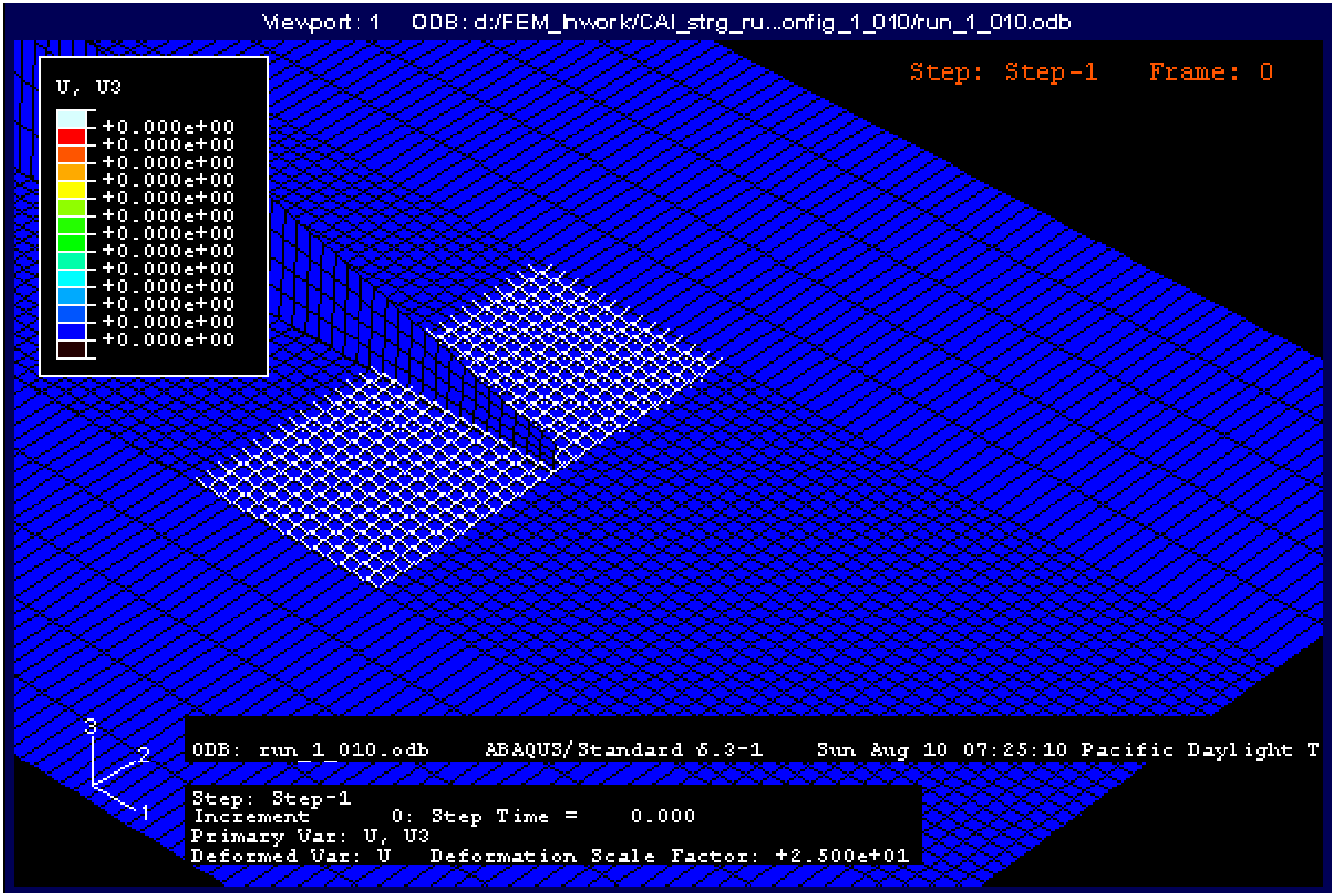
0.15 in. initial flaw was placed under first row of stiffener elements

Early failure due to chevron notch, important to capture initiation values (Limit Load)

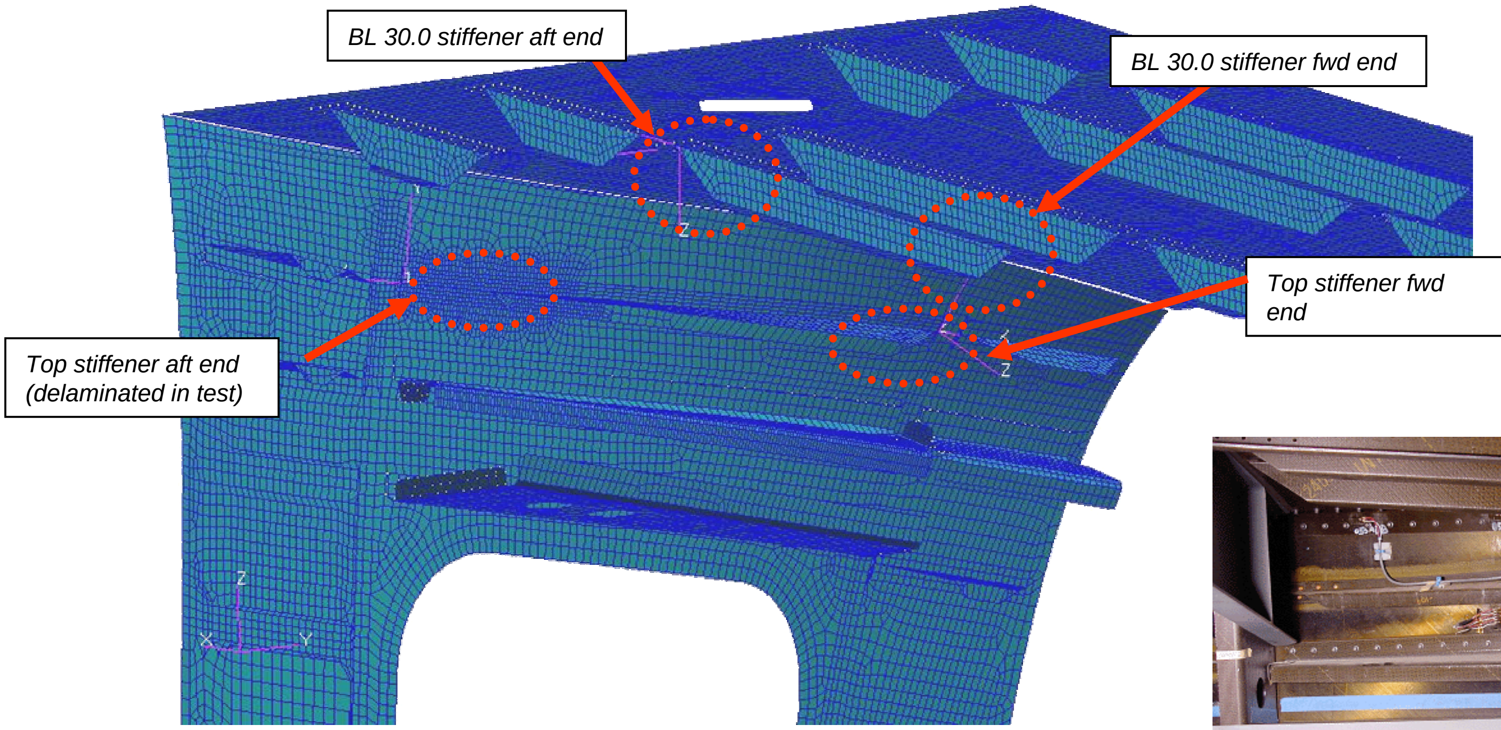
Also want final (peak) load (Ultimate Load)

