



NORTHROP GRUMMAN
Ship Systems



Design and Analysis Methodology for Cost Effective Pultruded Composite Joints

Phase II Small Business Innovation Research Program

Product Design and Materials Technology Panel Meeting

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National Harbor, MD

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Introduction

- Composite structures are being developed to achieve low weight and multifunctional performance for U.S. Navy ship systems such as DDG1000
- Set-up time, touch labor and mold costs associated with current qualified fabrication processes remain obstacles to meeting production cost goals set by the shipbuilding industry
- Automated pultrusion processing, combined with integrated composite structures and joint designs, offers promise for reduced fabrication costs and improved material performance

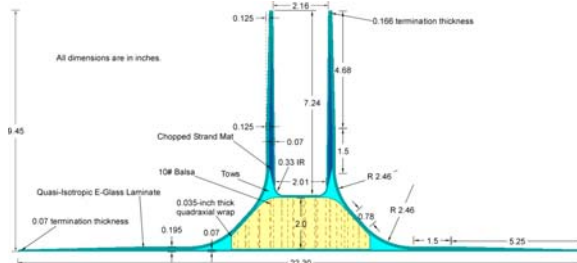




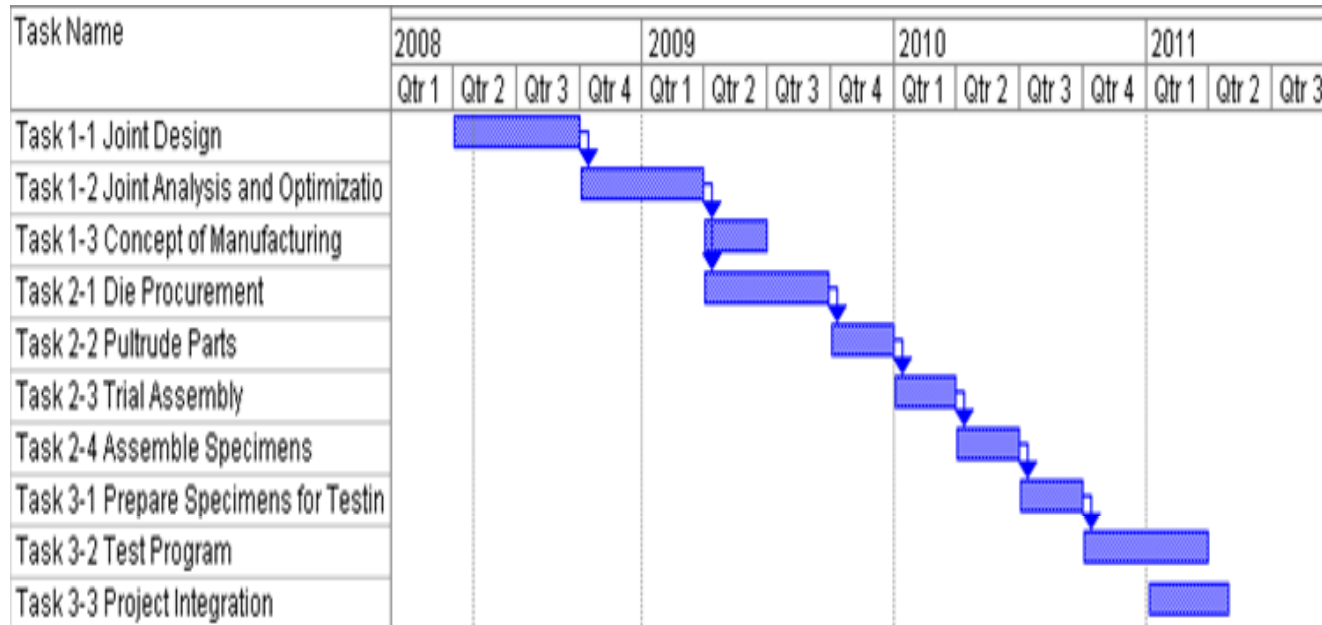
Objective and Integrated Product Team

Objective: Develop and demonstrate pultrusion manufacturing technology and integrated joining concepts that will reduce the cost to construct ships and thereby improve the competitiveness of the domestic shipbuilding industrial base.

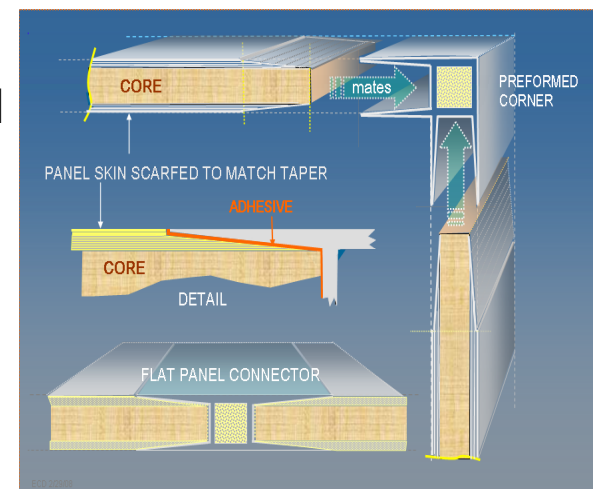
- Specific Technical Goals:**
1. Develop methods for joining pultruded panels.
 2. Demonstrate labor savings.
 3. Demonstrate equivalent strength.



Program Tasks



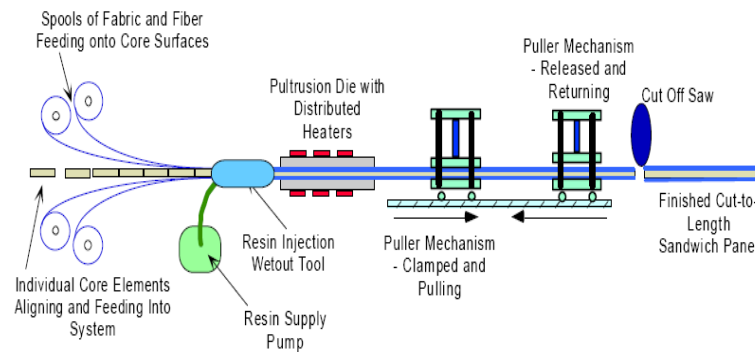
- Develop bonded joint system – goal is 100% strength of equivalent VARTM joint. Project would design, manufacture and test four standard joint connectors:
 - Flat
 - Corner
 - “T”
 - Cruciform



Pultrusion Technology - 1

Composites offer many advantages over conventional steel or aluminum structures, but the high initial cost of VARTM construction limits the application.

Low Cost Panel Manufacturing



Schematic of Pultrusion Process



10' wide panel manufacturing at KaZaK Composites

Production Capabilities for Automated Pultruder:

- Demonstrated rate of 9 inches per minute
- 3 technicians support machine while running
- One week of set-up and clean-up per run
- Material cost same or lower than VARTM

Comparison to VARTM:

- Panels are equivalent in strength
- Potentially higher quality and less variation
- Potential for on-line QA
- Lower waste and consumables
- Lower labor cost and fewer touches

Pultrusion Technology - 1

Pultruded Panel Assembly



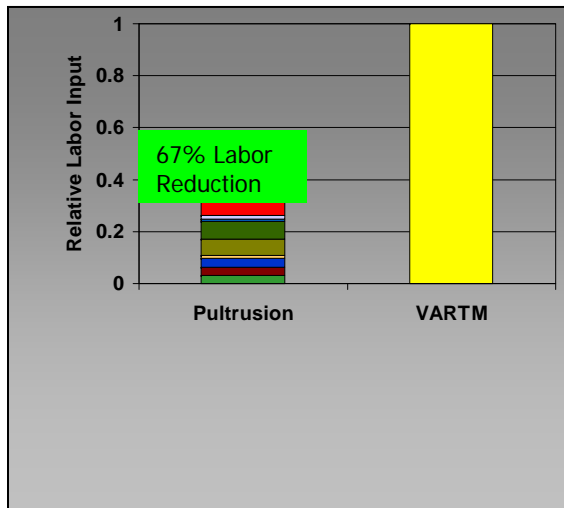
Staging



Assembly



20' x 40' Assembled Test Panel



Measured Labor Savings > 60%

Project Metrics

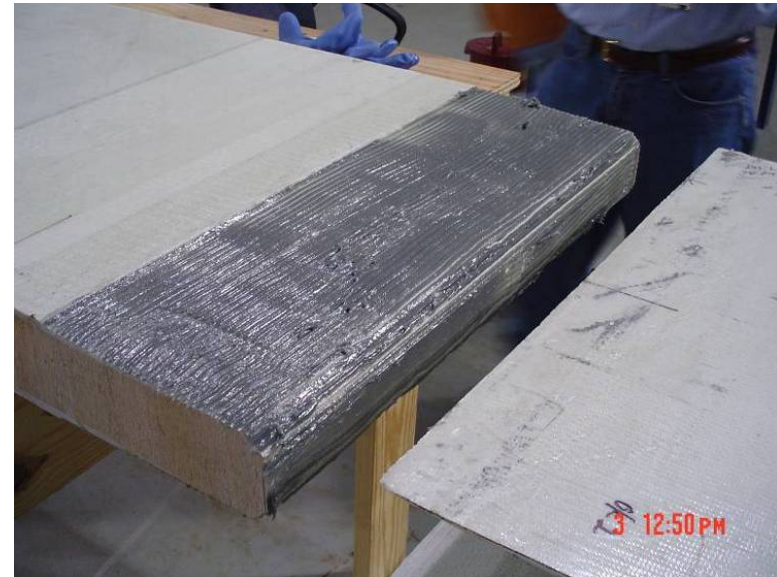
Panel Cost: Demonstrated > 60% reduction in labor hours compared to VARTM
 Bonded joint strength – goal is 100% of VARTM panel

