Composite Bonded Joint Stress Analysis

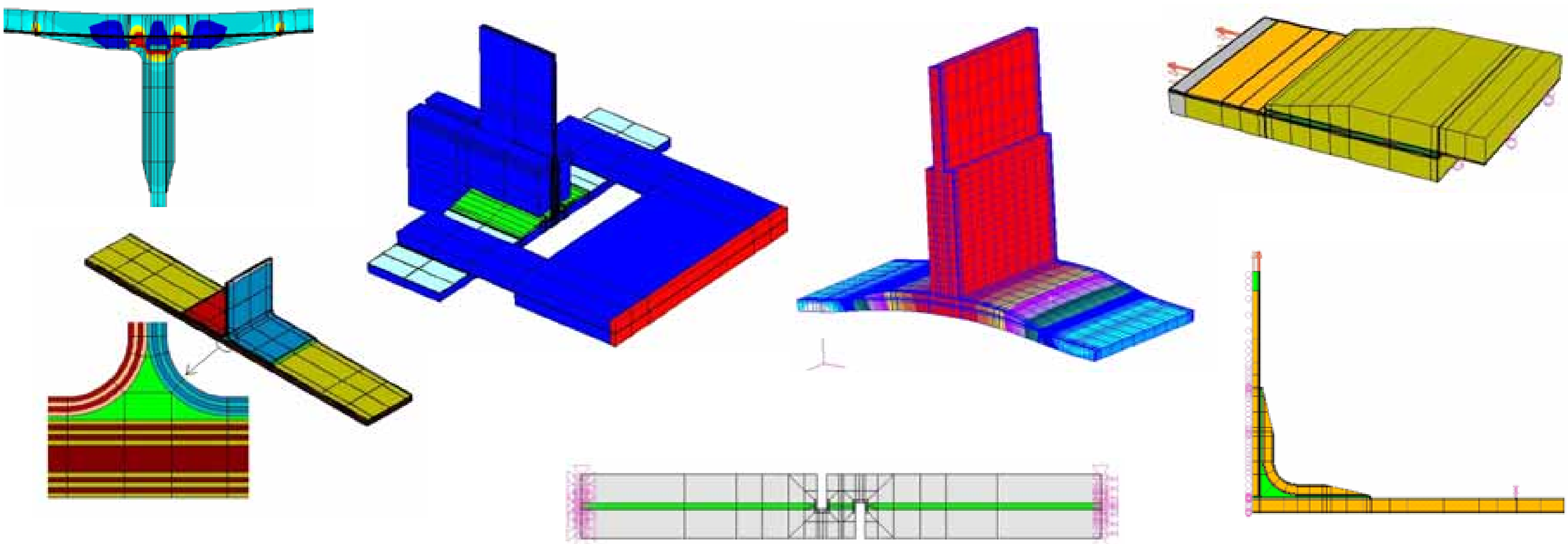
Composites Affordability Initiative Technology Advances

ASIP 2006

28 November 2006

Steve Engelstad

Lockheed Martin Aeronautics Company



Participants

LM Aero	**Boeing**
Steve Engelstad	Steve Wanthal
Owen Berry	Gary Renieri
	Jeff Wollschlager
Northrop Grumman	**Bell Helicopter**
Dave Kane	Xiaoming Li

Outline

- Overview
- StressCheck
  - Advantages
  - CAI-funded enhancements
  - Validation
- Zig-Zag Elements
- Summary

Analysis of Large Bonded Composite Structural Assemblies

- **Validated Analysis Tools Viewed as the Key Enabler for Application of Innovative Manufacturing and Bonding Technologies for Airframe Primary Structure**
- **Prior Analysis Techniques (such as A4EI) are Limited for Widespread Production Application of Bonded Joints**
- **Certification of Bonded Joints Hinges on Availability of Validated Analysis Tools**
- **This lead to our overall Objective:**

Objective

To develop improved analysis tools to support the timely analysis of bonded/cocured joints and IRC structures including structural trade studies, detailed stress analysis and failure prediction

Background

- **In 1997, CAI down-selected the StressCheck p-version software and Zig-Zag h-element capabilities as potential targets for this analysis tool**
- **Focus during CAI Static Tools development**
  - Provide the Analysis Tool necessary to obtain the correct stress/strain distributions in the adherends and adhesive bondlines
  - To provide Electronic Handbooks Analysis Capabilities to our programs
  - Investigate new failure criteria as necessary to provide Analysis Methodology for failure predictions of adherends and bondlines
  - Provide guidance to others on how to implement the Tools and Methods to solve composite bonded joint problems

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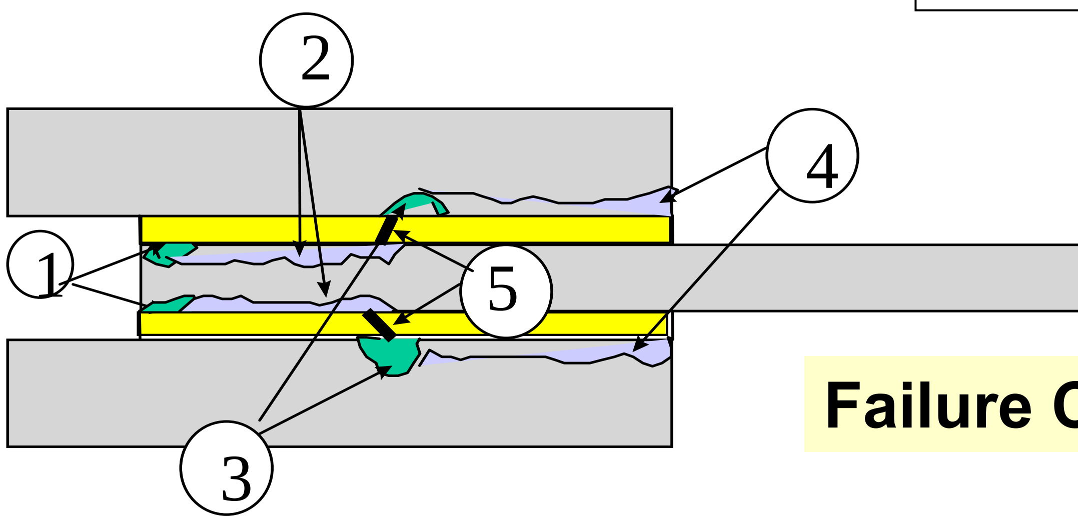
Analytical Tools Example

Analysis Must Predict Real Joint Failure Modes

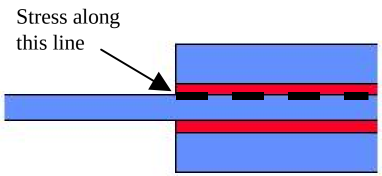
- **Bonded Joint Failure Scenarios**
  - **1. Damage Initiation at Adhesive/Adherend Interface**
  - **2. Damage Propagation Along Weak Interface**
  - **3. Secondary Damage Initiation Site**
  - **4. Transverse Tension Failure in Adherend Plies**
  - **5. Adherend or Adhesive Strength Failure**