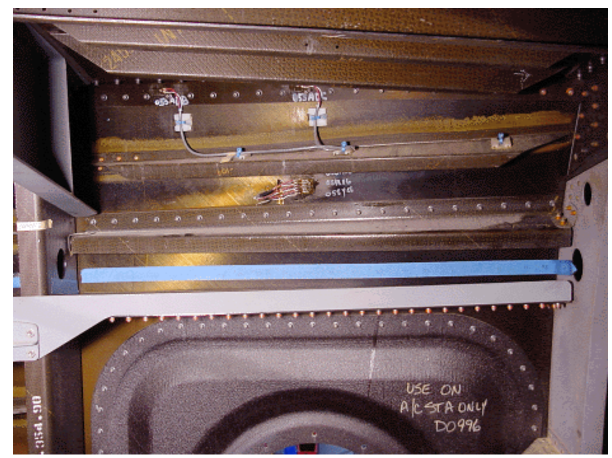


Delamination Analysis of Bonded Stiffener Termination



VCCT Analysis Scale-up





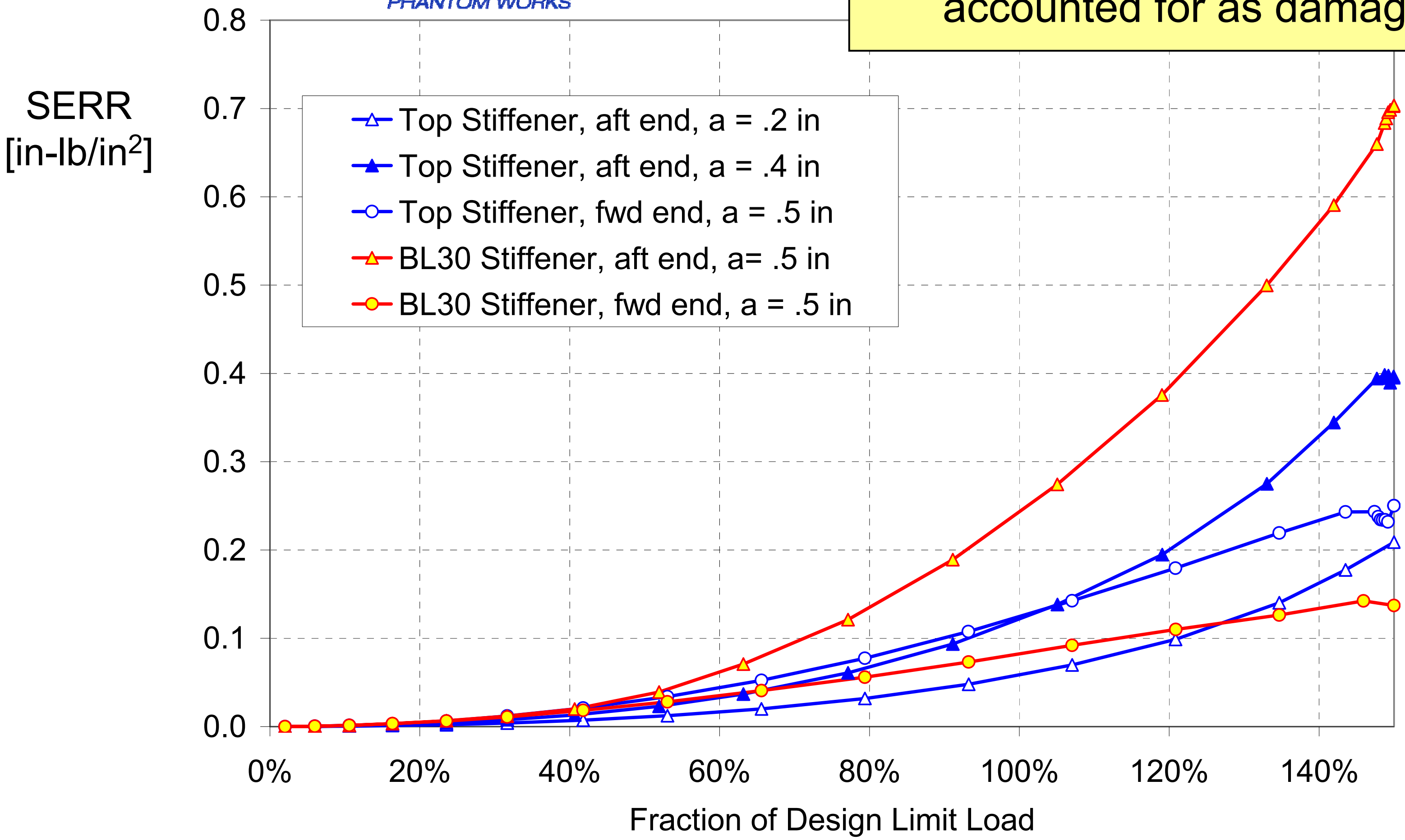
Co-cured fuselage

- Stiffener disbonding is the controlling mechanism in post-buckled stiffened panels failure
- SERR is calculated at 4 stiffener terminations under test load condition
- Stiffener and skin modeled as shells.

Reference: Minguet, Pierre, presentation to ASTM/FAA Workshop on Fracture Mechanics for Composites, SLC, March 2004

SERR vs. Applied Load

- SERR can be assessed at multiple locations simultaneously.
- Compliance changes in structure accounted for as damage grows.



- SERR in this configuration is driven by axial load in stiffeners.

NSE COMPOSITES

Reference: Minguet, Pierre, presentation to ASTM/FAA Workshop on Fracture Mechanics for Composites, SLC, March 2004

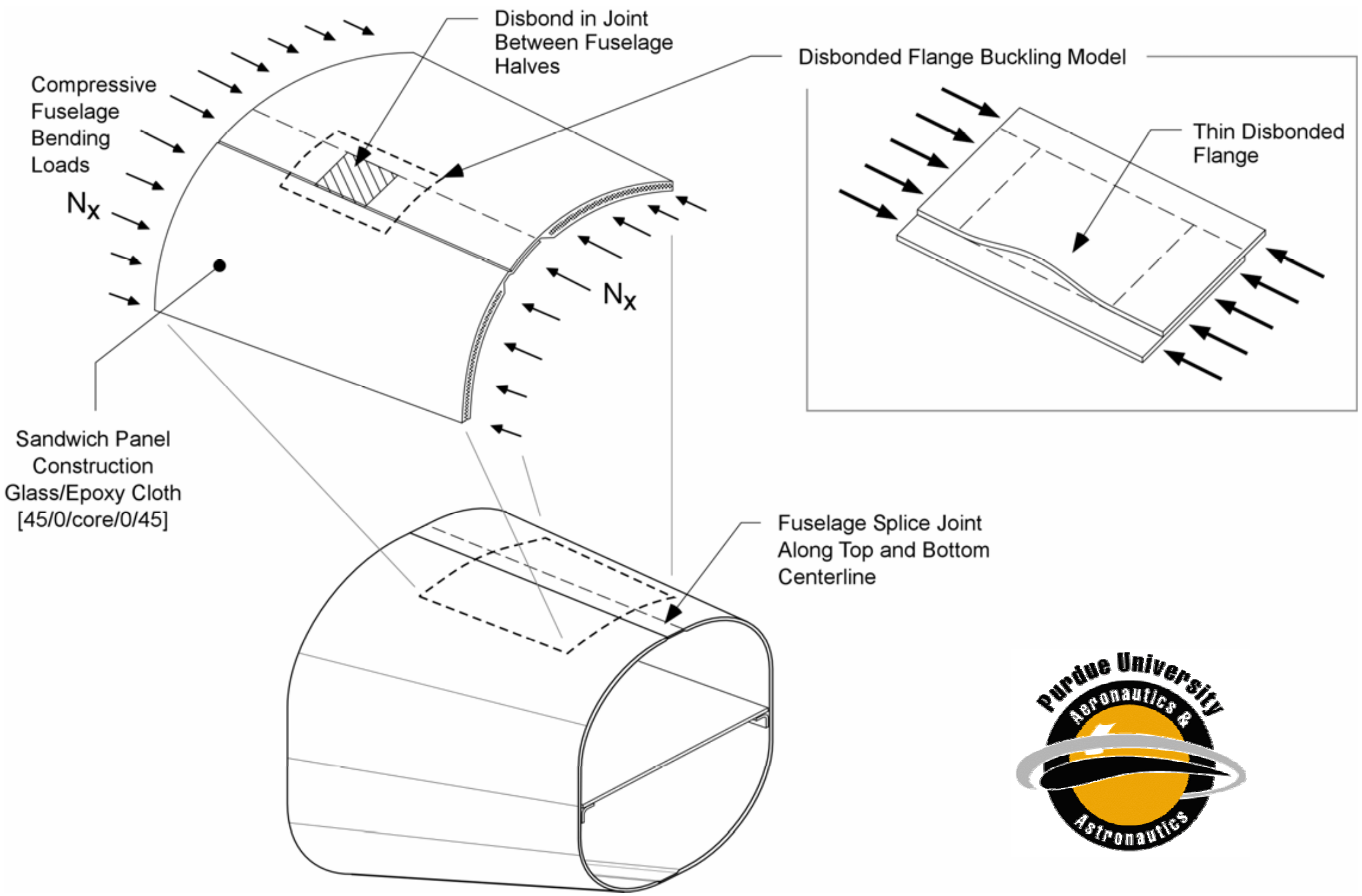
“Simple” Fracture Mechanics

Damage Tolerance Evaluation:

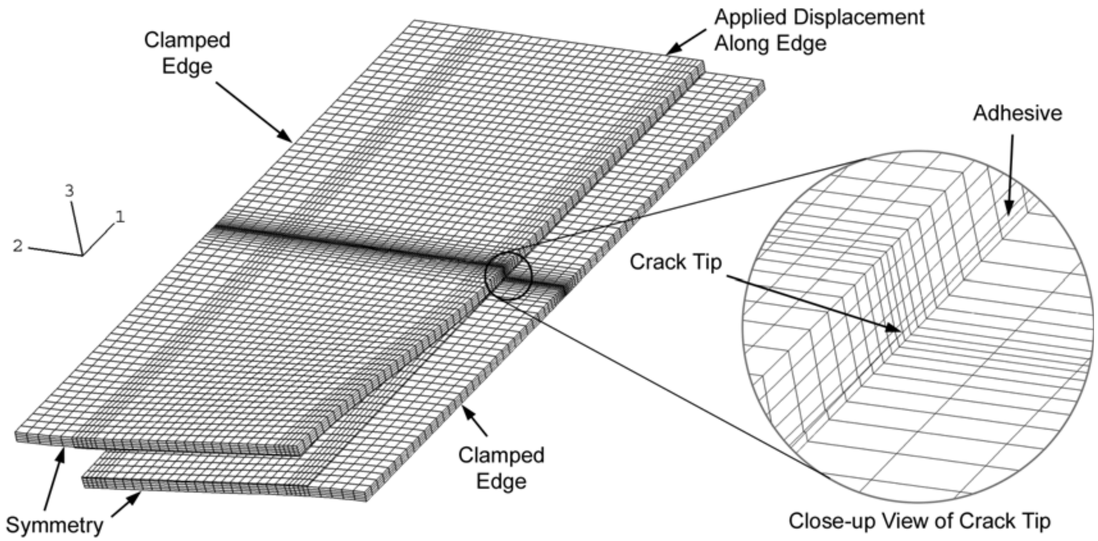
- *Compression causes buckling*
- *Subsequent disbond growth possible*

Practical use of fracture mechanics for bonded joints.