Funding Plan and ROI

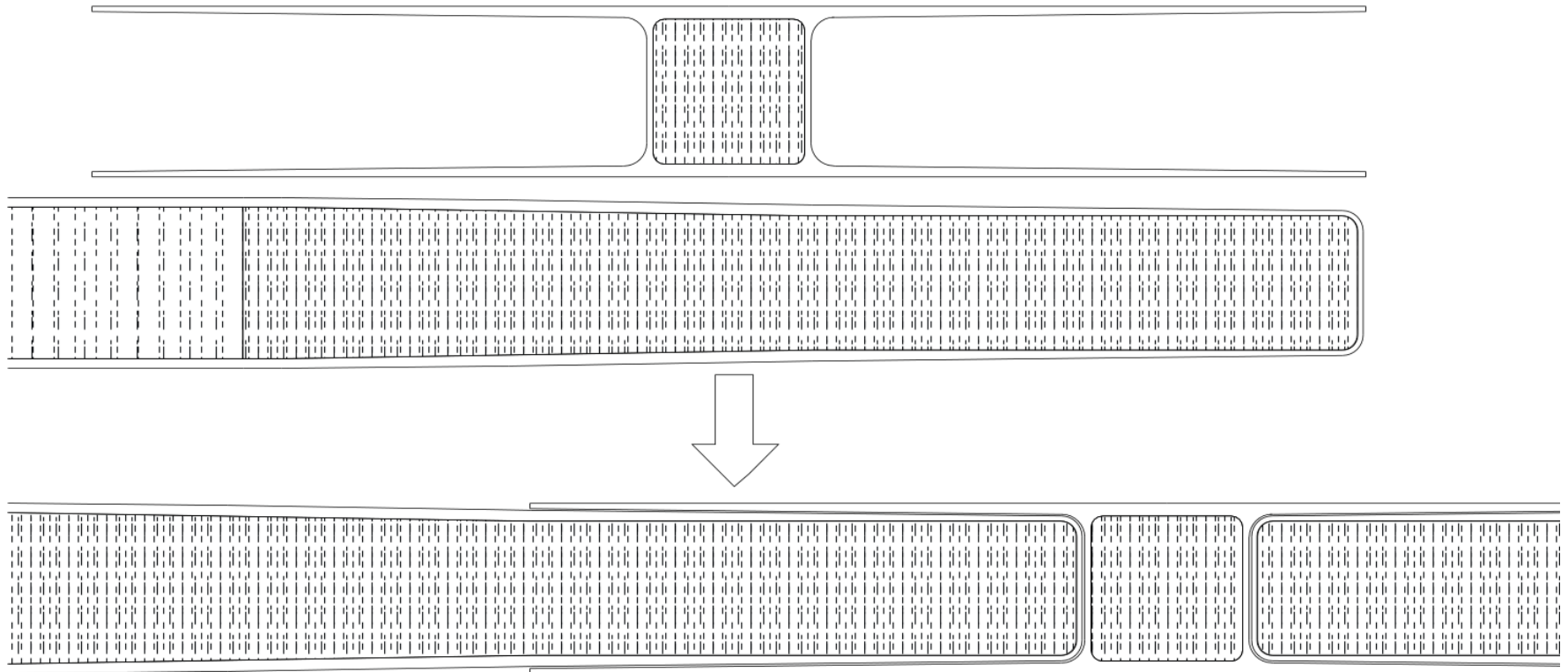
Funding: \$1.9m over 1.5 years
 ROI is >100% with 10 year with a NPV of ~ \$15MM



Assembled Panel Joint



Panel-Panel Joint Design

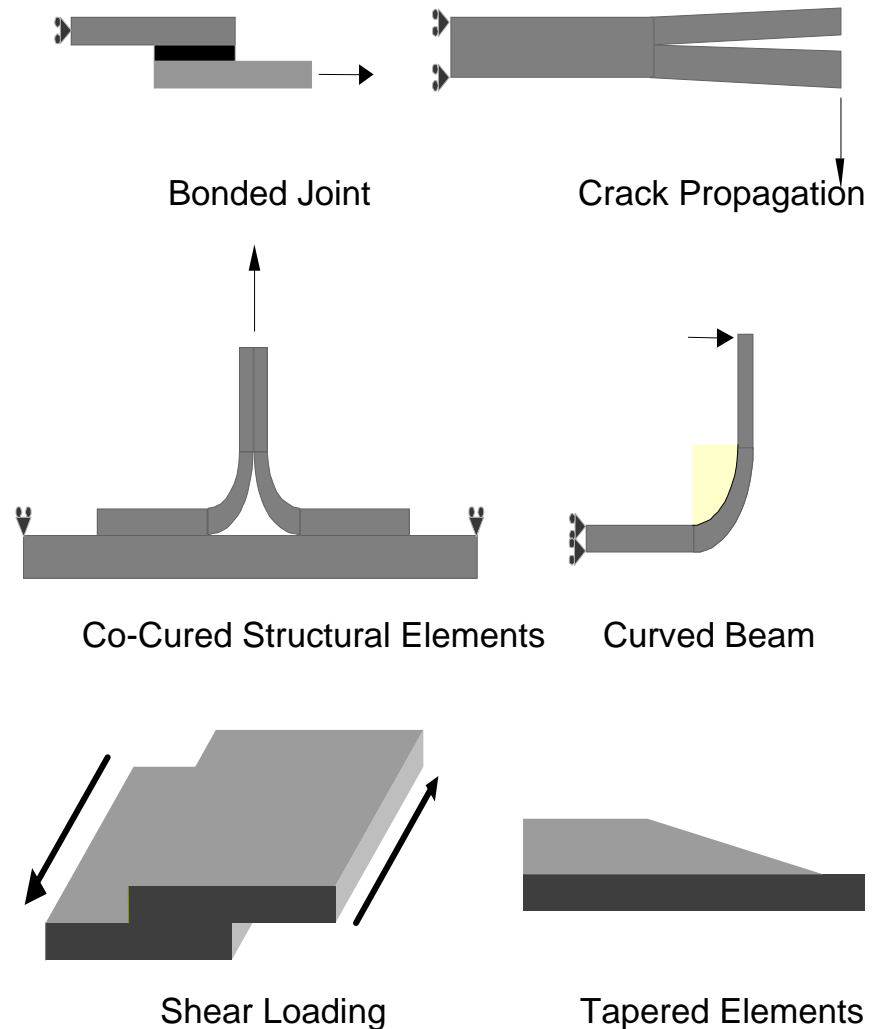


- Traditional FEA:
 - Pros:
 - Complex geometry can be modeled.
 - FEA can model highly nonlinear adhesives.
 - Cons:
 - Difficult to perform parametric studies on geometry.
- MSC Sublam:

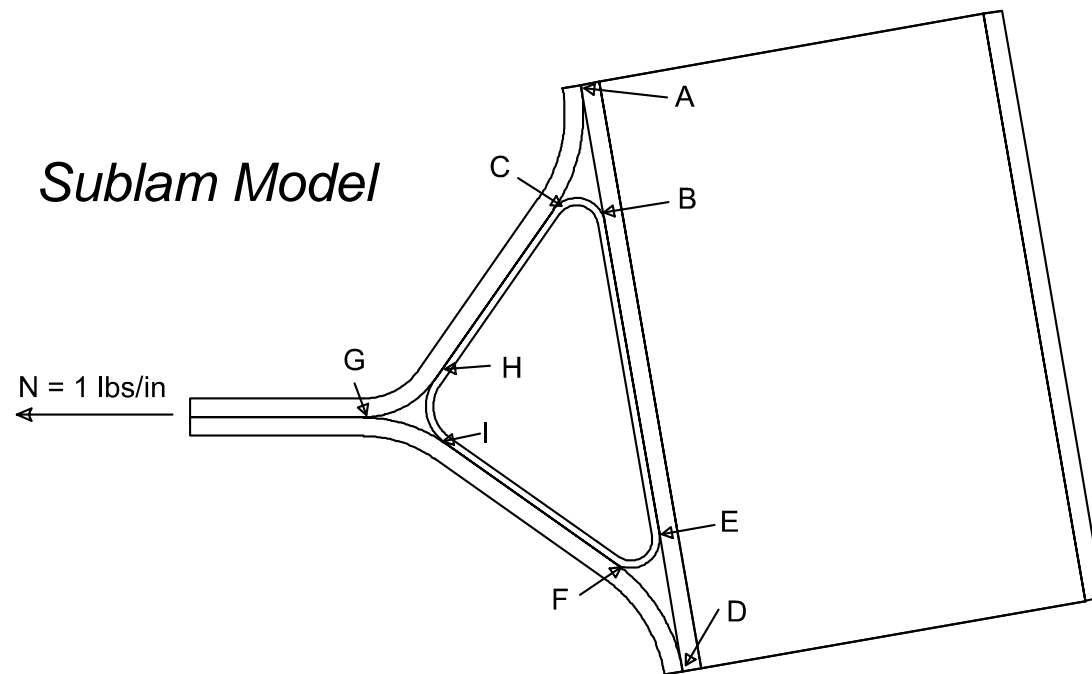
SUBLAM is an efficient tool that can be used for interlaminar stress analysis of composite laminates and structures, and for rapid evaluation of strain-energy-release-rate

 - Pros:
 - Elastic-plastic nonlinear adhesives can be modeled.
 - Parametric studies can be easily performed.
 - Cons:
 - Some complex geometry might be difficult / impossible to model.