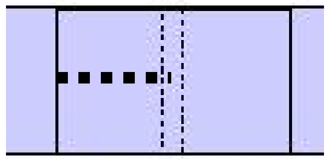
StressCheck targeted these failure modes



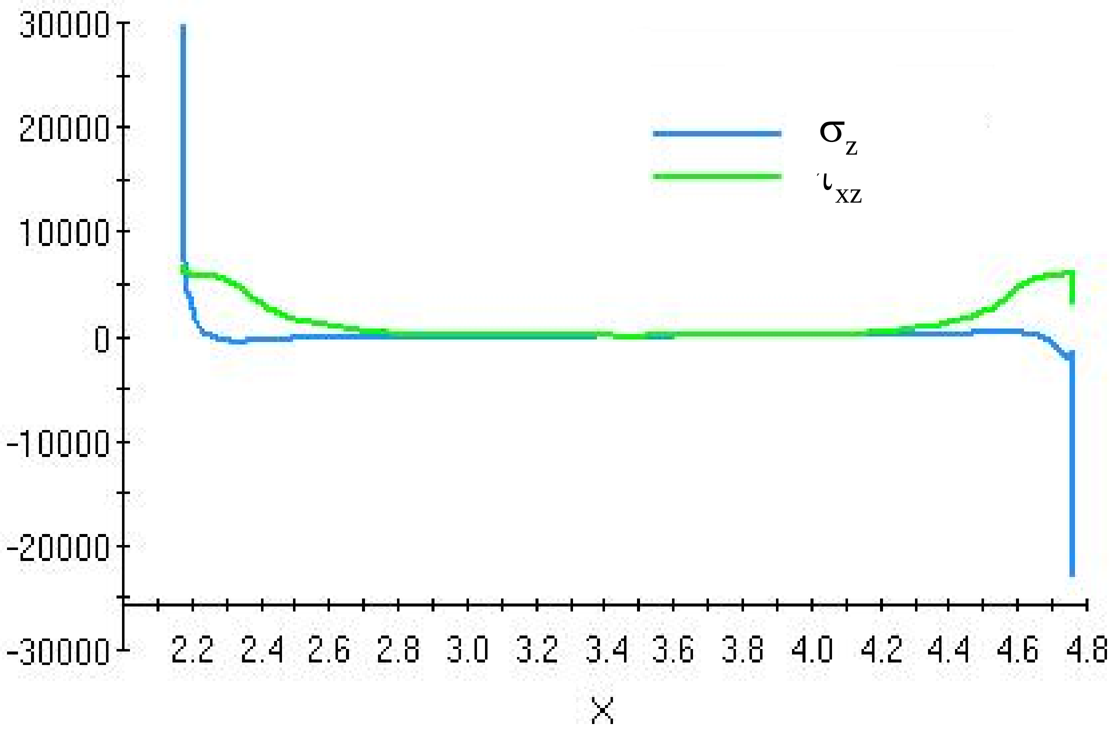
Failure Criteria

Peel and Shear Stresses





Singularities Occur at free edge and reentrant corners



Why p- versus h-version?

- Accurate modeling of singularity gradients required
  - Utilize stress/strain computed at a distance from the singularity
  - Energy of singularity does not pollute neighboring region where stress/strain information is extracted
  - p-version allows much faster mesh transition rates - 7:1 for p-version as opposed to 3:1 for h-version
- Composite joints have very large length to thickness ratio; requires thin elements with large aspect ratios away from singularities
  - p-version allows very high element aspect ratio - as high as 200:1
  - h-version has tighter restrictions on aspect ratio - as high as 10:1
- Variable polynomial degree of p-version elements allows for automatic convergence reporting
- p-version allows coarser meshes, better for parameterization without element distortion problems
- p-version less sensitive to element distortion

Why Stress Check?

- **Handbook Format Available for the non-FEM expert**
  - **Parameterized meshes for standard problems**
  - **Failure criteria implemented for sizing**
  - **Controlled convergence and extraction removed mesh dependency issues in failure analysis**
- **Very good interface for pre- and post-processing; Stress/strain can be extracted continuously throughout elements**
- **Capable of Material and Geometric Nonlinear Analysis**
- **Can be automatically extruded to a 3D solution if Plane Strain not considered the appropriate solution**

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Complete List of Stress Check Enhancements for Bonded Joints

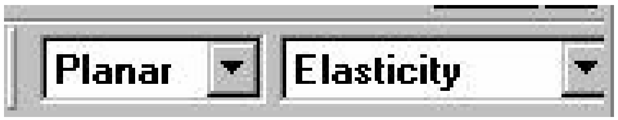
- **Phase I: Air Force STTR with CAI directed modifications**:
  - Post processing Stress/Strain Average
  - Extrusion Contour Plotting
  - Extraction in Local System
  - Nonlinear load incrementation for Margin criteria failure analysis
  - Orthotropic property input improvements
- **Phase II: CAI subcontract**:
  - Thin solids
  - Laminate material properties in cylindrical coordinate system
  - Stress/strain extraction in principal material coordinates, including separation of mechanical and thermal strain
  - Additional Post-processing features
  - Incremental approach for geometric nonlinear algorithm
  - Orthotropic/laminate material properties update during nonlinear incrementation
- **Phase III: CAI Subcontract**:
  - Global/Local Modeling

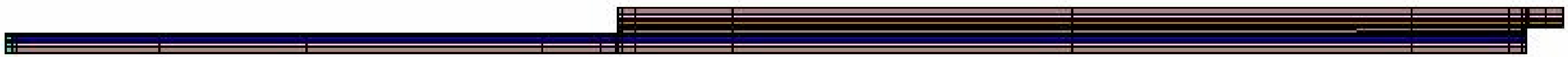
Thin Solid Elements for Extruded 3D Handbooks