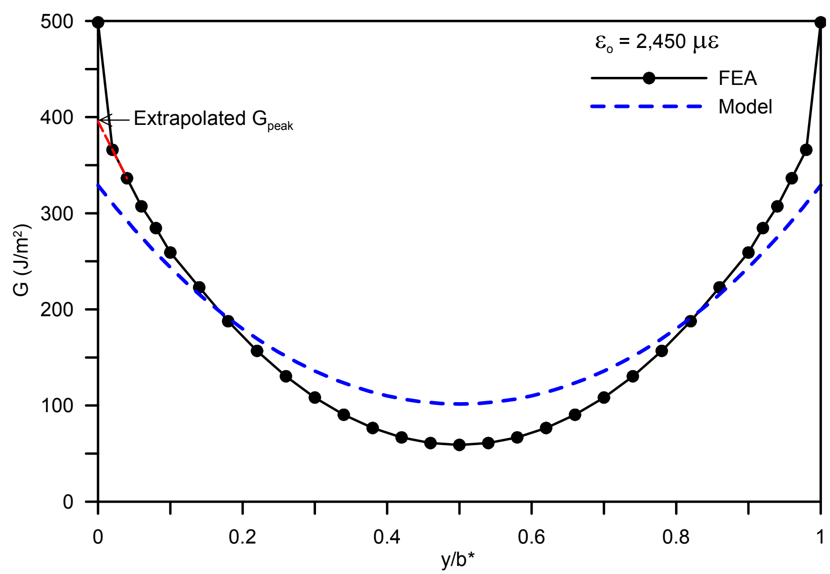
Source: Prof. Hyonny Kim (Purdue)



Comparison with VCCT/FEA



- Detailed view of *G* along disbond front
- Predicts corner disbond initiation
- Comparison with VCCT/FEA

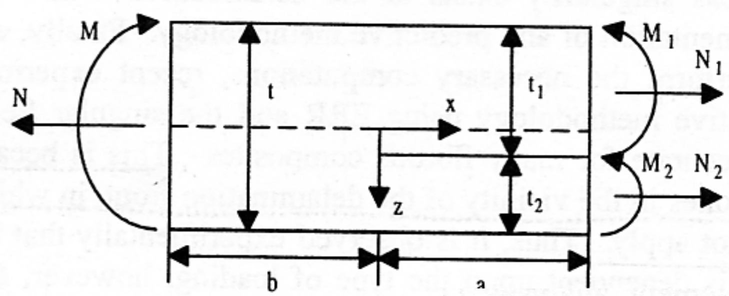


Closed-form solution sufficient for initiation values.

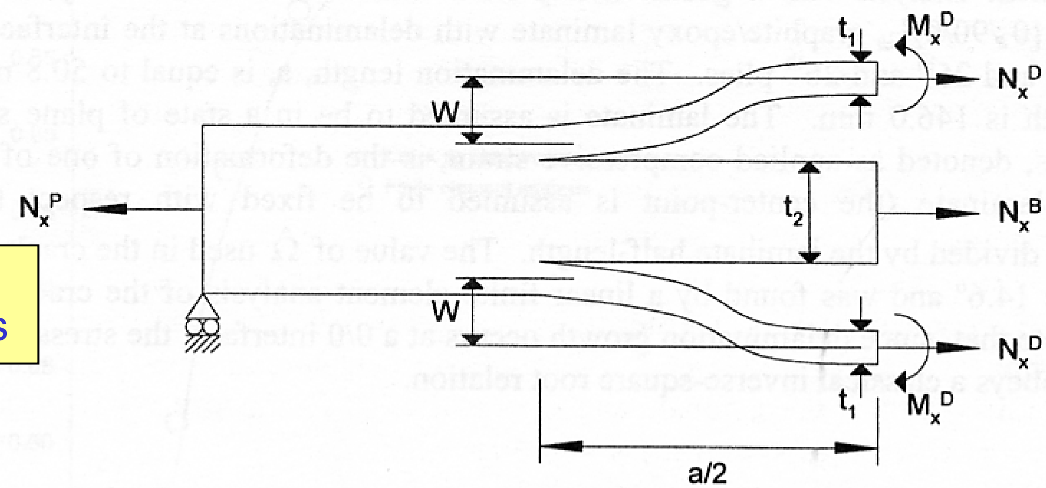
Davidson "Crack Tip Element"

Closed-form linear-elastic solution aimed at overcoming computational difficulties in determining strain energy release rate and mode mix.

Obviates need for locally detailed 2D and 3D FEMs



Linear-elastic solution may be enough for "initiation" values.



Post-buckled delaminations

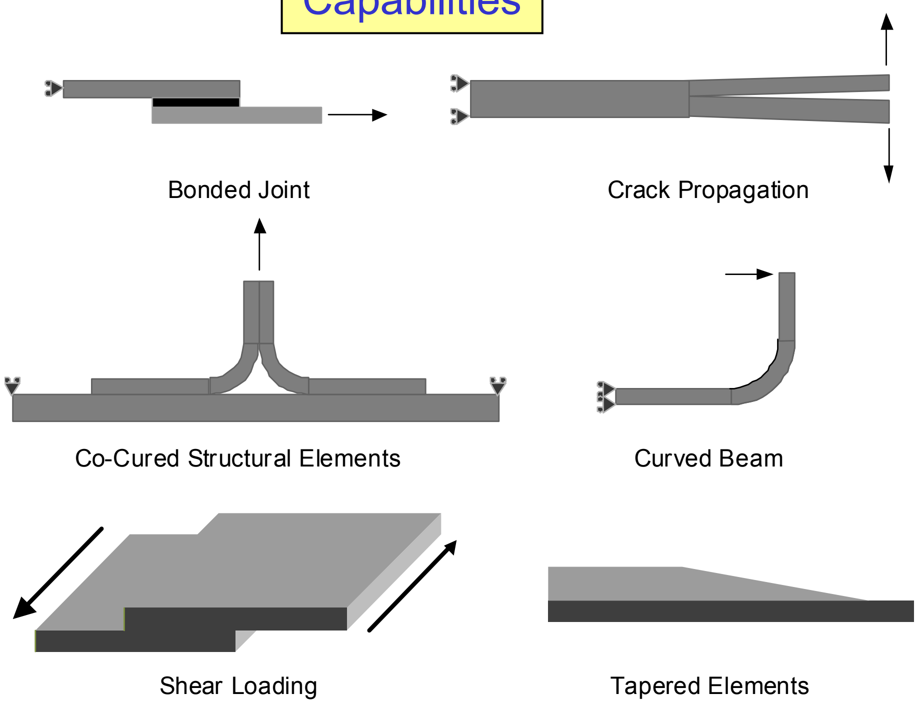
Reference: Davidson, B.D., "A Predictive Methodology for Delamination Growth in Laminated Composites", April 1998.

“SUBLAM” Capabilities

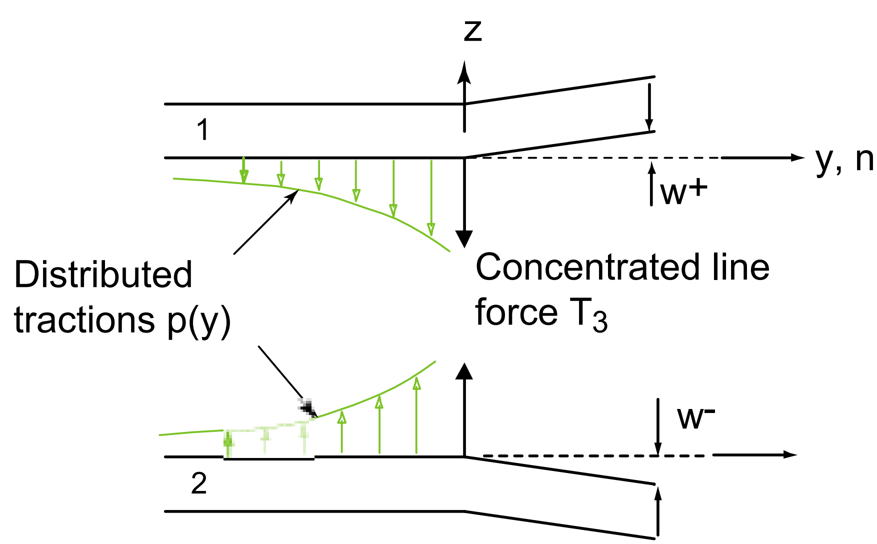
MSC working on an SBIR contract with the FAA to develop SUBLAM for use with General Aviation bonded joints.

- Closed-form solutions for complex geometries
- Can be used to calculate SERR as a function of disbond length

Capabilities



Single-Step SERR Calculation



Reference: Flanagan, G., Material Sciences Corp., “SUBLAM Code for Fracture Analysis,” presented to Mil-17, October 2003.