Example Sublam models



Cross-Section of Typical Built-Up Joint

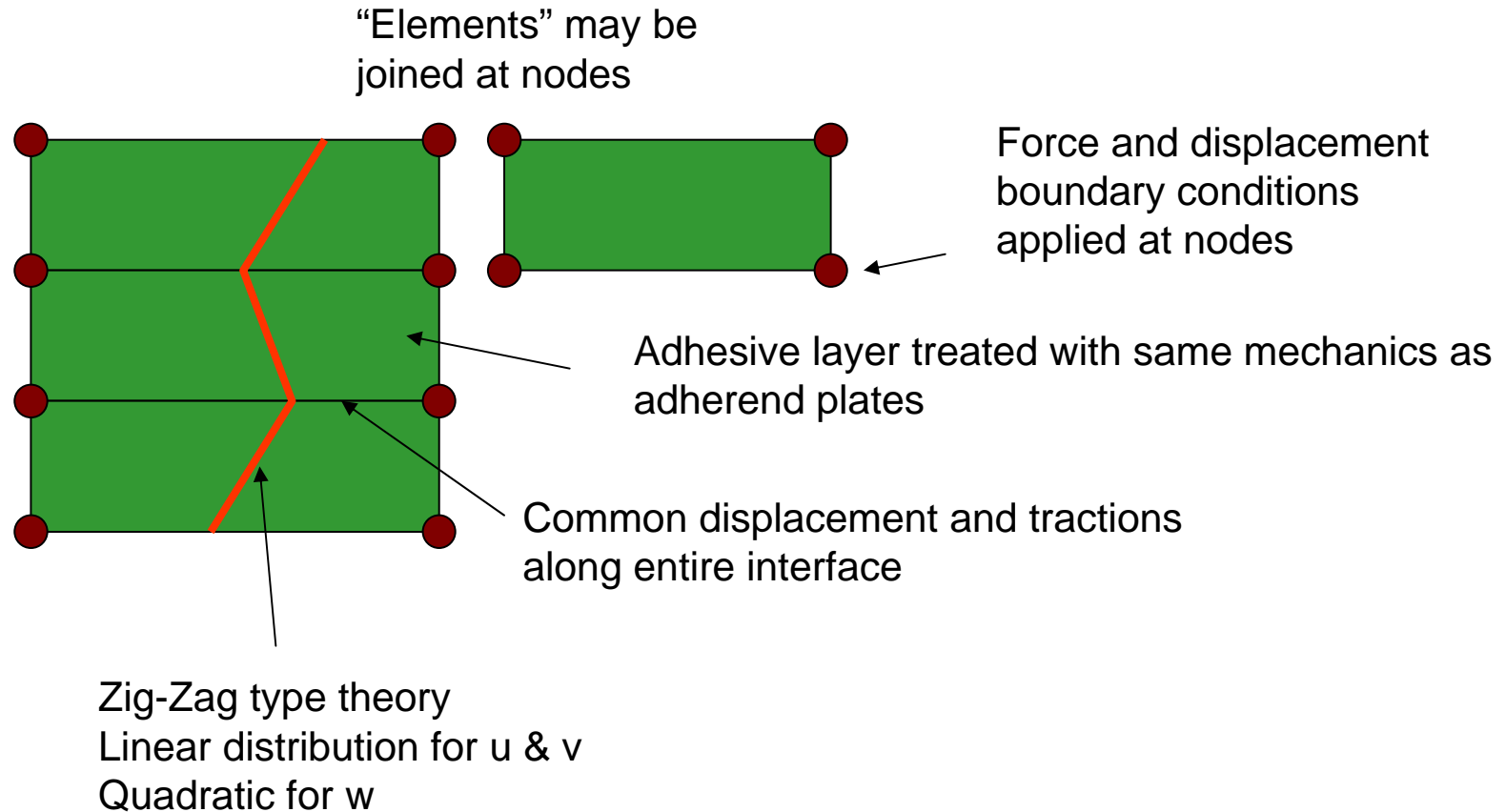


- Labeled spots are interlaminar stress “hot-spots” that can initiate a delamination
- Delamination propagation is the typical failure mode for these types of joints
- Designers need a convenient tool for predicting the strength of composite joints.

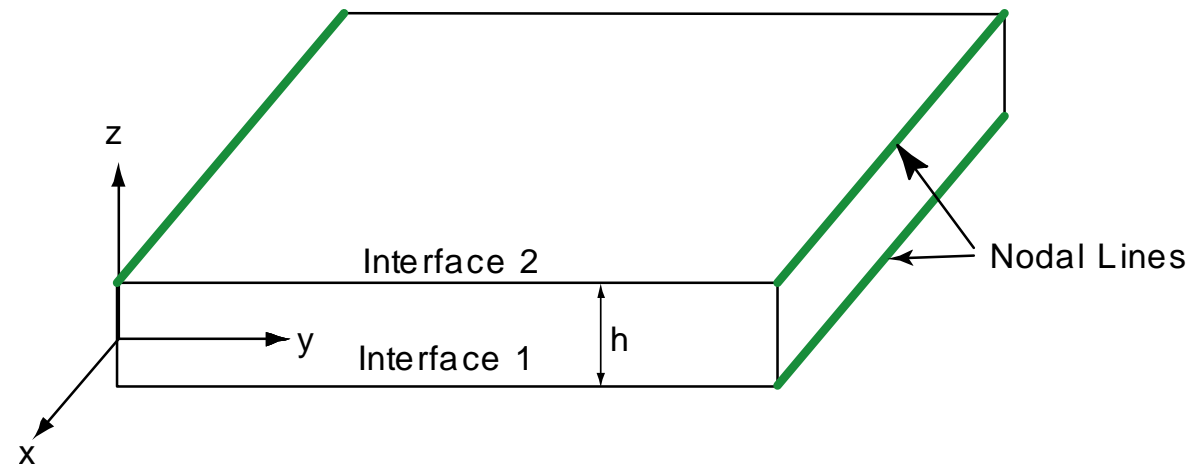
SUBLAM Analysis Approach

- High-Order plate theory for each sublaminates
 - Linear shear and quadratic through-thickness stretching
- Stacking sequence within sublaminates accounted for explicitly, including higher-order moments
- Sublaminates can be stacked such that displacement and traction continuity is maintained along entire interface
- Closed-form solutions computed for resulting coupled differential equations
 - No discretation error. Steep stress gradients are not a problem
- For nonuniform plates, solution switches to approximate energy method using Legendre polynomials (P-Element method)
 - Equilibrium equations used to extract interfacial tractions
- A stack of sublaminate form a single element. Elements can be joined as in FEA method. Boundary conditions applied as in FEA method

Some Concepts from SUBLAM



Kinematics of a Single Layer



$$u(x, y, z) = \frac{1}{2} [u_2(x, y) + u_1(x, y)] + \frac{z}{h} [u_2(x, y) - u_1(x, y)]$$

$$v(x, y, z) = \frac{1}{2} [v_2(x, y) + v_1(x, y)] + \frac{z}{h} [v_2(x, y) - v_1(x, y)]$$

$$w(x, y, z) = \frac{1}{2} [w_2(x, y) + w_1(x, y)] + \frac{z}{h} [w_2(x, y) - w_1(x, y)] +$$

$$\Psi_w(x, y) \left[\left(\frac{2z}{h} \right)^2 - 1 \right]$$

Stacking Sequence Dependence

- Within a plate, stacking sequence information is retained using through-thickness integrations similar to CLT.

$$\{A_{ij}, B_{ij}, D_{ij}\} = \int_{-h/2}^{h/2} C_{ij} \{1, z, z^2\} dz \quad (i, j = 1, 2, \dots, 6)$$

$$\{N_i^T, M_i^T, R_i^T\} = \Delta T \int_{-h/2}^{h/2} C_{ij} \alpha_j \{1, z, z^2\} dz$$

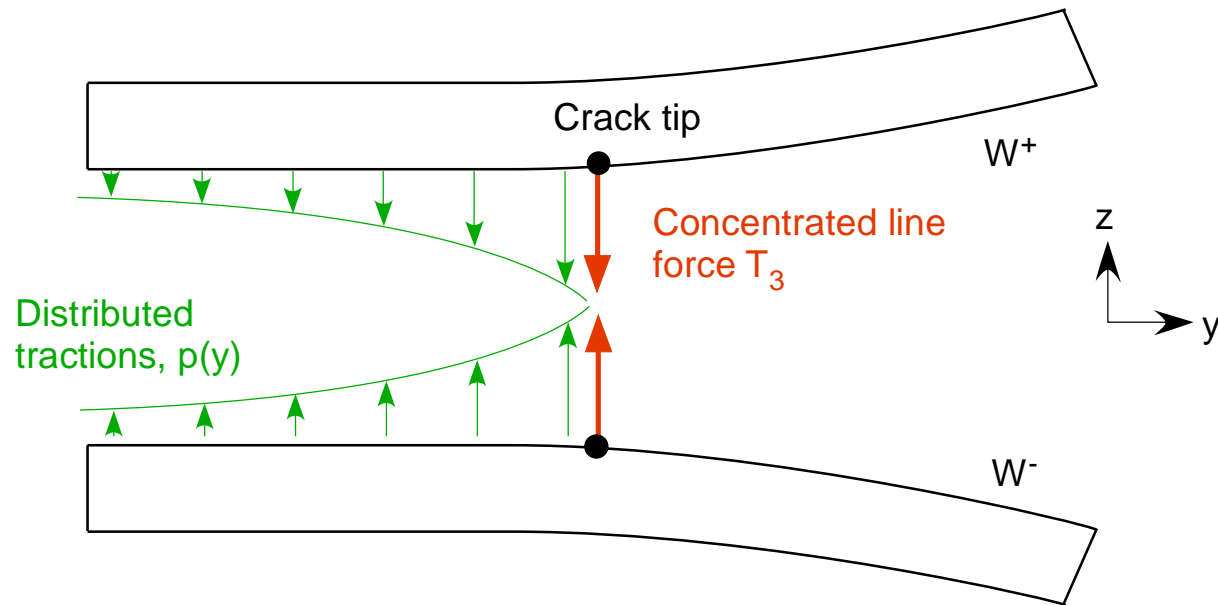
$$(i, j = 1, 2, 3, 6)$$

- Additional matrices that result from kinematic assumptions

$$(D_{ij}^{(3)}, D_{ij}^{(4)}) = \int_{-h/2}^{h/2} C_{ij} \{z^3, z^4\} dz \quad (i, j = 4, 5)$$