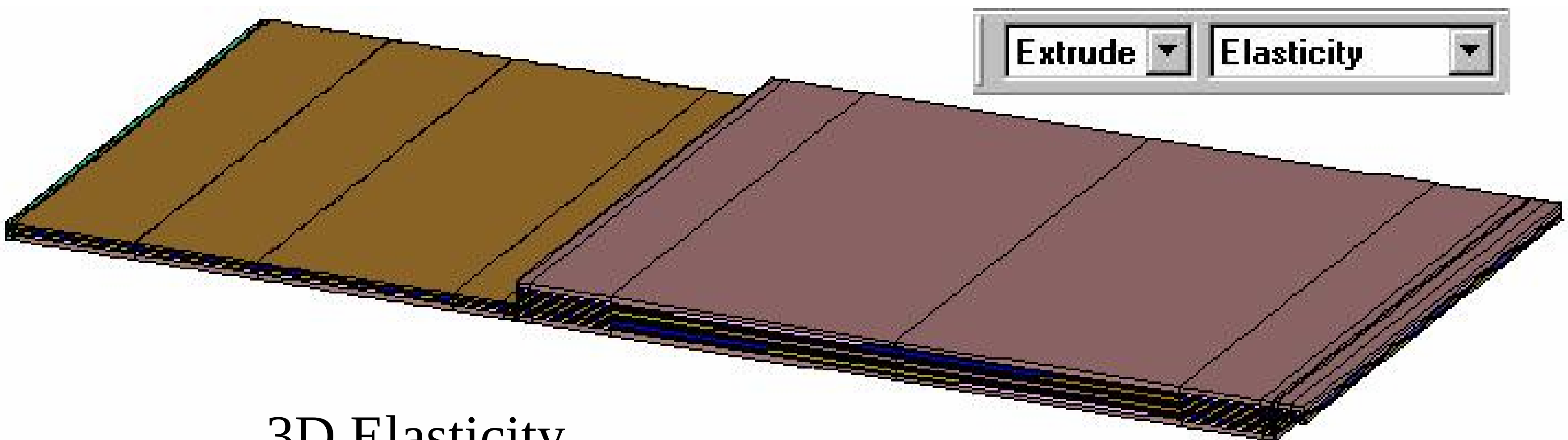
- **Extruded 3D solutions can be used in StressCheck Handbooks to account for 3D effects such as: *off-axis ply deformations which violate the plane strain assumptions***
- **Thin solid elements were developed to allow more efficient computation of 3D solutions when solid elements are used to model thin laminated composite structures**
  - **Lower interpolation is necessary in the transverse direction of thin elements than in the in-plane directions**
  - **The ability to reduce the p-discretization in the transverse direction independent of the in-plane directions is necessary**
  - **Substantial savings in computation time, without reduction in quality and accuracy of solution**

StressCheck Extrusion Capability

2D Plane Strain Elasticity





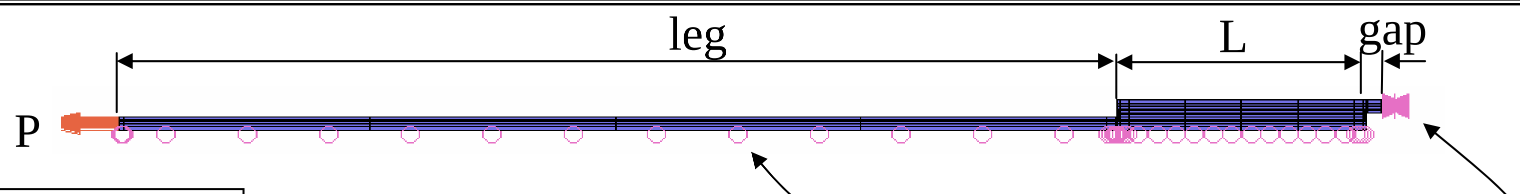


3D Elasticity
One element in extruded direction

Example Handbook Bonded Joint Analysis

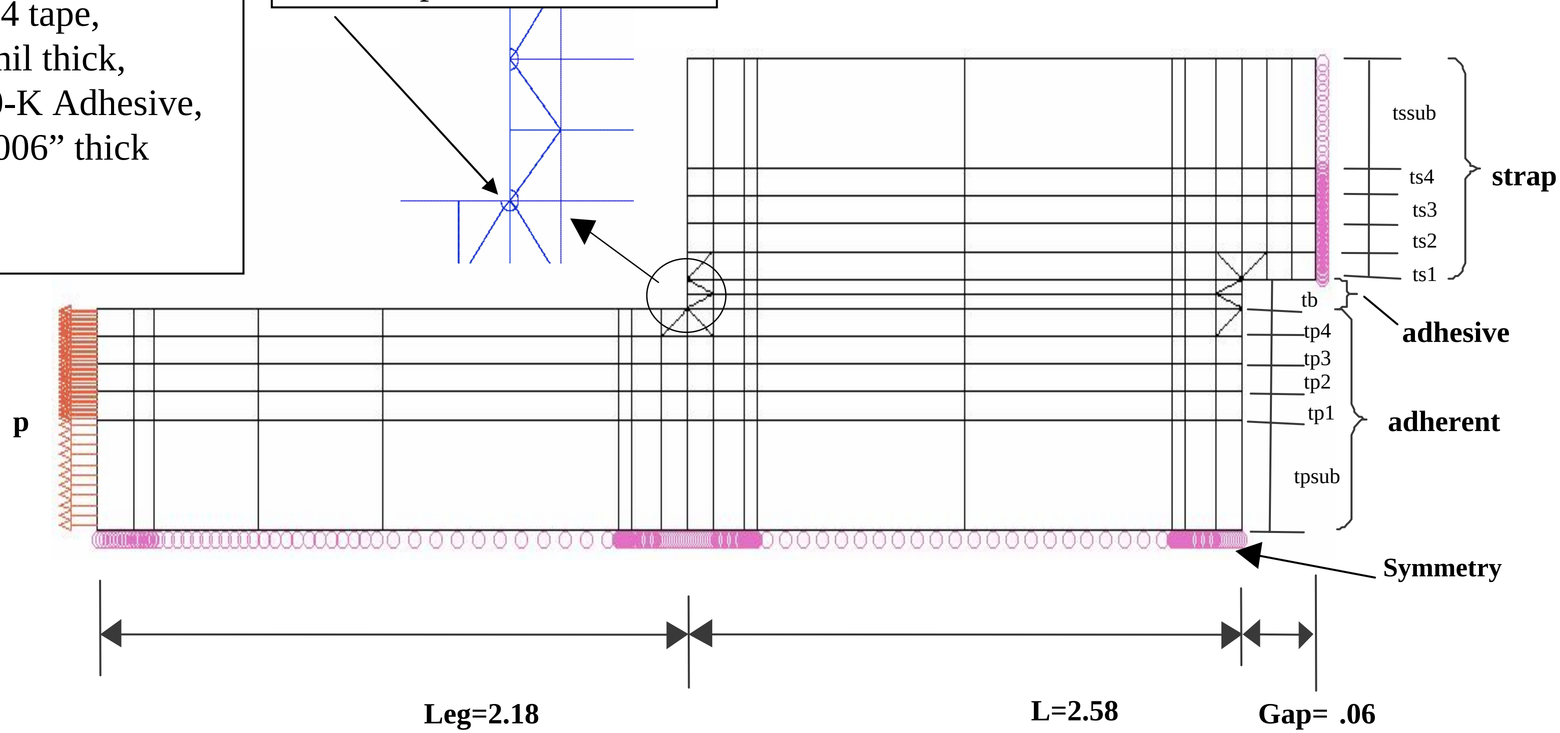
CAI COMPOSITES AFFORDABILITY INITIATIVE a government-industry partnership