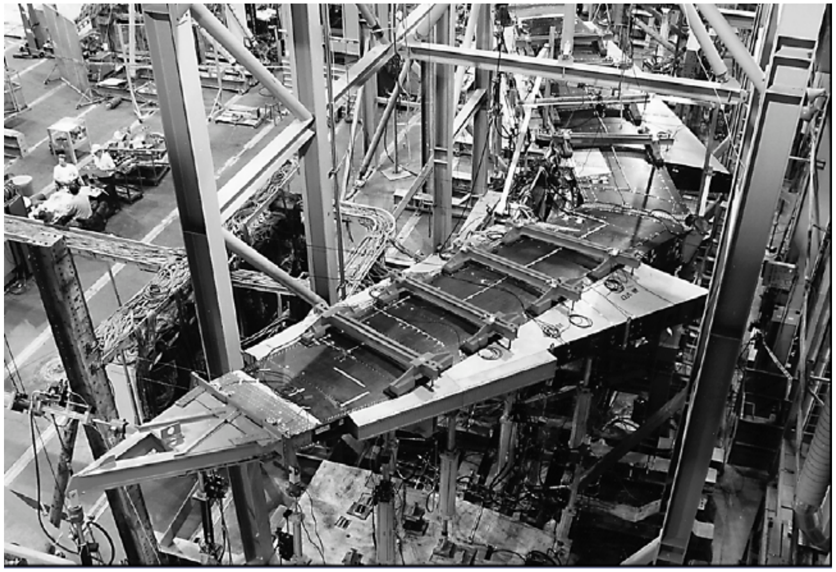
Fatigue Analysis of Bonded Joints

No Analysis - verify “no disbond growth” by test except for rare applications.

Durability and “no growth” assumptions typically demonstrated by test.

Stress-Based Methods

- PABST/ MDC A4EI approach
  “rules of thumb” -stay in elastic region at peak limit load in spectrum.
- O’Brien/Minguet damage initiation (e.g., T-stiffened skins)



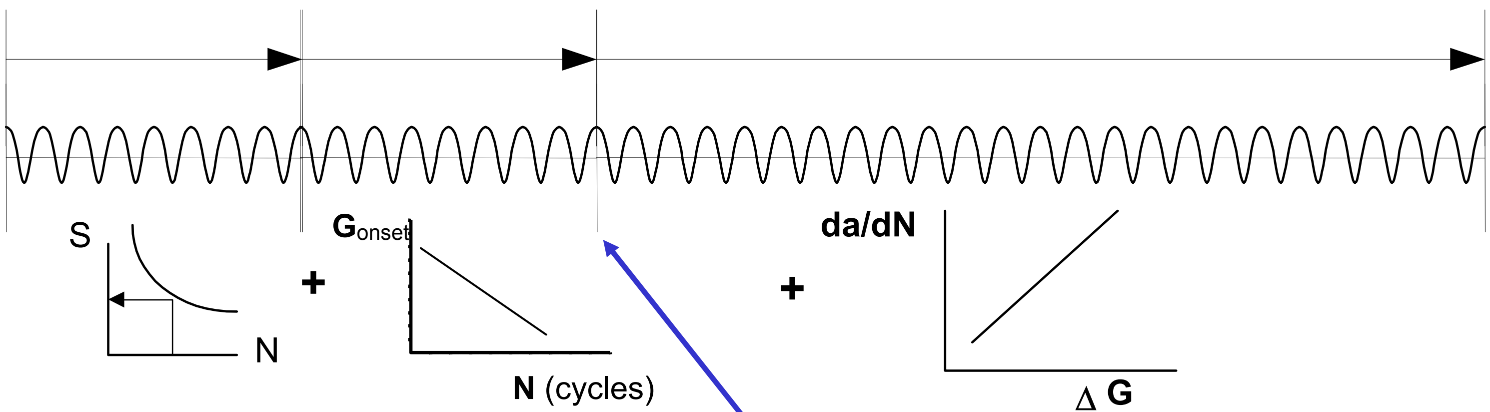
Fracture Mechanics

- G_{onset} approaches (O’Brien, et. al.)
- Disbond/Delam growth under cyclic loading (da/dN vs. G_{max})
- Boeing/ABAQUS interface element

Assumed Initial Delamination or Disbond

Criteria often dictate that test and analysis address pre-existing flaws/damage.

No Initial Damage → Damage Initiation → Delamination Onset → Damage Growth →

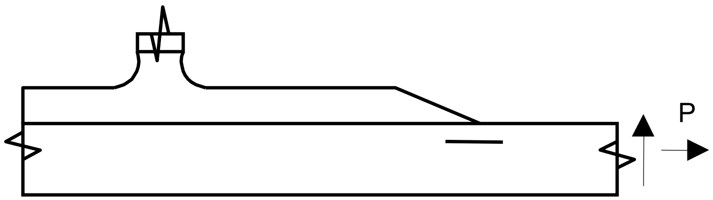


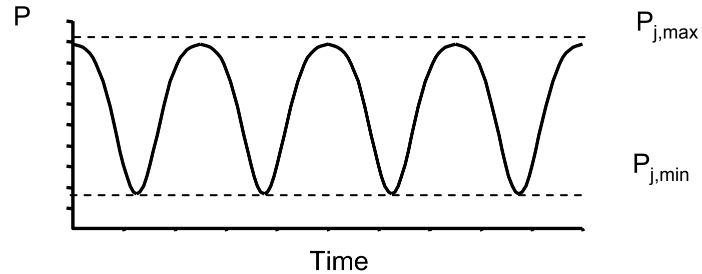
If assuming an initial flaw or delamination, *start here*

Disbond/Delam. Growth Under Cyclic Loading

Certification approach and criteria often assume that criteria-based disbonds don't grow under operating loads.

- Currently use criteria such as "no buckling of delams at operating loads" but need better approaches.





Fatigue Damage Growth Methods may:

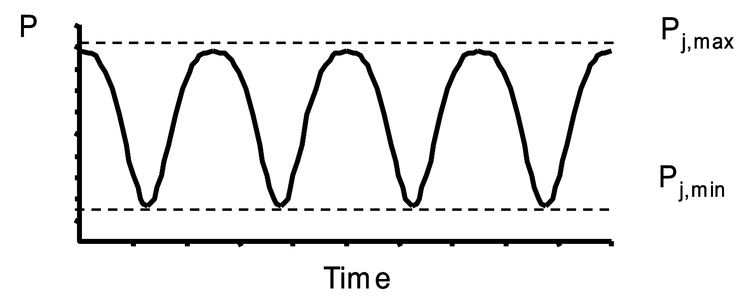
- Support "no growth", "slow growth", or "arrested growth" certification approaches (Rotorcraft Advisory Circular)
- Be used to understand the stability and threshold of growth, regardless of certification approach.
- Help us understand growth of rare, local debonding or delamination defects or possibly events (impact) that are below threshold of detectability.

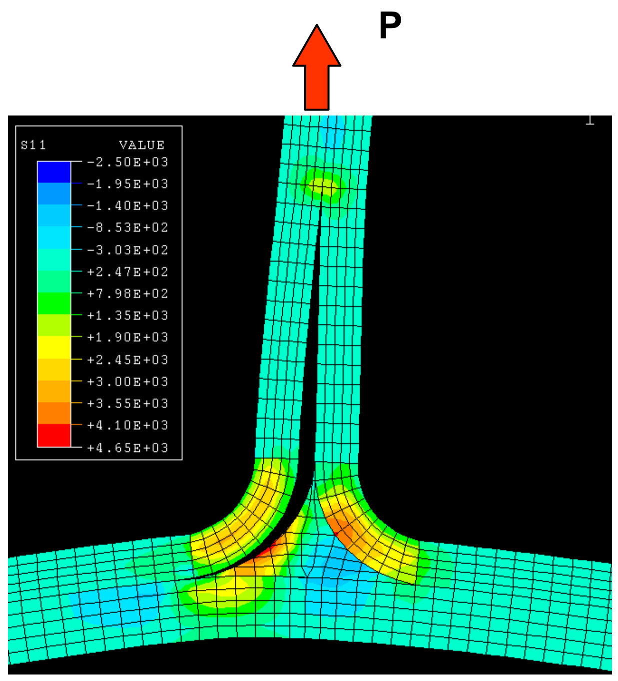
Motivation exists to develop analysis methods for predicting disbond growth (or "no growth").

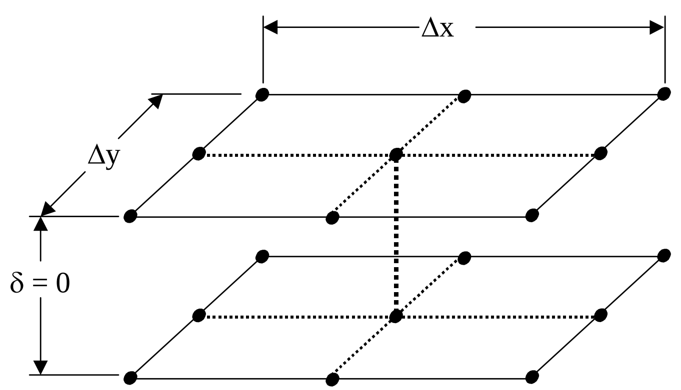
Boeing/CAI Interface Element for Fatigue

Efforts underway to extend I/F element to damage growth under cyclic loading

- Would apply to bonded joints as well as interlaminar damage growth.
- Validation testing on DCB and element testing.
- Rotorcraft industry will lead but possible applications in commercial transport, engines, automotive.







Bonded Joint Analysis - Issues

Stress-Based Methods (current industry benchmark)

- Work in many cases with conservative assumptions and full-scale validation testing. Often require high-fidelity stress-strain field for use with stress failure criteria.
- Average-stress cut-offs and A4EI/PABST approaches will not hold up for post-buckled structures or for T-pull off loading.
- Do not capture physics of disbond/delam. growth

Fracture Mechanics (gaining industry acceptance)

- FEM/VCCT approaches enabling but need to focus on simplified fracture methods, as well.
- Fracture methods are immature relative to comparable methods for metals. Still many open issues and challenges with using and validating fracture methods to design and certify structures (ref. FAA/ASTM Workshop, SLC March 2004).

Fatigue Fracture Methods (evolving through R&D)

- Still need substantial development and validation.