- For curved plates, there are additional matrices, including a $\log(r+z)$ dependence

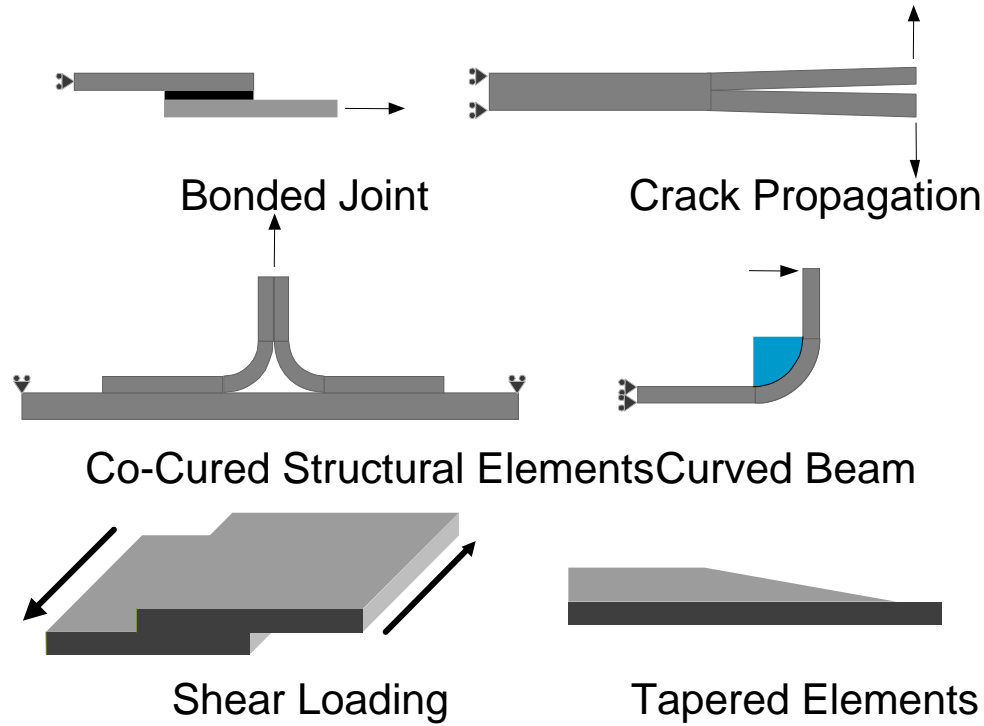
Single-Step SERR Calculation



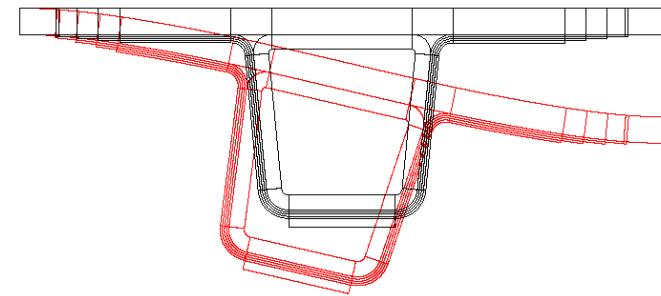
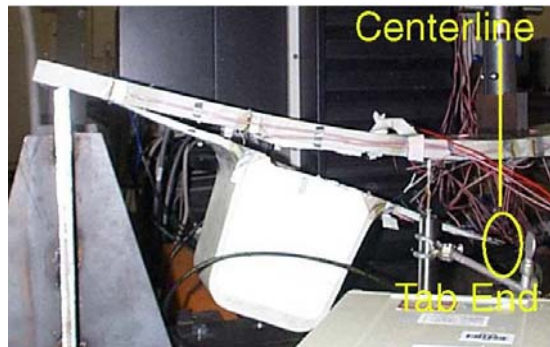
$$G_I = \mathit{Limit}_{\delta a \rightarrow 0} \left[\frac{1}{2\delta a} \int_0^{\delta a} t_3(y) w^*(y_1) dy_1 \right] \longrightarrow G_I = T_3 w^{*'}(0^+) / 2$$

T_3 is a nodal line, concentrated force
 W^{*} is the gradient of the opening displacement at the crack tip

Modeling Features

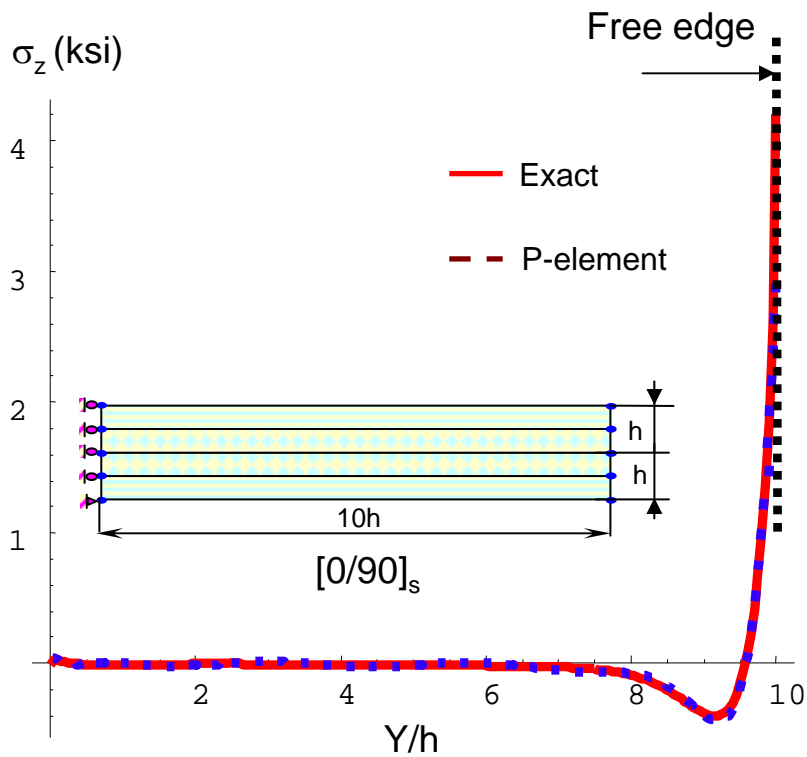


“Complex” models

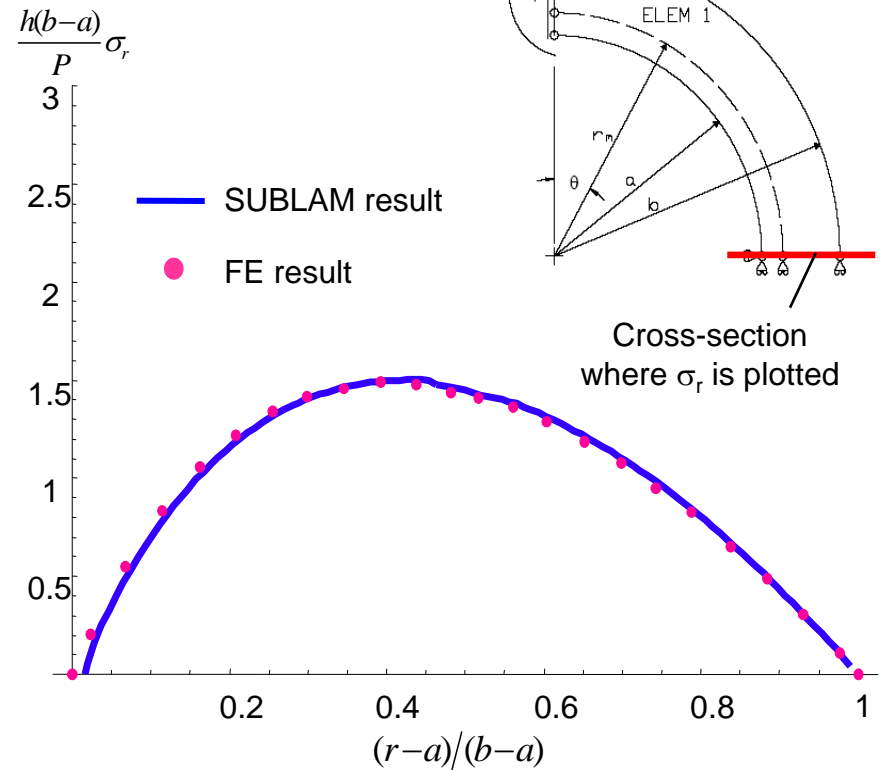


Analytic Checks

Element verification:

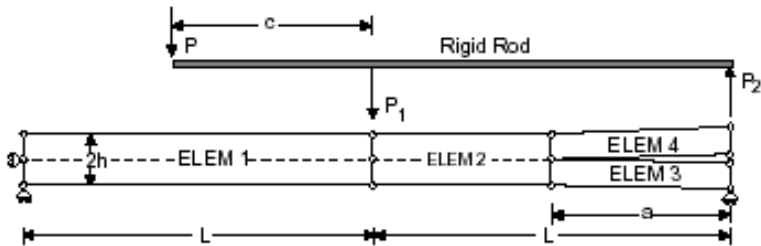


Free edge stress



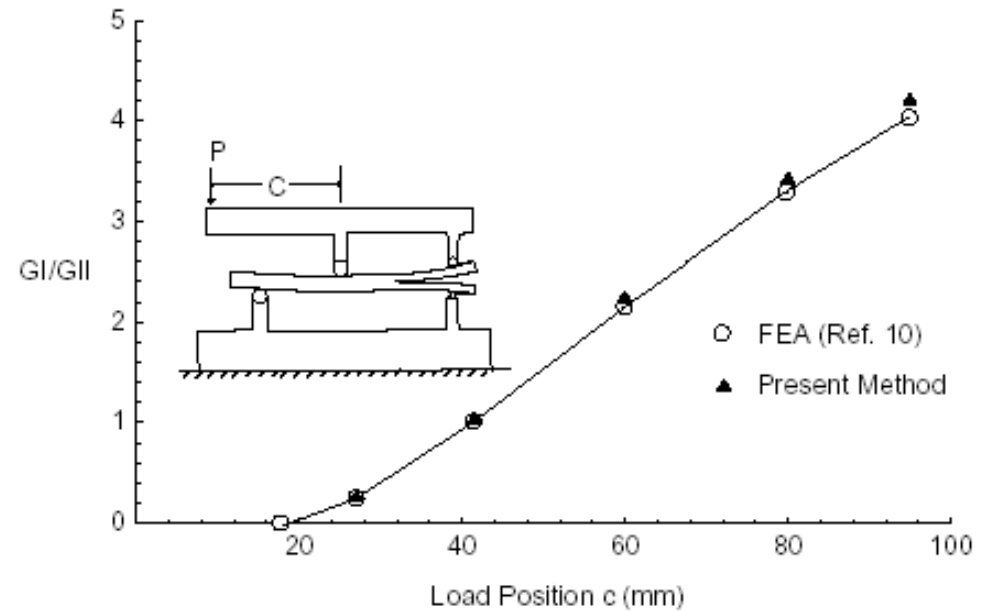
Curved Beam under end load

Simulation of Fracture Tests

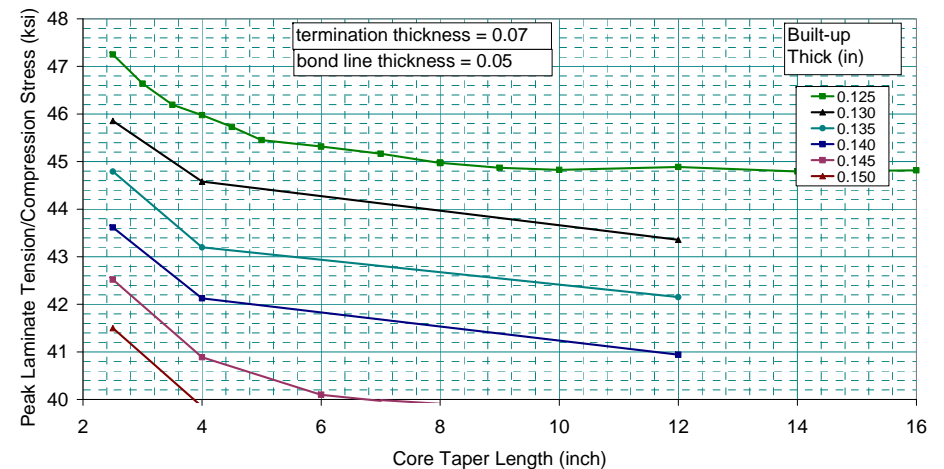
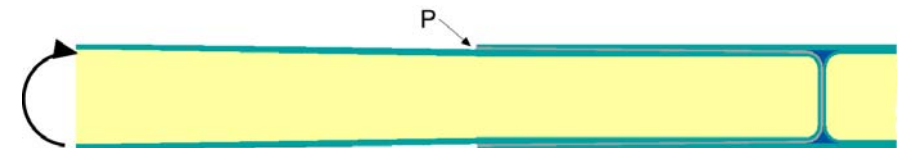
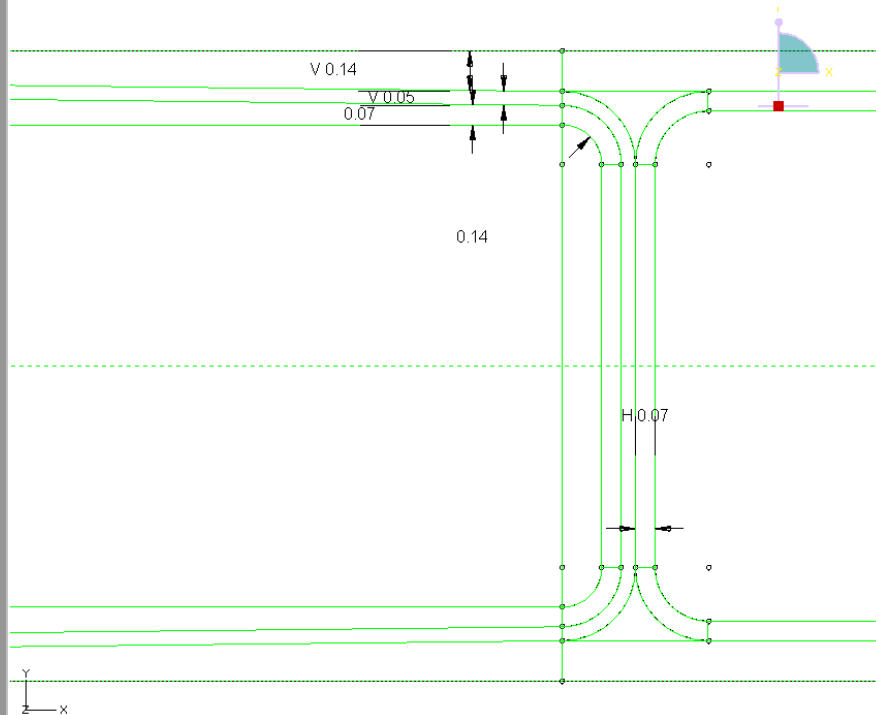


SUBLAM and reference results
for mode I to II ratio

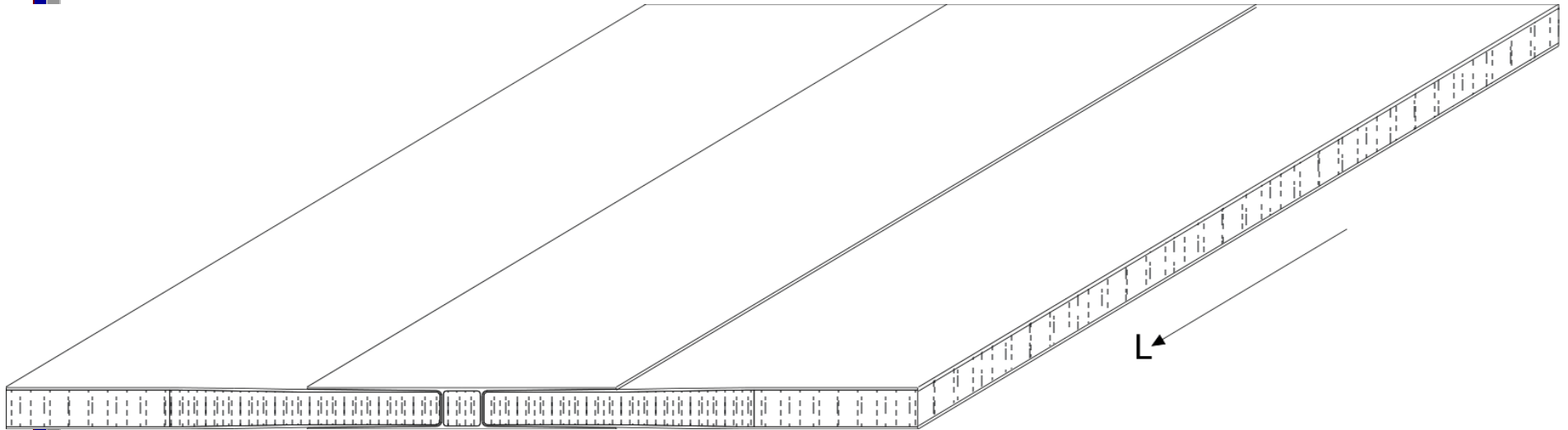
Mixed-mode fracture test



- Geometry defined parametrically in Abaqus CAE (a commercial FE pre- and post-processor)
- Python scripts update geometry and post-processes stress predictions for plotting.