Bonded Joint Double Lap Shear Model



Parent $[0_2/90_2]_{2s}$
Strap $[0_2/90_2]_s$
Material: T650/F84 tape,
5.5 mil thick,
FM 300-K Adhesive,
0.006” thick
Width: 1.0”

Radius of circle = rfac * tb
rfac is a parameter



StressCheck Handbook Interface

Operates on WINDOWS PC's

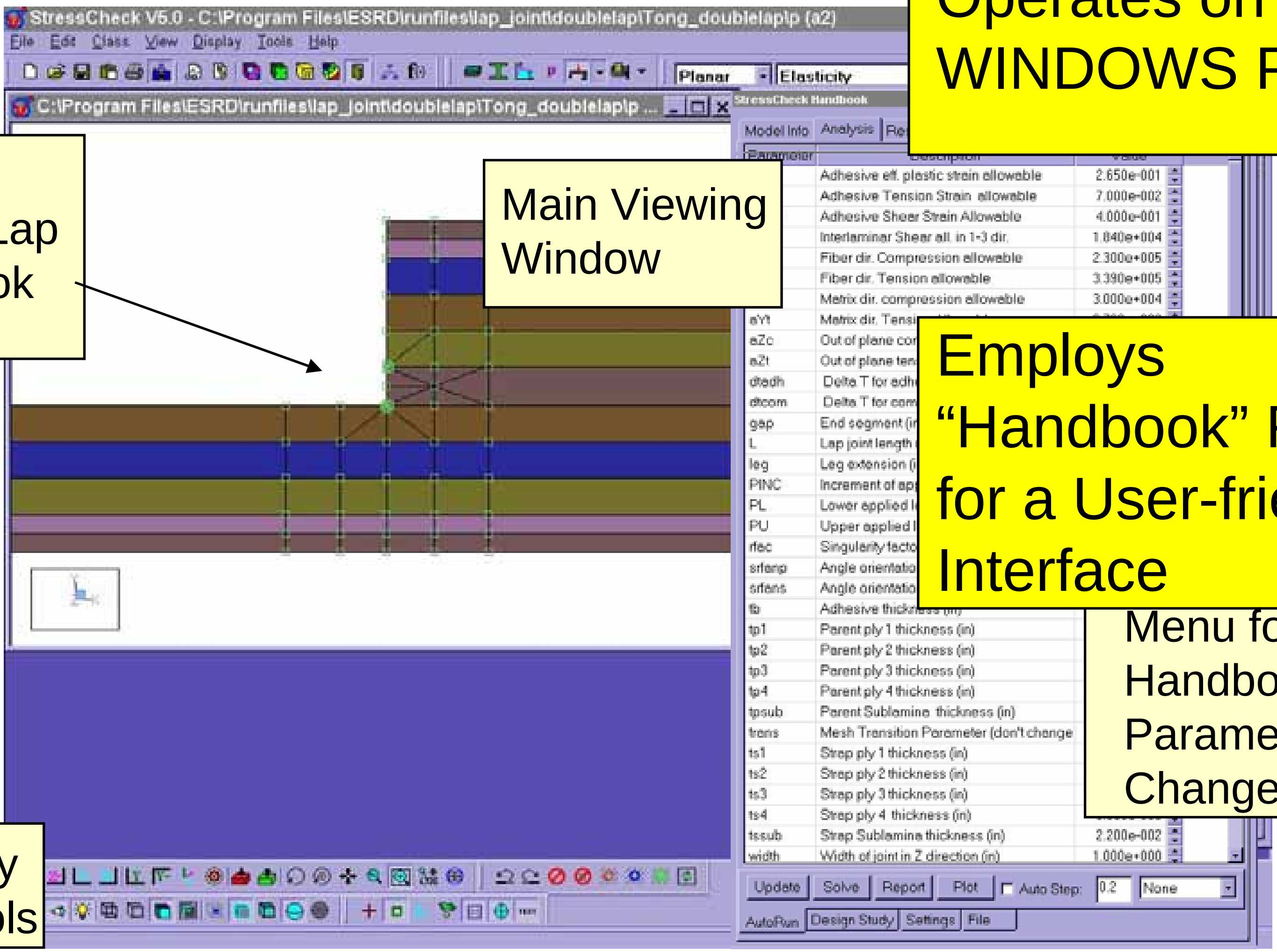
CAI Double Lap Handbook Model

Main Viewing Window

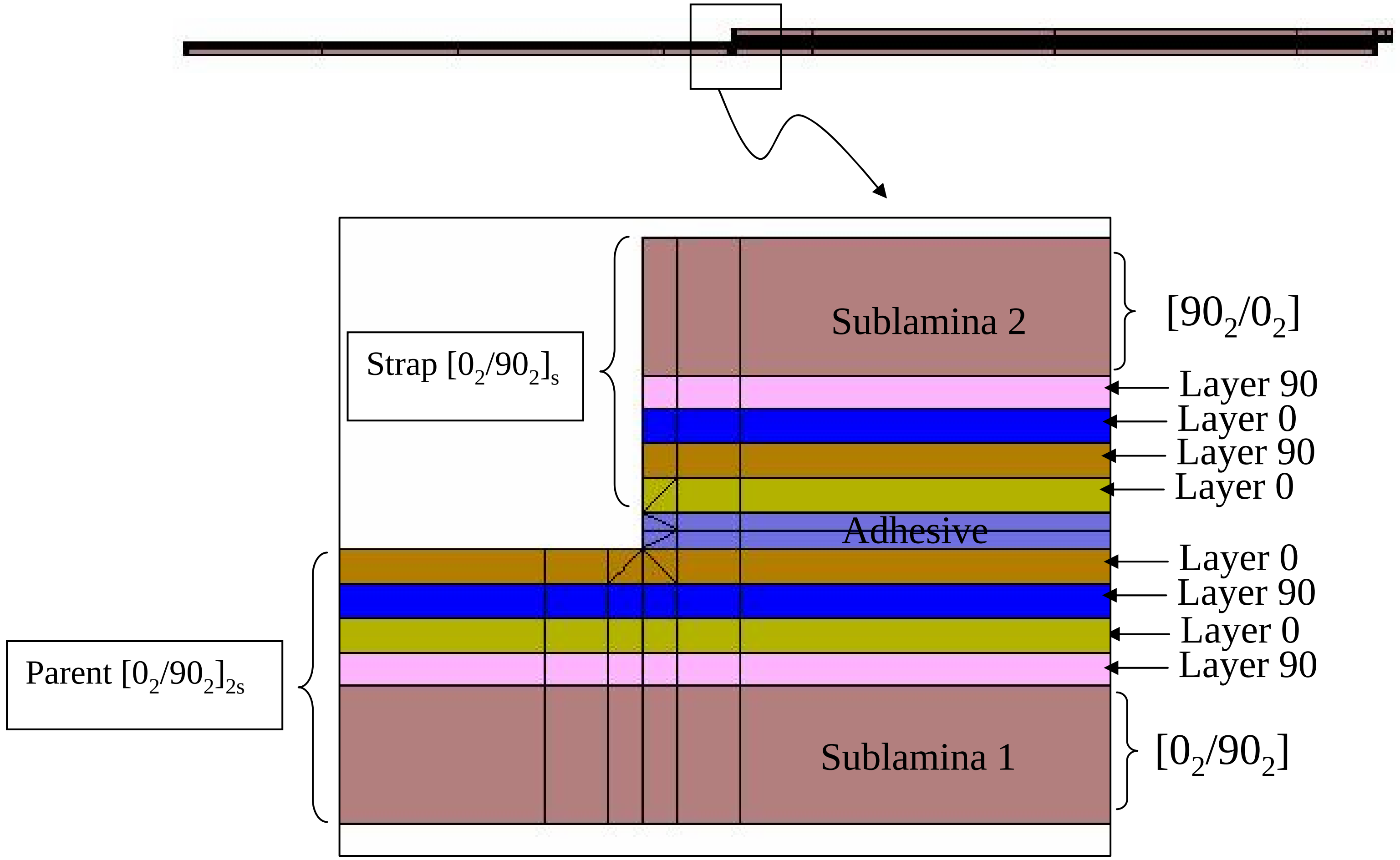
Employs "Handbook" Format for a User-friendly Interface