Need fracture mechanics methods in the “tool box”

Need to work issues to gain industry acceptance.

Overview - Analysis, Data, and Substantiation

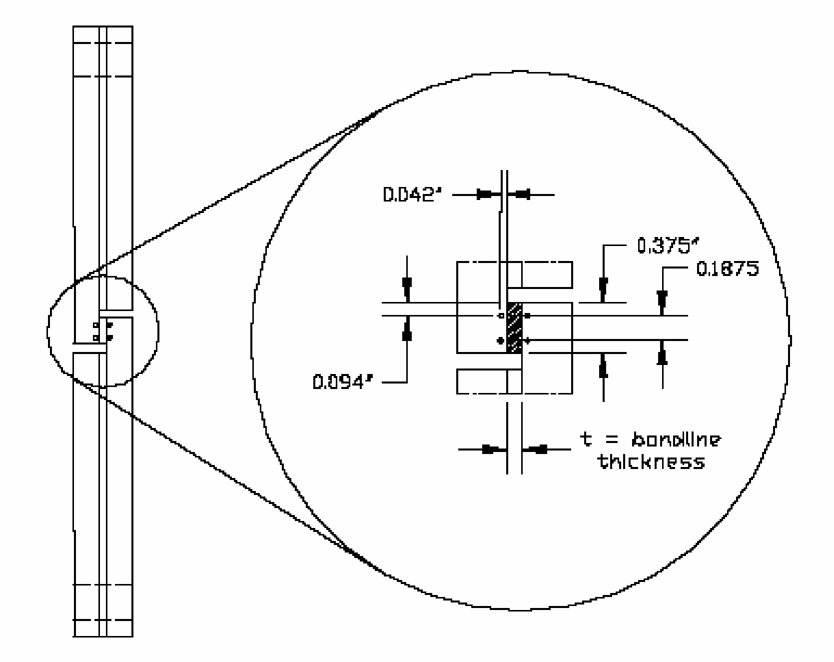
- Design/Flaw Criteria
  - *Certification requirements*
  - *Flaws, damage, NDI threshold*
- Analysis Methods
  - *Closed-form eqns, A4EI, 2D vs. 3D, FEA*
  - *Failure criteria*
  - *Fracture, VCCT*
  - *Durability, damage tolerance*
- Design Data and Allowables
  - *Material properties for analysis*
  - *Design allowables, statistics*
- Substantiation
  - *Validate design, manufacturing processes, analysis methods*
  - *Satisfy certification requirements*
- Summary of Issues
  - *Safety critical items*
  - *Open issues, need for guidelines, R&D*

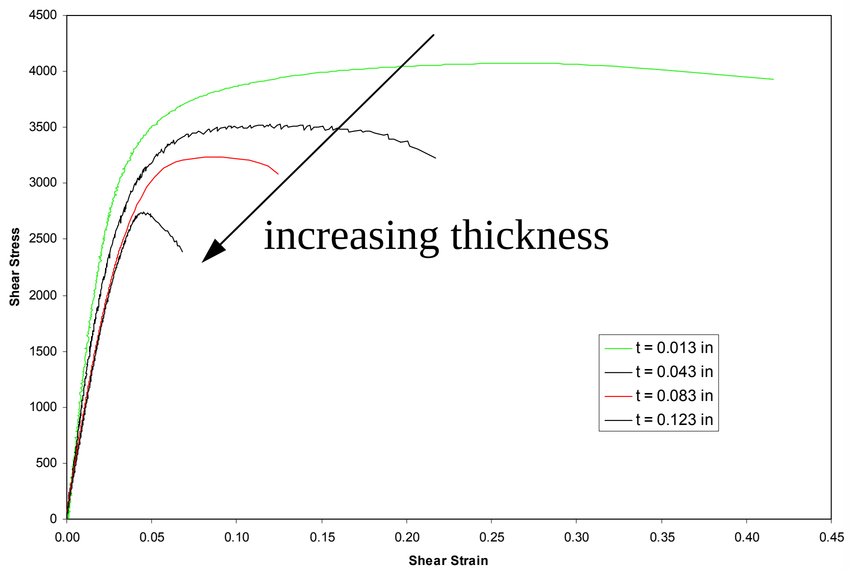
Design data is closely linked to particular analysis method(s)

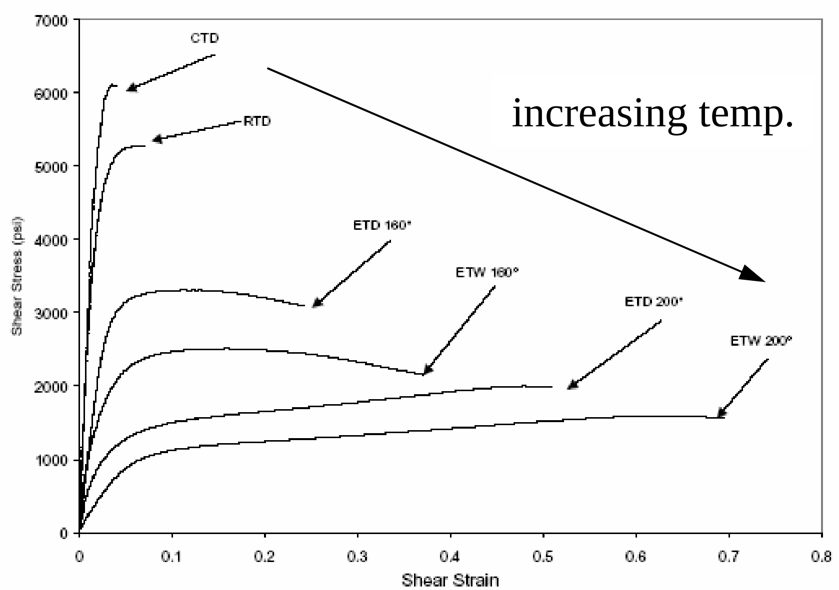
Adhesive Properties

Stress-strain curves

- from thick adherend test, ASTM D5656
  - *Adhesive characterization*
  - *Elastic limit and plastic strain*
  - *Reduced peel stresses*
- function of temperature, moisture
- function of bondline thickness
  - *Increasing thickness results in reduced plastic strain and lower yield stress*

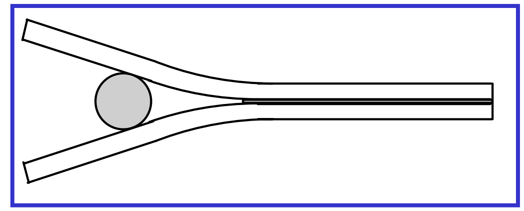




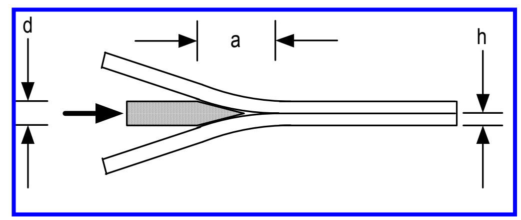


Adhesive Properties (cont'd)

- Lap shear tests (single, double shear)
  - *stress results generally only valid for lap length tested*
  - *poor evaluation of surface prep, durability*



- Wedge tests (static, traveling)
  - *good for evaluating surface prep (traveling wedge)*
  - *durability, environmental resistance*
- Toughnesses – GIc, GIIc, mixed GIc/GIIc



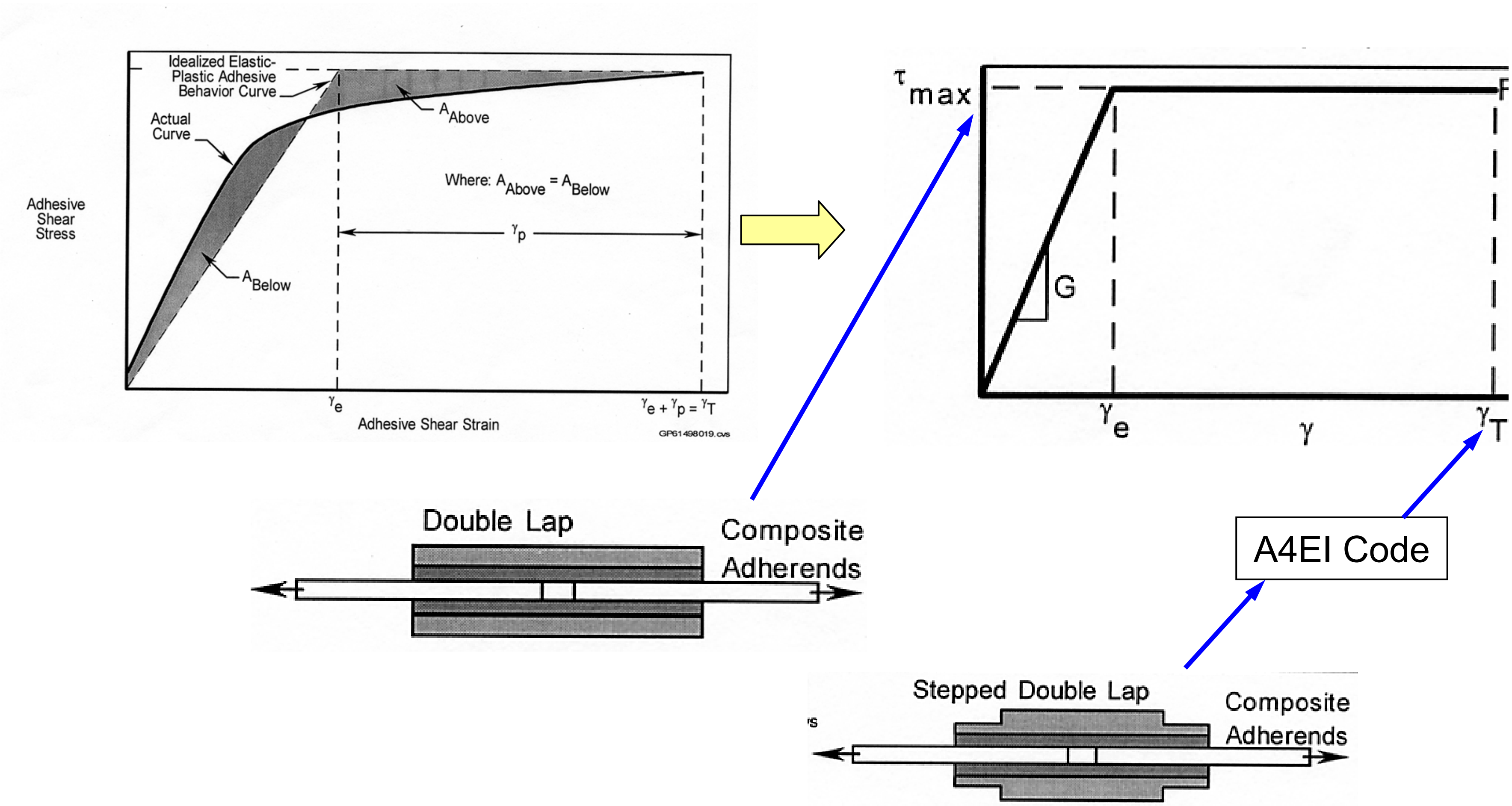
- Element-level tests often used to back-out shear/tensile strengths
  - *linked to analysis method and failure criteria*
- Tests must be representative of actual manufacturing processes and conditions
  - *Evaluate manufacturing variations (<u>surface prep</u>, curing, bondline thickness)*
  - *Evaluate manufacturing defects/anomalies*