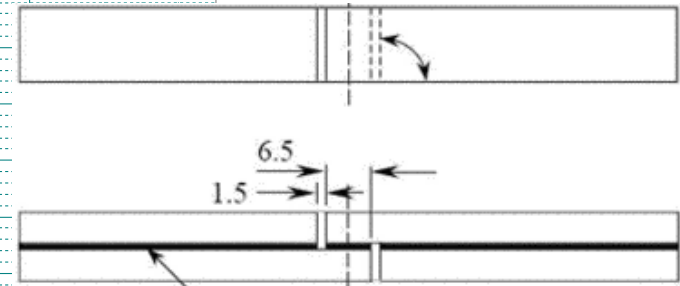
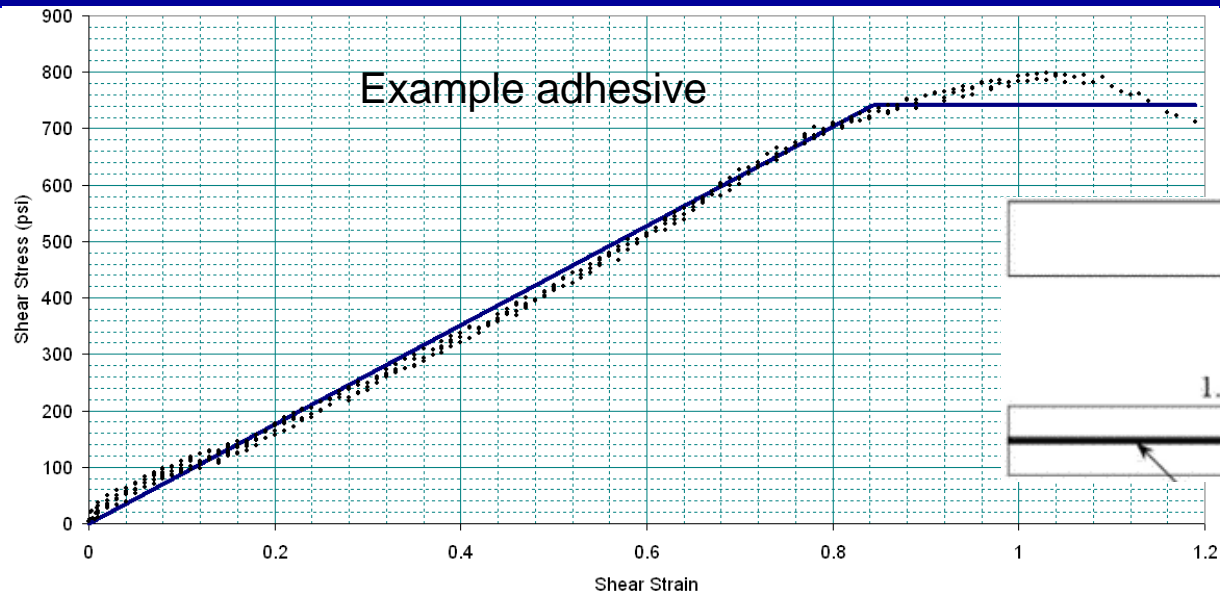


Stress at P vs design parameters



- Cross-section of the joint was modeled.
 - In prismatic structures such as our joint, the length of the structure is much greater than the other joint size. The strains associated with length are constrained by nearby material and are assumed small compared to the *cross-sectional strains*.
 - Laminate modeled as an equivalent homogenous material properties derived from ply-by-ply stiffnesses and strengths.

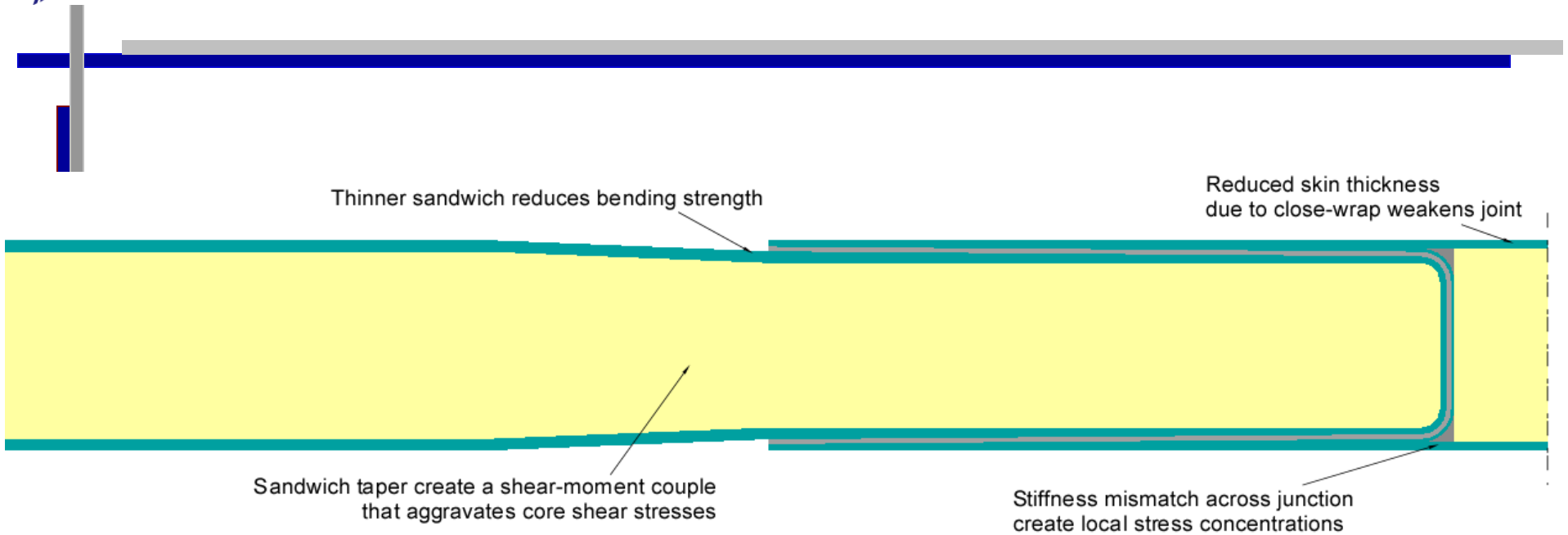
Elastic Perfectly-Plastic Adhesive Model



- Adhesive parameters chosen to simulate measured adhesive response.
 - The adhesive was modeled as a elastic-perfectly plastic in shear.
 - The adhesive acts linear-elastic until the threshold shear stress is reached. The shear stress is then constant until strain-to-failure occurs.
 - The parameters of the adhesive model are derived from test data.
 - The strain-to-failure is equal to the measured strain-to-failure.
 - The elastic shear modulus (G) and threshold shear stress (τ) are chosen to match energy-to-failure.
- Energy-to-failure is the area under the stress-strain curve.

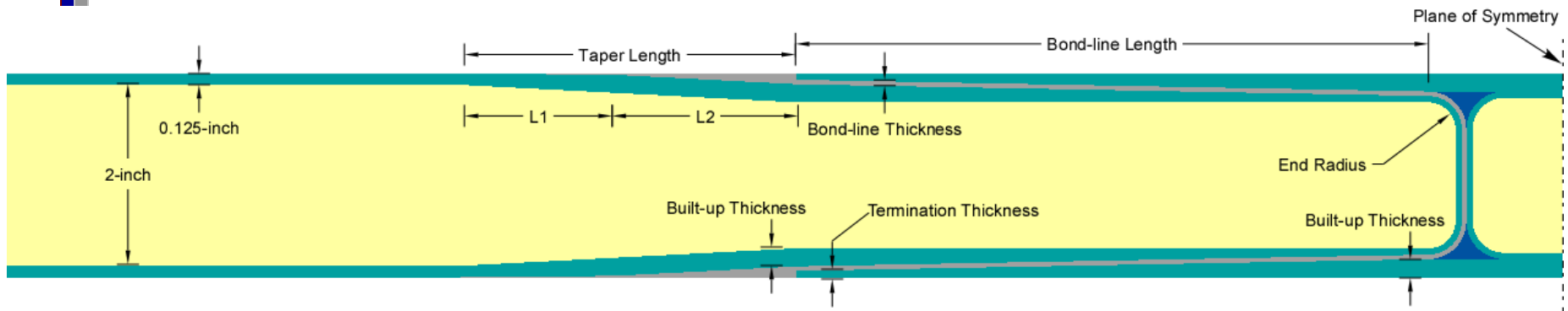


Challenges in Matching Panel Strength



- The bonded joint should exceed the strength of a similar unbroken sandwich panel.
- Necessary joint features can reduce strength. Facesheet thickness and core strength increased to compensate.