Menu for Handbook Parameter Changes

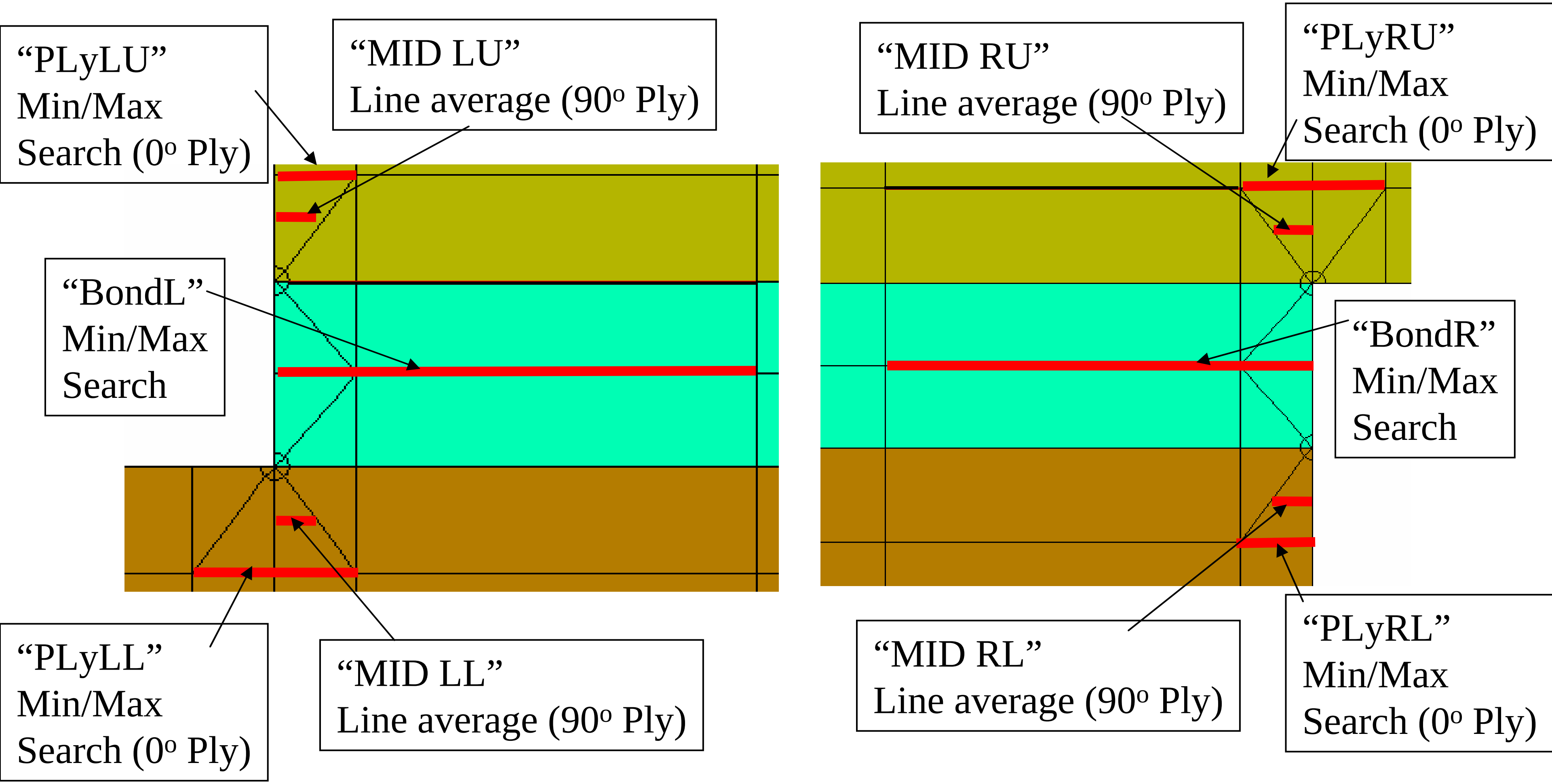
Display Controls



Double Lap Layup



Margin Extractions for Double and Single Lap



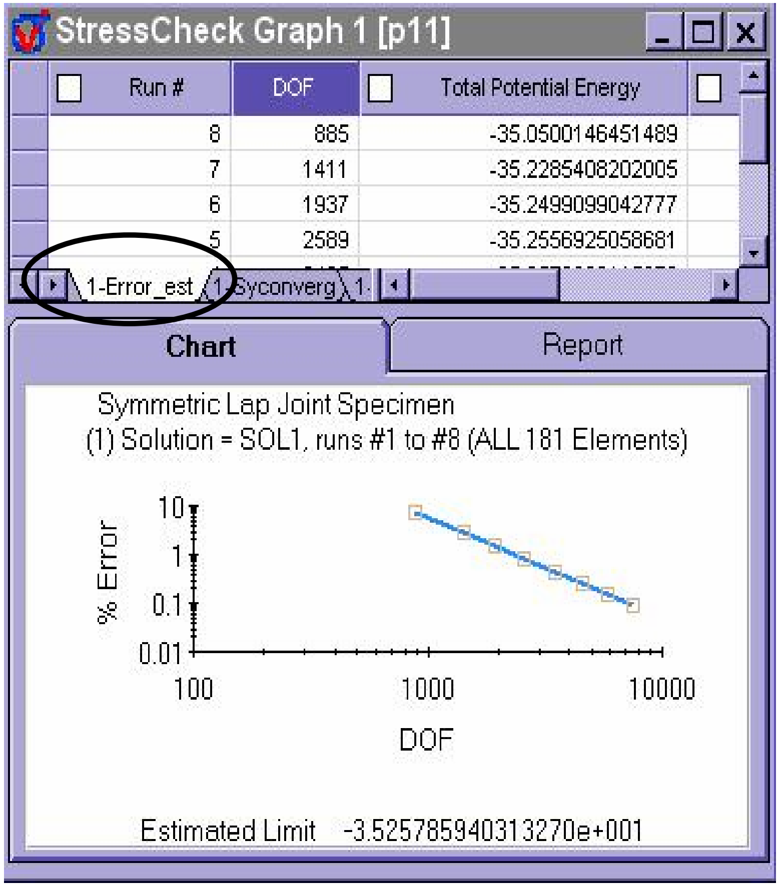
Failure Criteria

Criteria	Ply	Bond
Margin of Safety	MS_2	MS_1

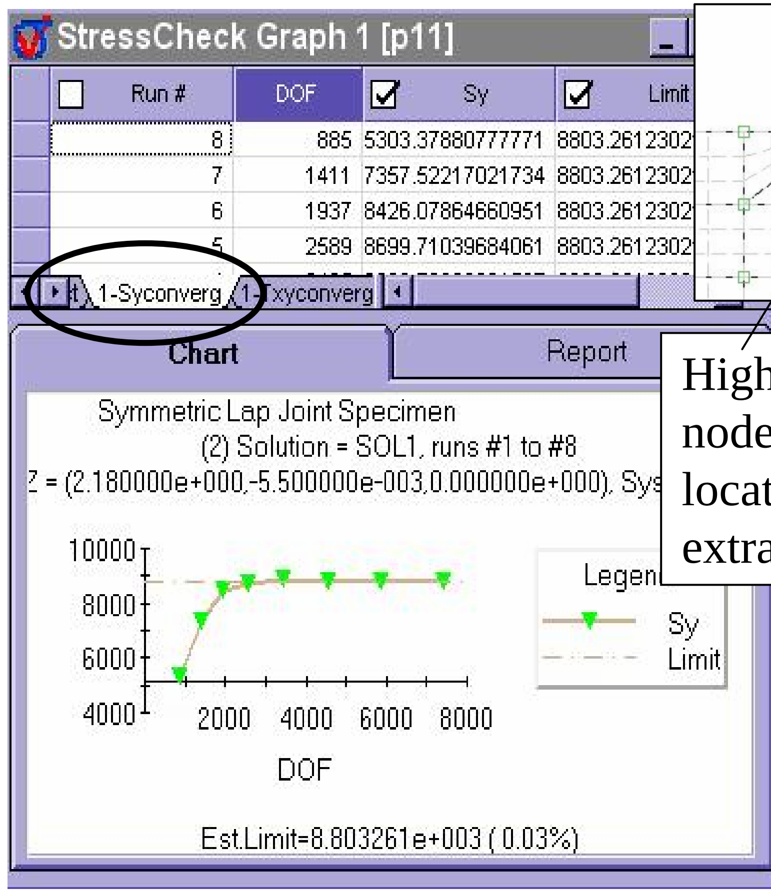
$$MS_2 = 1 - \left[\left(\frac{\sigma_x^2 - \sigma_x \sigma_z}{X_t X_c} \right) + \left(\frac{\sigma_z}{Z} \right)^2 + \left(\frac{\tau_{xz}}{S_{ILS}} \right)^2 \right]$$

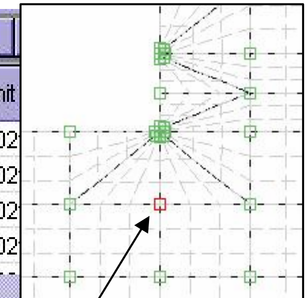
$$MS_1 = 1 - \frac{\tilde{\varepsilon}_{eq}}{\varepsilon_0}$$