Bonded Joint Design Values

Shear stress-strain curve truncated to account for other failure modes.

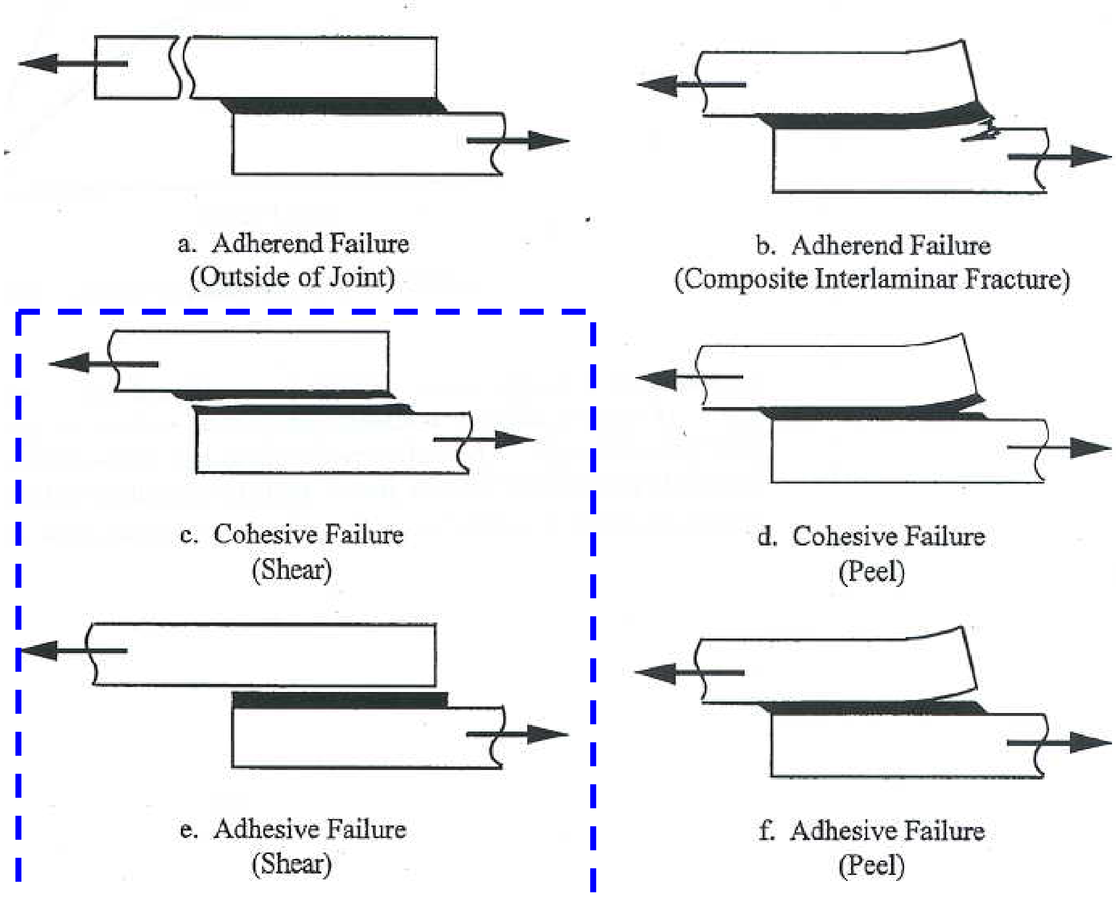
One approach to development of point design allowables

- Obtain stress-strain curve; idealize as elastic-plastic
- Truncate using double-lap and step-lap data **@ design lap length**



Failure Modes

Adhesive shear data is not relevant for many failure modes.

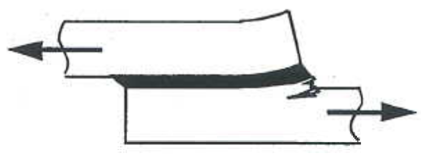


ASTM D5656

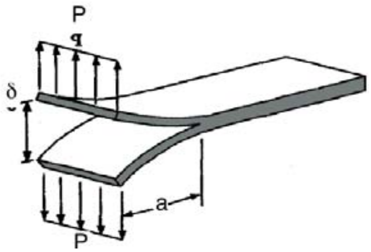
Adherend Data

Needed since failure is often in composite adherend.

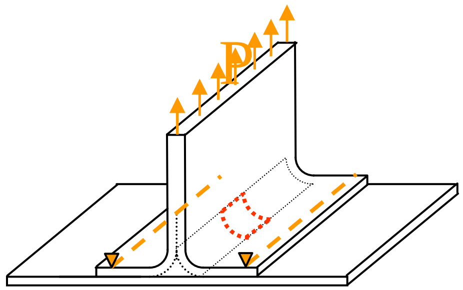
- Lap shear tests with failure in the composite adherends
  - *often used as "fictitious" adhesive shear data*



- CILS – interlaminar shear
- Transverse matrix cracking (tape materials)
  - *from incrementally loaded [0/90]n coupons*
- Interlaminar tensile strength
  - *from radius detail bending tests*



- Toughnesses – GIc, GIIc, mixed GIc/GIIc
- Element-level tests often used to back-out shear/tensile strengths
  - *linked to analysis method and failure criteria*



Fracture Test Data Issues

- Test standards still evolving (see table)
- Pre-cracks, insert size issues
- Crack growth from an as manufactured insert (0.5-2.0 mils thick) doesn't necessarily represent a sharp crack tip and may be unconservative.
- BUT pre-cracked specimens have process zone effects that cause increased apparent toughness.
- Materials that have "run-arrest" characteristics (saw tooth G vs. a curve)

We don't yet have standardized tests for composite interlaminar fracture toughness

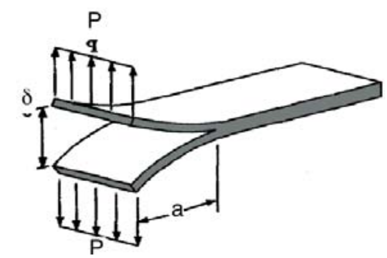


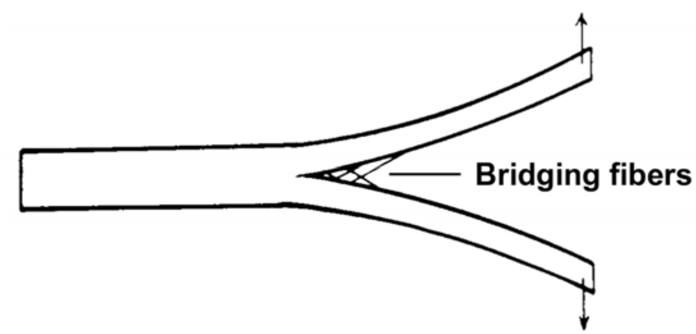
Table 6.8.6.5.a ***Fracture toughness test methods for MIL-HDBK-17 data.***

Property	Symbols	Fully Approved, Interim and Screening Data	Screening Data Only
Mode I Delamination Toughness	G_{Ic}	ASTM D 5528	--
Mode II Delamination Toughness	G_{IIc}	--	4ENF, 3ENF
Mode III Delamination Toughness	G_{IIIc}	--	ECT
Mixed-Mode I, II Delamination Toughness	$G_c=f(G_{II}/G_T)$	ASTM D6671	