Design Parameters

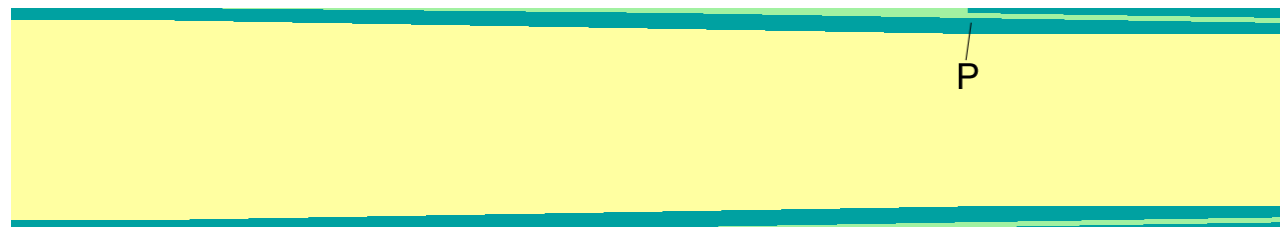
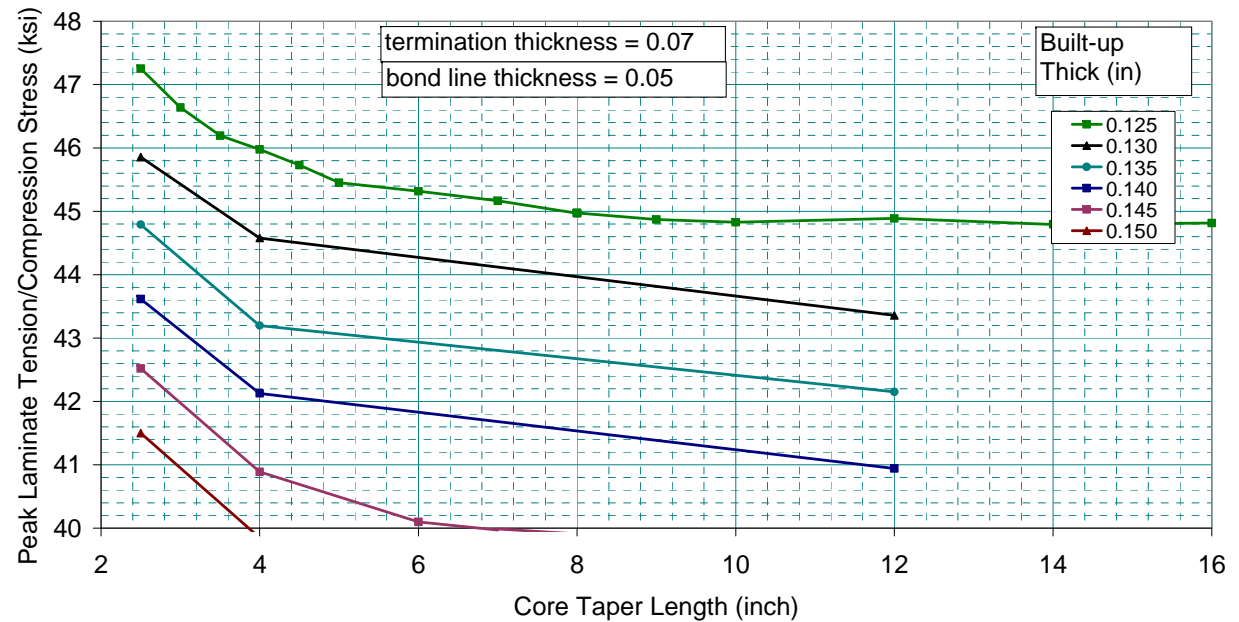


- Joint geometry defined parametrically to assess core and laminate stresses.
- Approximately 500 variants were modeled. Stress response was charted against design variables.

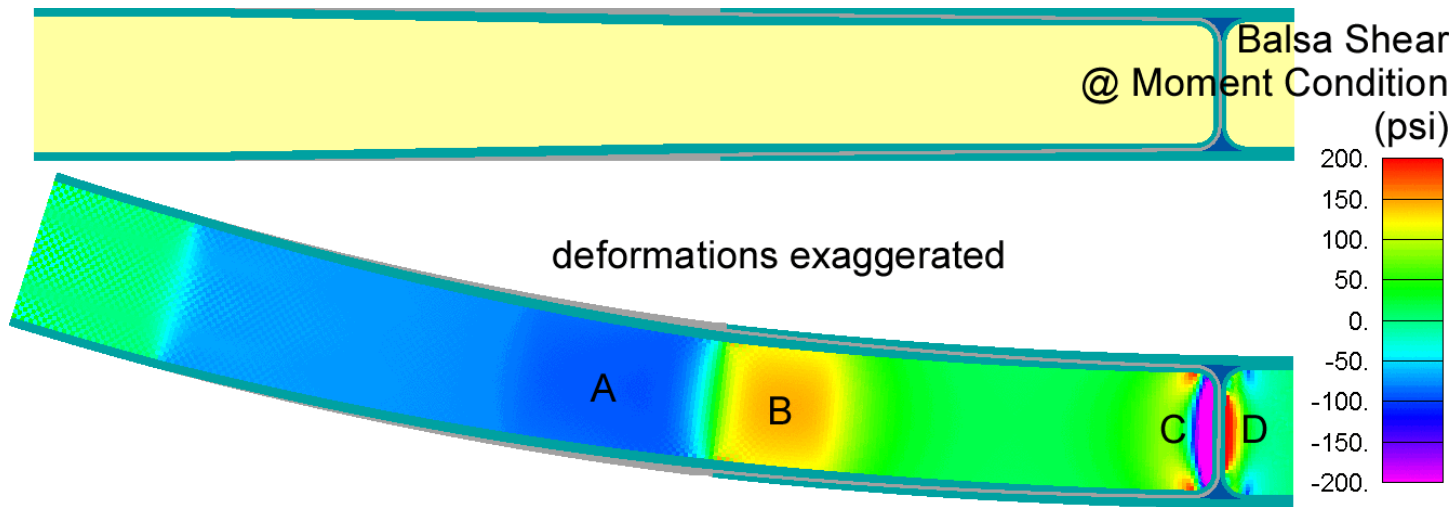
Facesheet Stresses

The laminate is built-up along the taper to reduce peak stress at P.

- Build up thickness depends upon the termination thickness, the bond-line thickness, and the taper length.
- Too short a taper length will bend the laminate at the inside corner between the tapered and flat core (location P).

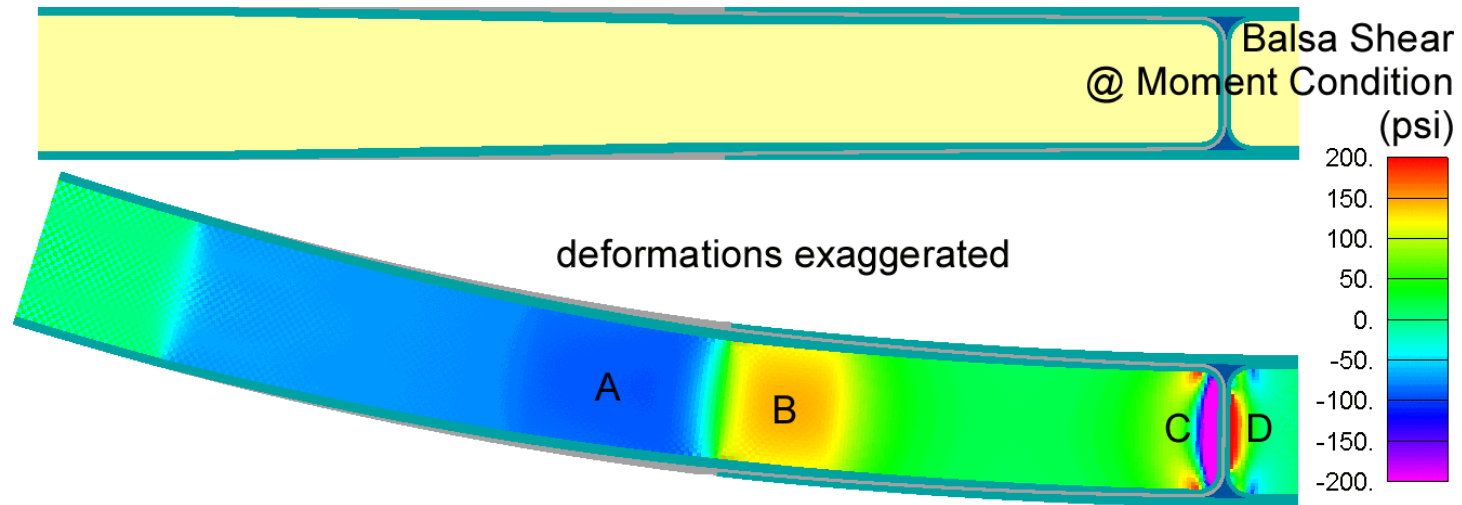


Core Shear Issues



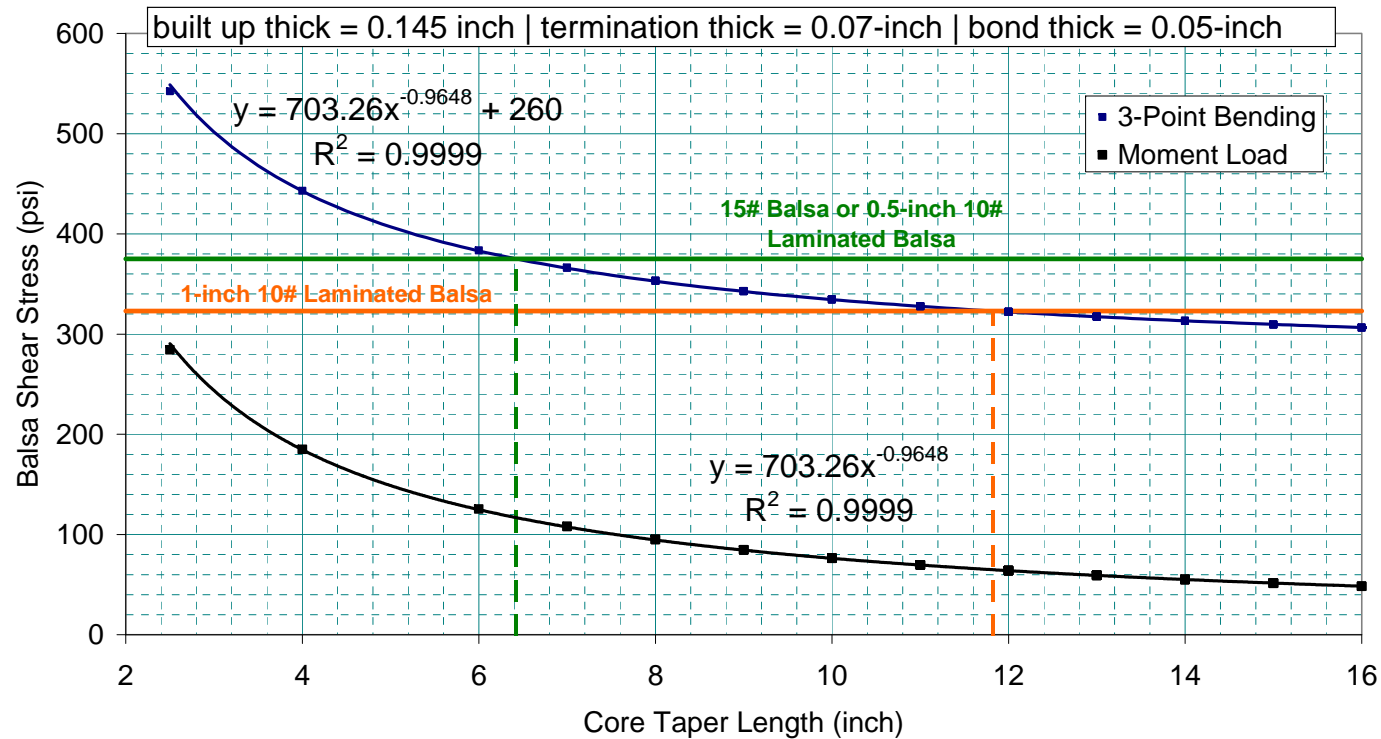
- Unlike in a uniform sandwich panel, bending and tension loads stress the core significantly.
 - The sandwich taper and abrupt changes in facesheet stiffness create large stress concentrations.