Automatic Convergence Reporting



Typical global energy norm convergence plot

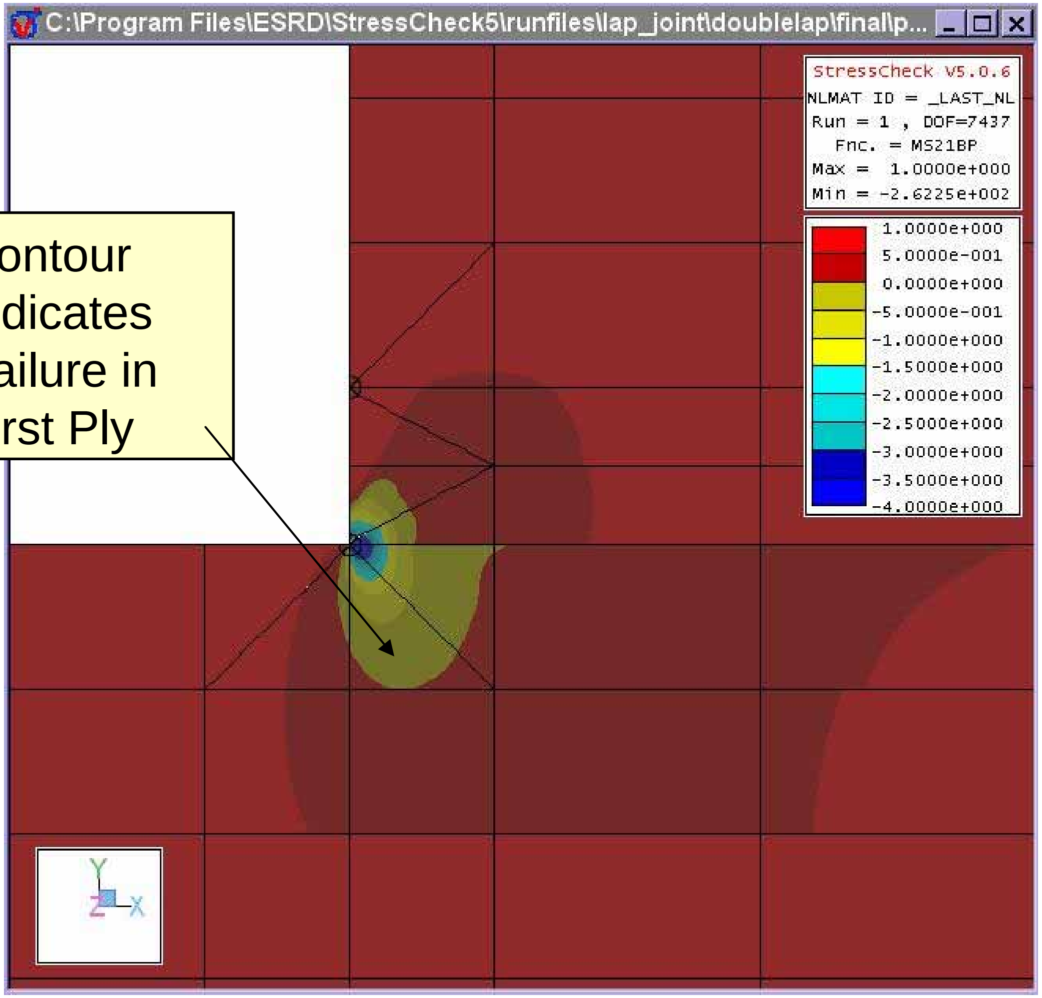




Highlighted node indicates location of stress extraction

Convergence plot of local peel stress

Margin Contour Plot At Failure Load



Contour Indicates Failure in First Ply

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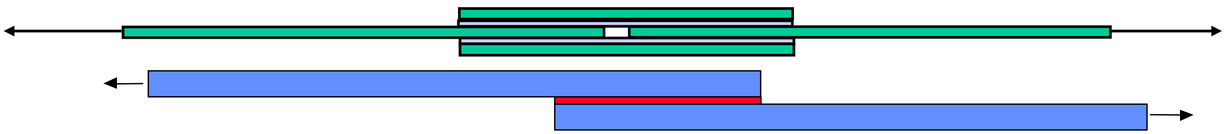
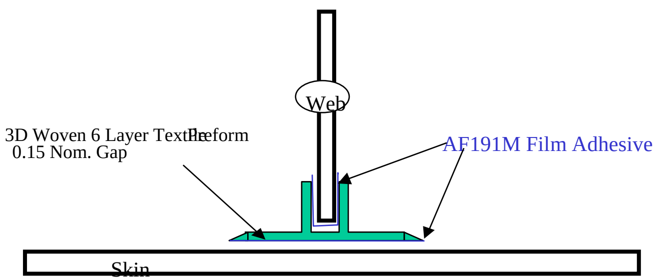
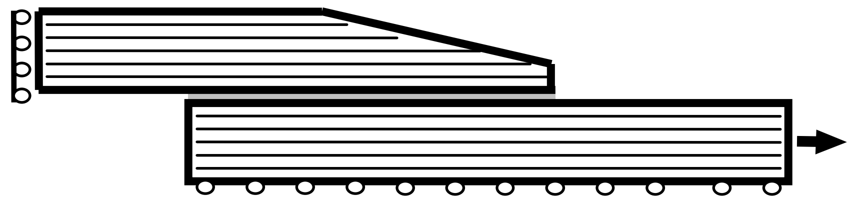
Model Verification Problems for ZIG-ZAG and StressCheck

Double Lap and Single Lap Joints

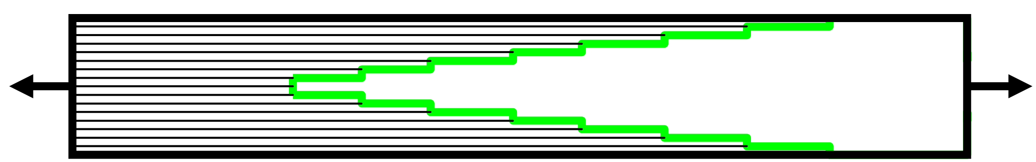