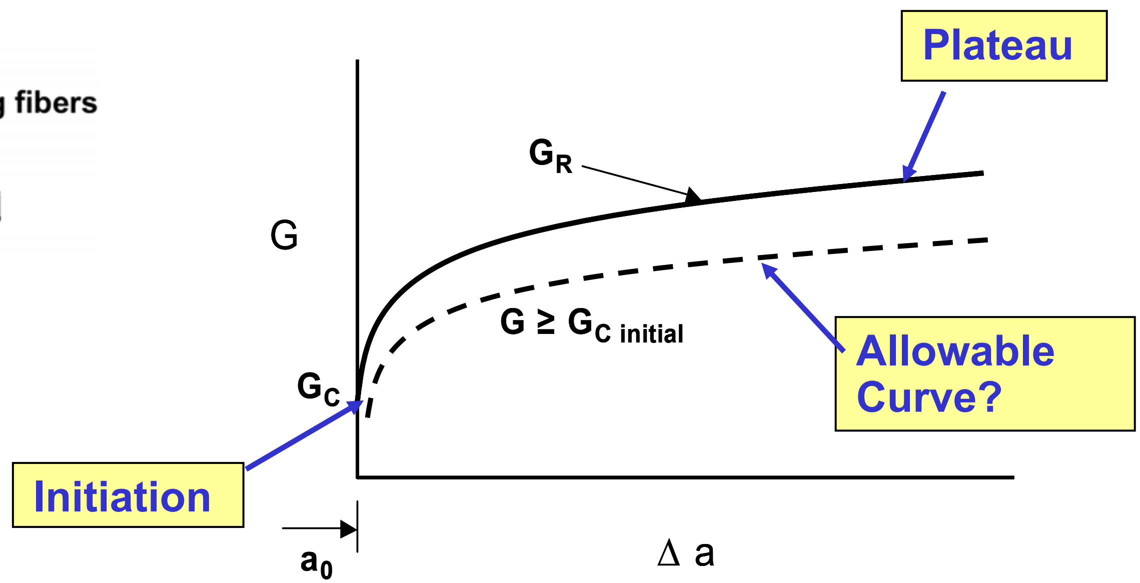
Similar situation for fatigue delamination onset and growth test standards

Fracture Toughness R-Curve Behavior

- Apparent fracture toughness (Gc) often increases significantly as delamination grows causing a crack resistance curve, or "R-curve" behavior.
- Behavior is fairly well understood; struggling with how to use.
- If take advantage of R-curve effect, how to guarantee that it will always occur
- Statistical allowables over Δa range? Scale-up issues?

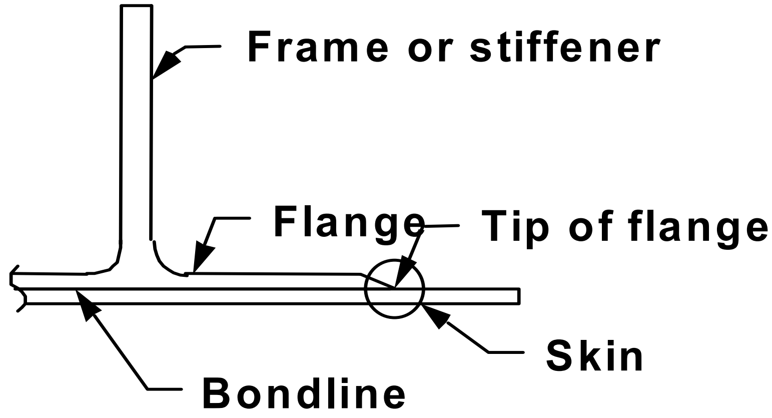


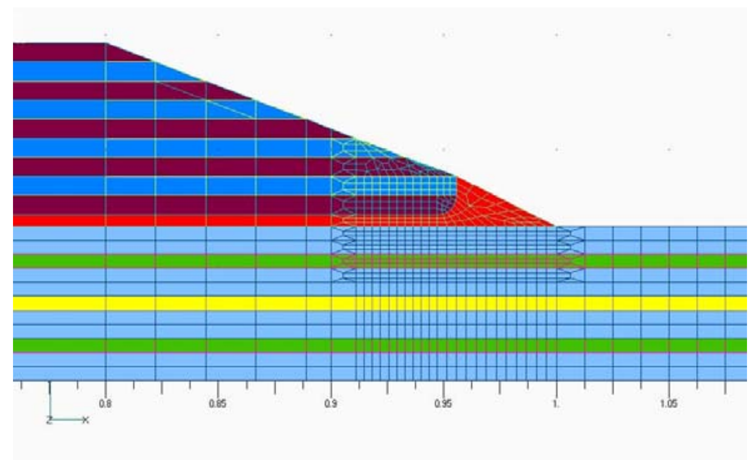
Which Gc value should be used and when?



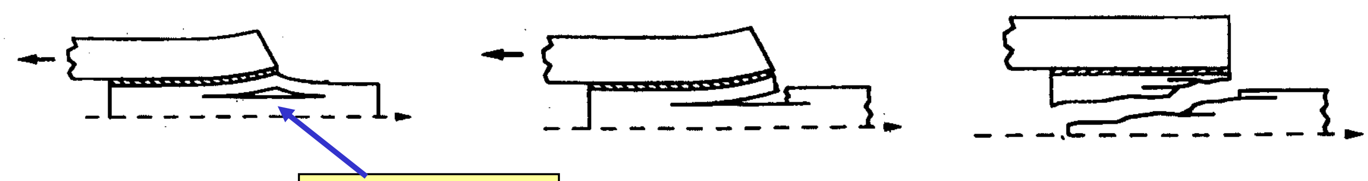
Effective Gc - Bonded Joints

- Bonded joints - bondline is more susceptible to flaws but adhesive is tougher.
- Develop R-curves for adhesive, uni-directional plies, fabric, etc.. at critical environments and use lowest common denominator?
- Too conservative?
- Assume failure occurs in least tough composite layer? One ply down? Take advantage of “ply bridging” that shields crack?





What is the “effective Gc” for a complex bonded structure?



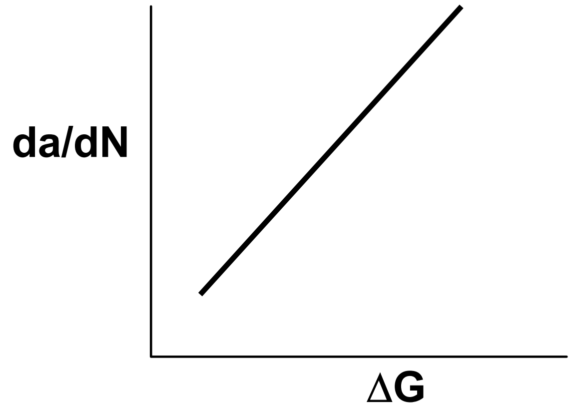
ply bridging

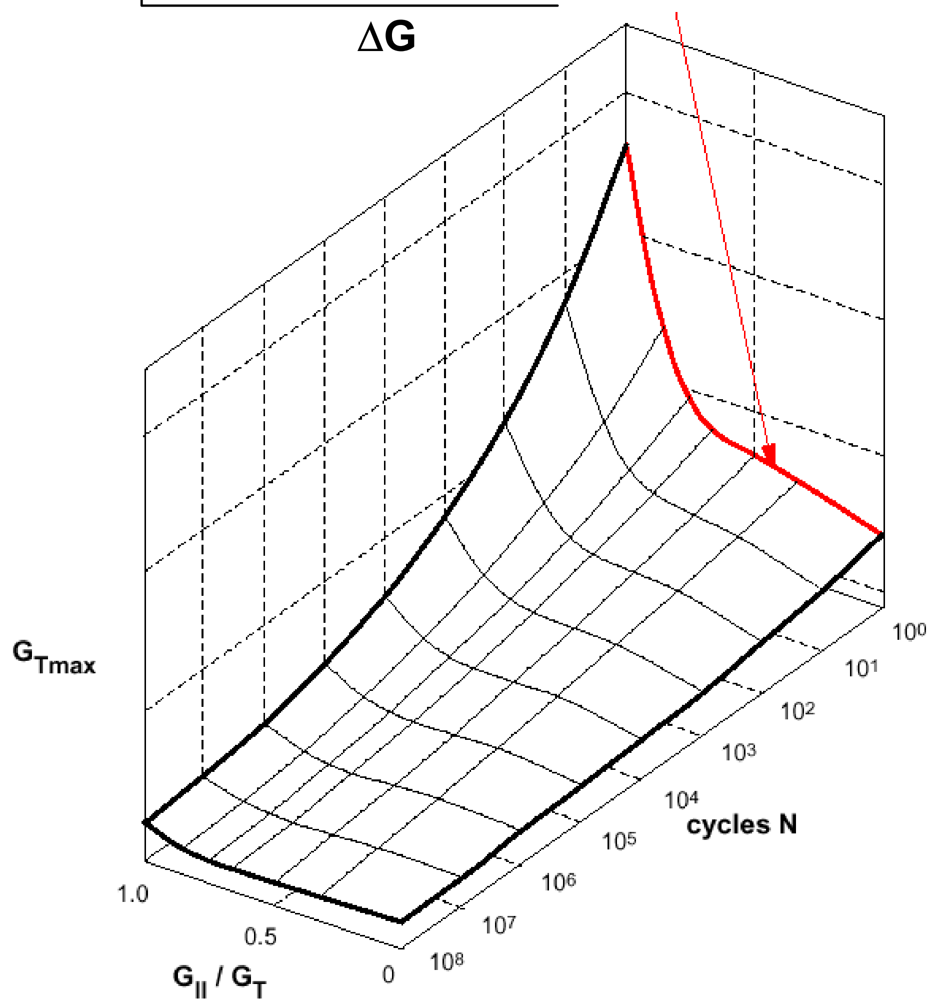
Fatigue Data Issues

- High fatigue data scatter
- Steep da/dN curve
- Together with current in-service NDI practices leads to “no growth” approaches

- Which G value(s) to use?
  - *G_{tot_MAX} (G from max cyclic load)*
  - *ΔG_{tot} (G_{tot_MAX} - G_{tot_MIN})*
  - *need mode mix?*
  - *normalize by R-curve?*

- Need complex data characterization or is there something simpler?