Parameters that Affect Core Shear



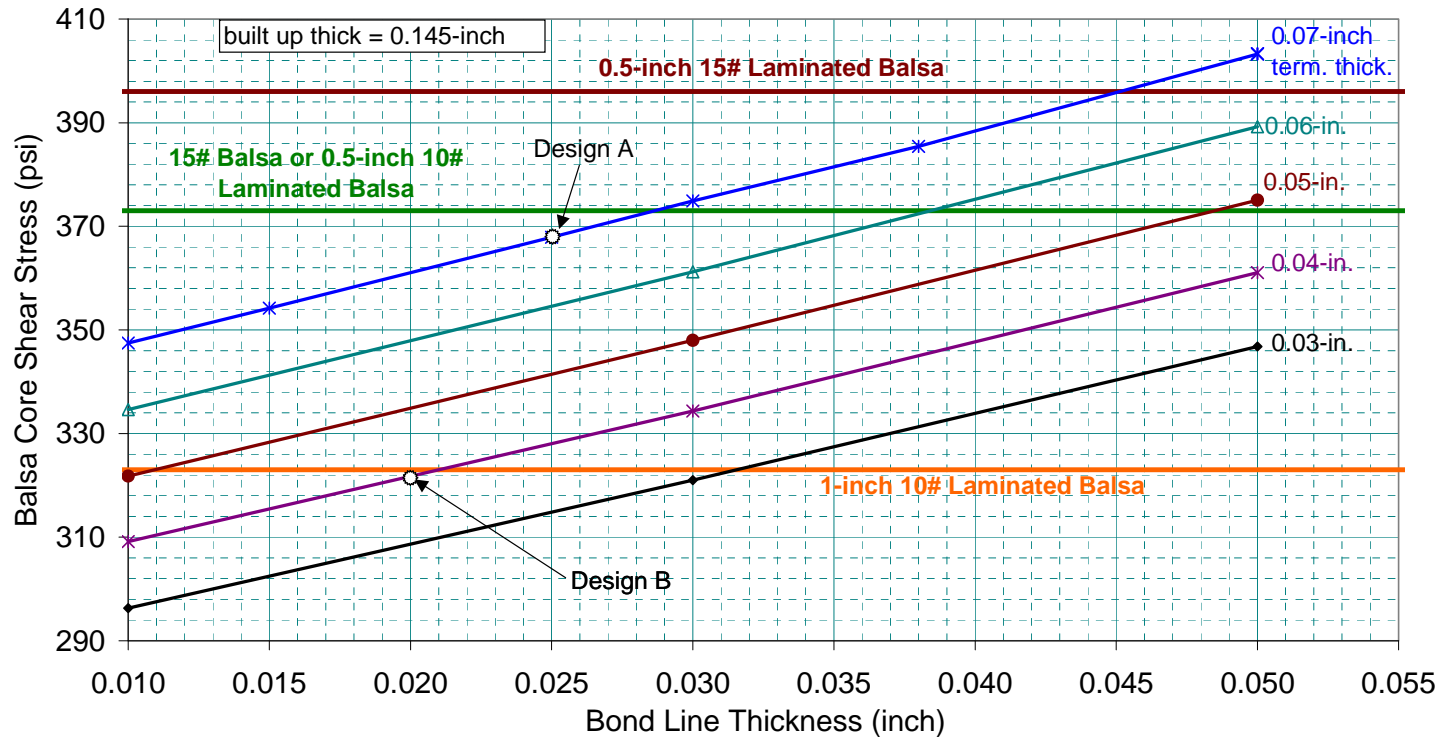
Region	Built-up Thickness	Built-up Location (L1/L2)	Termination Thickness	Taper Length	Bond-Line Thickness
A	Detrimental	Insensitive	Detrimental	Beneficial	Detrimental
B	Insensitive	Insensitive	Detrimental	Insensitive	Detrimental
C	Beneficial	Insensitive	Detrimental	Insensitive	Insensitive
D	Beneficial	Insensitive	Detrimental	Insensitive	Detrimental

Shear Stresses at Region A



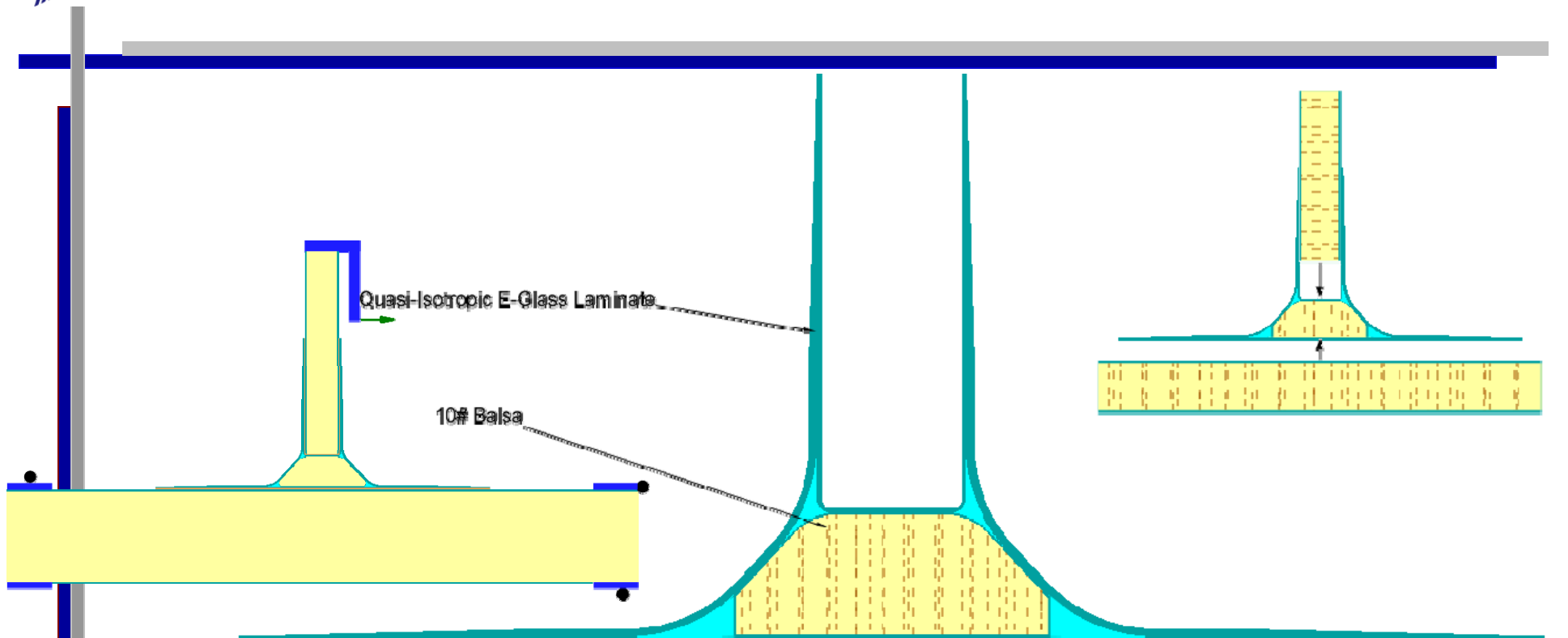
- Geometric parameters and core materials can be chosen for expected stresses.
 - Iterate to see if changes to core stiffness affects expected stresses.

Shear Stresses at Region B



- Under the tension design load, the core shear stress was minor.
- Under the shear design load, the core shear stress can be computed by scaling the far-field stress of 222-psi by the ratio of the far-field core thickness to the local core thickness.
- Under the moment and 3-point bend design loads, the eccentricity creates significant shear stresses at B. Of the parameters varied, the shear stress at region B under moment loads is only affected by the termination thickness and bond-line thickness. 3-point bend is the superposition of the shear and moment conditions, so the trends of both conditions apply.

T-Joint Design and Analysis



- T-connector can be adhered to any thickness and strength continuous panel.
 - The T-joint connector was designed to remain intact when bonded to weak or relatively strong panels and loaded to failure.
 - The joint was modeled for pull-off and bending conditions.
 - Loads easily simulated in a lab and represent typical structural loads.



Summary and Future Work

- Panel-panel joint design and laminate detail completed for pultrusion manufacturing development and demonstration
- T-joint connector and cruciform design completed for pultrusion manufacturing development and demonstration
- Pultruded panels and T-connectors to be produced at Kazak
- Assembled panels to be loaded to failure under cyclic fatigue and quasi-static conditions.