CAI PI-Preform T- Specimen
Model with ZIG-ZAG and StressCheck



Scarfed Double Lap Shear Joint
Model with ZIG-ZAG and StressCheck

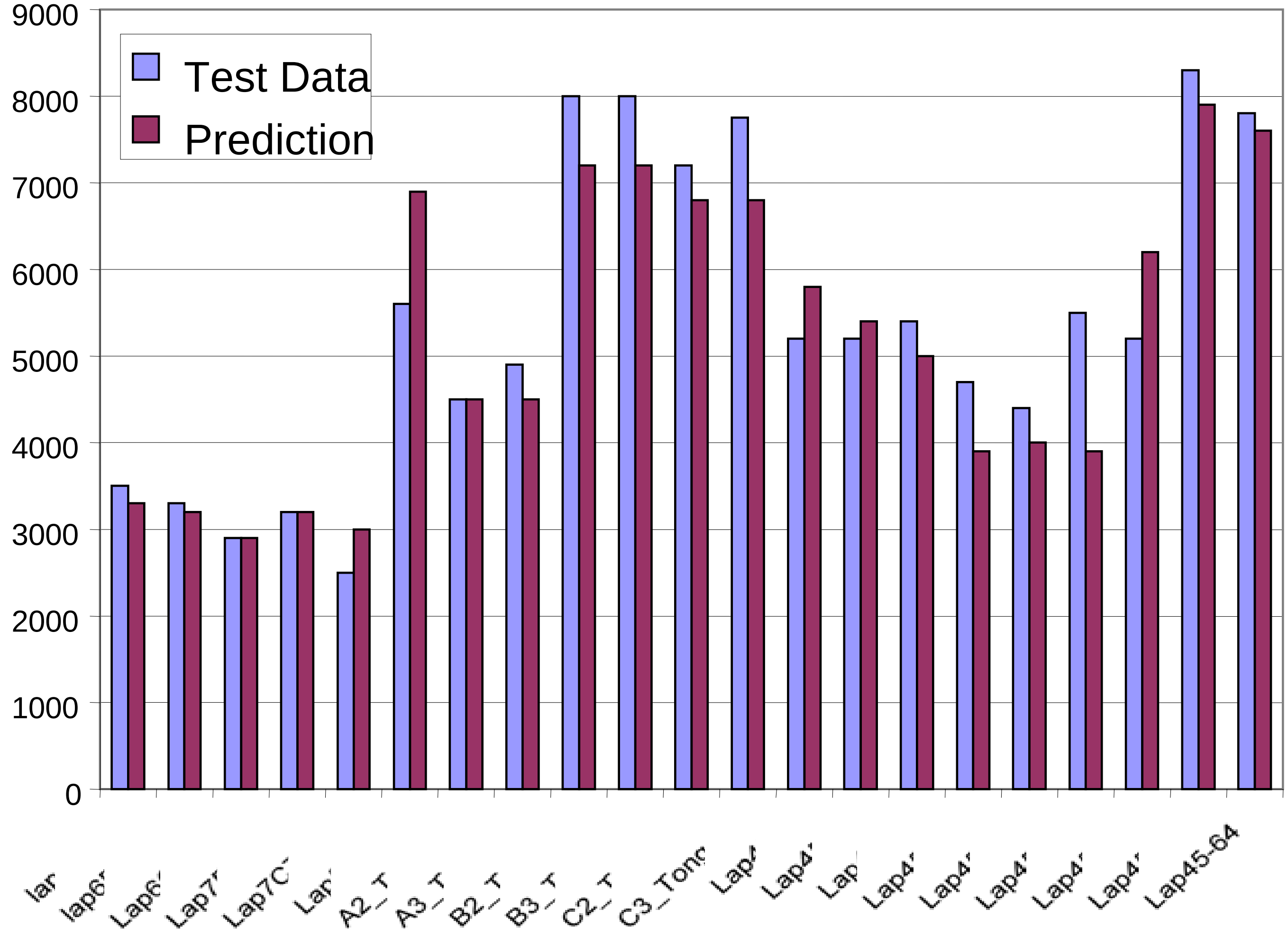


F/A18-E/F Step Lap Joint
Model with StressCheck

Stress-Based Failure Comparisons

- **Phase II and Phase III comparisons using semi-empirical method**
  - **Stress based failure theory**
  - **Empirical distance rule (generally half a ply thickness) tuned to represent element overall failure**
  - **In all cases, the failure mode (failure location) was predicted**
  - **Final failure load (not initiation) is compared with predictions**