Overview - Analysis, Data, and Substantiation

- Design/Flaw Criteria
  - *Certification requirements*
  - *Flaws, damage, NDI threshold*
- Analysis Methods
  - *Closed-form eqns, A4EI, 2D vs. 3D, FEA*
  - *Failure criteria*
  - *Fracture, VCCT*
  - *Durability, damage tolerance*
- Design Data and Allowables
  - *Material properties for analysis*
  - *Design allowables, statistics*
- Substantiation
  - *Validate design, manufacturing processes, analysis methods*
  - *Satisfy certification requirements*
- Summary of Issues
  - *Safety critical items*
  - *Open issues, need for guidelines, R&D*

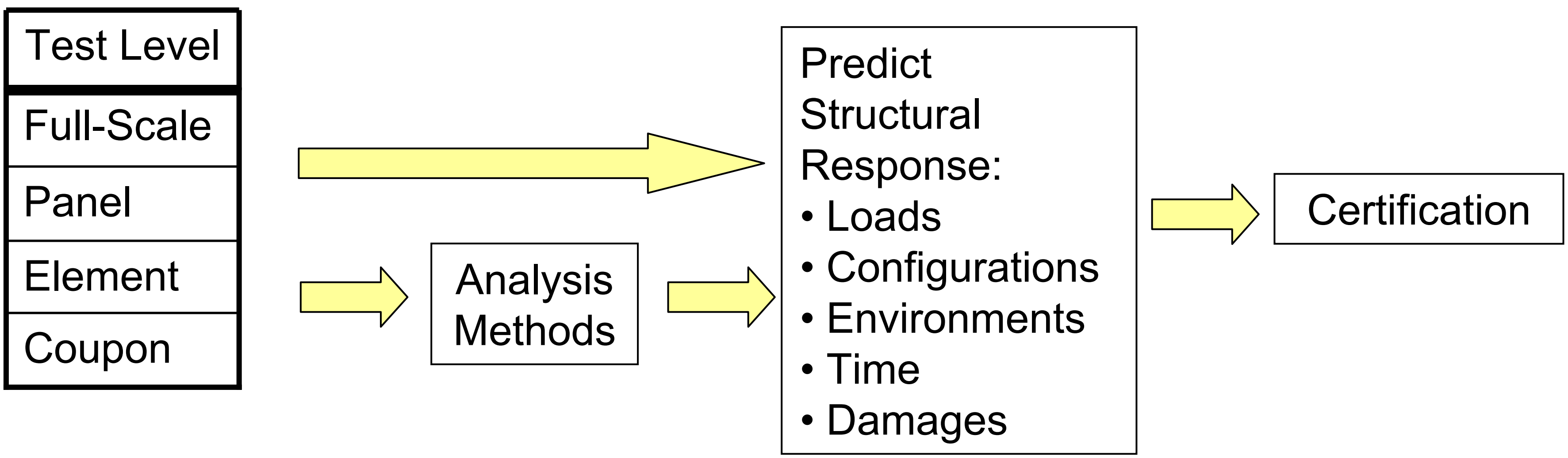
Structural Substantiation and Validation

Combination of analysis, testing, and documentation to demonstrate that all certification requirements are met.

Approach	Issues	Possible Applications
Certification By Test	•May be easier or cheaper for simple structure. •Certified design space limited to what is tested. •May be only option if analysis methods not available.	•Small aircraft •Secondary structure •Durability substantiation
Certification by Analysis (Validated by Test)	•For complex structure, less data needed to validate methods than to certify by test. •Analysis can be used to substantiate non-tested conditions.	•Primary structure •Static strength substantiation •Damage tolerance substantiation

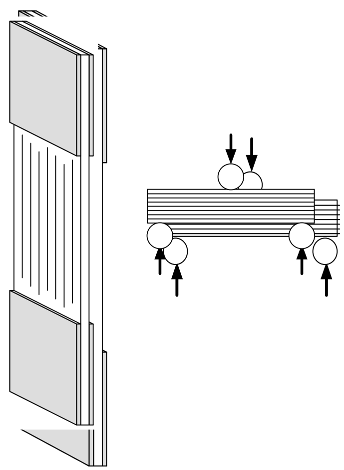
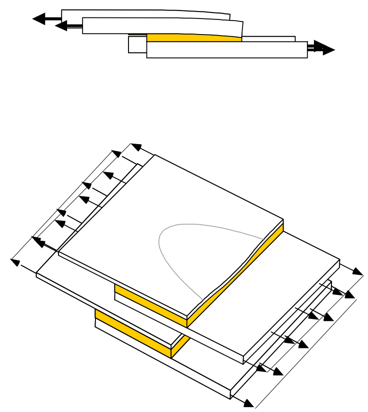
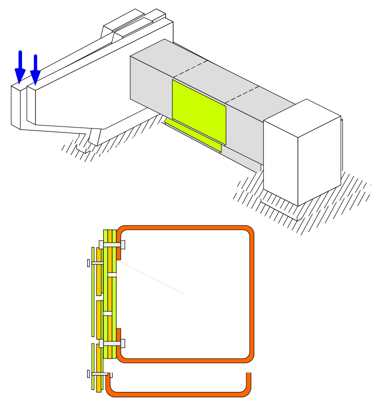
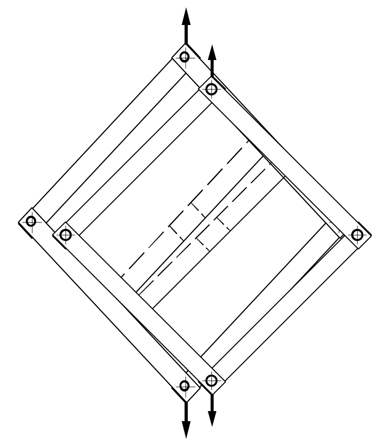
Structural Substantiation - Static Strength

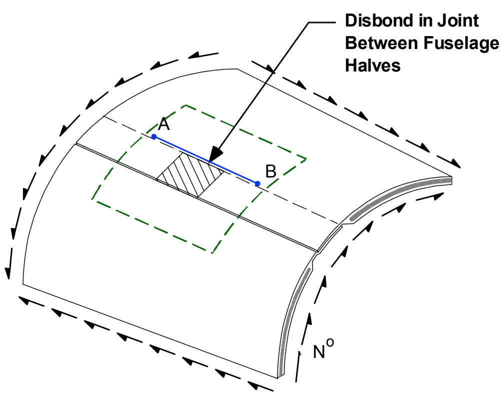
- Validate analysis methods over range of design variables, environments
- Validate manufacturing process over range of variables, conditions
  - *Include evaluation of process "failures"*
  - *For repairs, evaluate using real-world repair conditions*
- Element, panel, full-scale tests with non-detectable defects, damages
  - *Range of environments, multi-axial loading conditions*

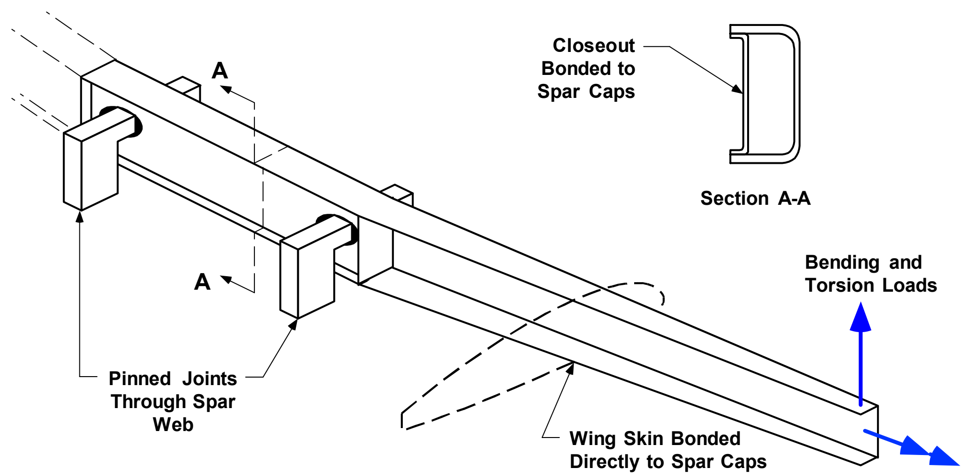


Validation and Substantiation Tests

Range of testing used to validate analysis methods and coupon design data.

Lamina and Laminate Properties	Effect of Variable Bondline Thickness	Box Beam Torsion Lap Shear	Disbonded Shear-Loaded Lap Joint
			





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Summary of Key Open Issues

Design/Flaw Criteria

- Need to balance economic realities of in-service inspection with need to detect damage/disbonds --> drives criteria
- Criteria to cover for large area process failures? Covered by DT criteria?
- At what size does the “no growth” assumption break down?
- Repairable damage limits for bonded repairs?

Analysis Methods

- Need fracture methods in “tool box”, needs to be “demystified”.
- Benchmarks and guidance needed to gain industry confidence.
- FEM/VCCT enabling, but also need to focus on simplified fracture methods.
- Pursue fatigue fracture methods to better understand growth thresholds.

Data and Substantiation

- Adhesive data not relevant for many failure modes.
- Appropriate level to generate statistical allowables?
- Fracture toughness data issues
  - *Standards needed*
  - *Effective Gc issue*
  - *Fatigue data issues*