Double Lap Verification Results



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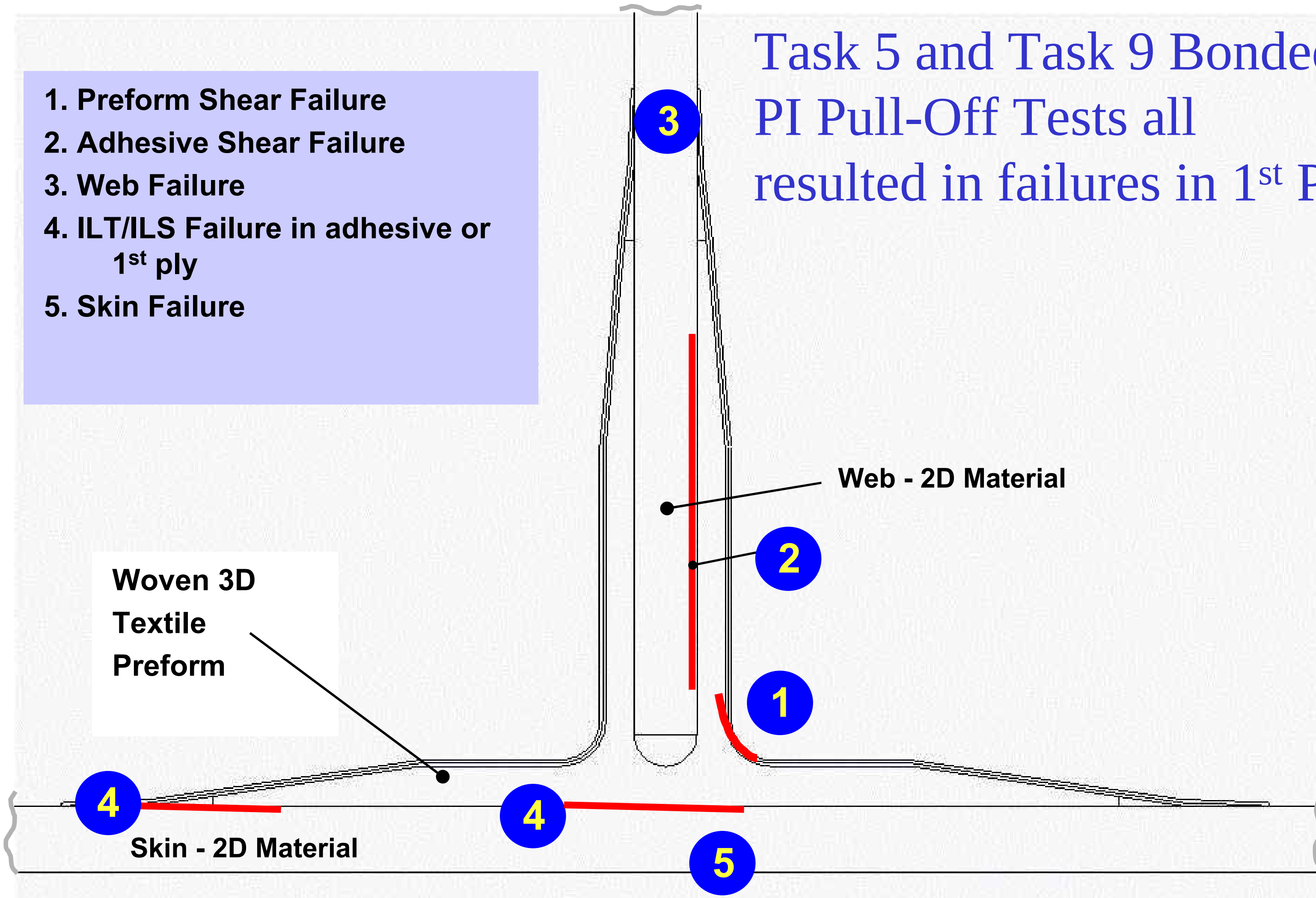
PI-Joint
Potential Failure Modes

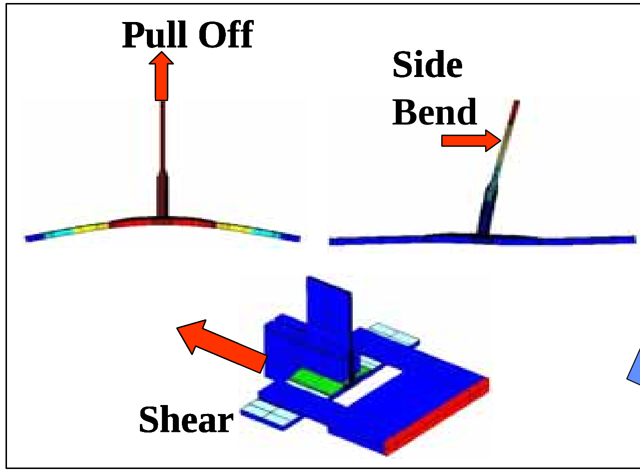
1. Preform Shear Failure
2. Adhesive Shear Failure
3. Web Failure
4. ILT/ILS Failure in adhesive or 1st ply
5. Skin Failure

Task 5 and Task 9 Bonded PI Pull-Off Tests all resulted in failures in 1st Ply

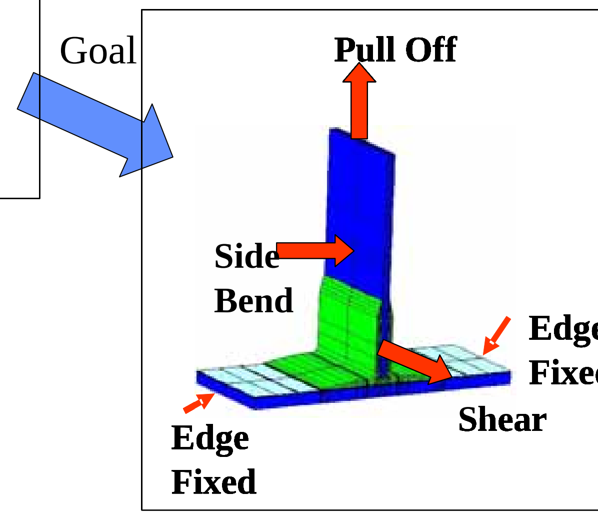


StressCheck - Generalized Loading of Extruded PI Model

- **Pi-Joint StressCheck models have been developed and validated for separate side-bend, pull-off and shear loading BC's**
- **The model is applicable for general loading and boundary conditions**

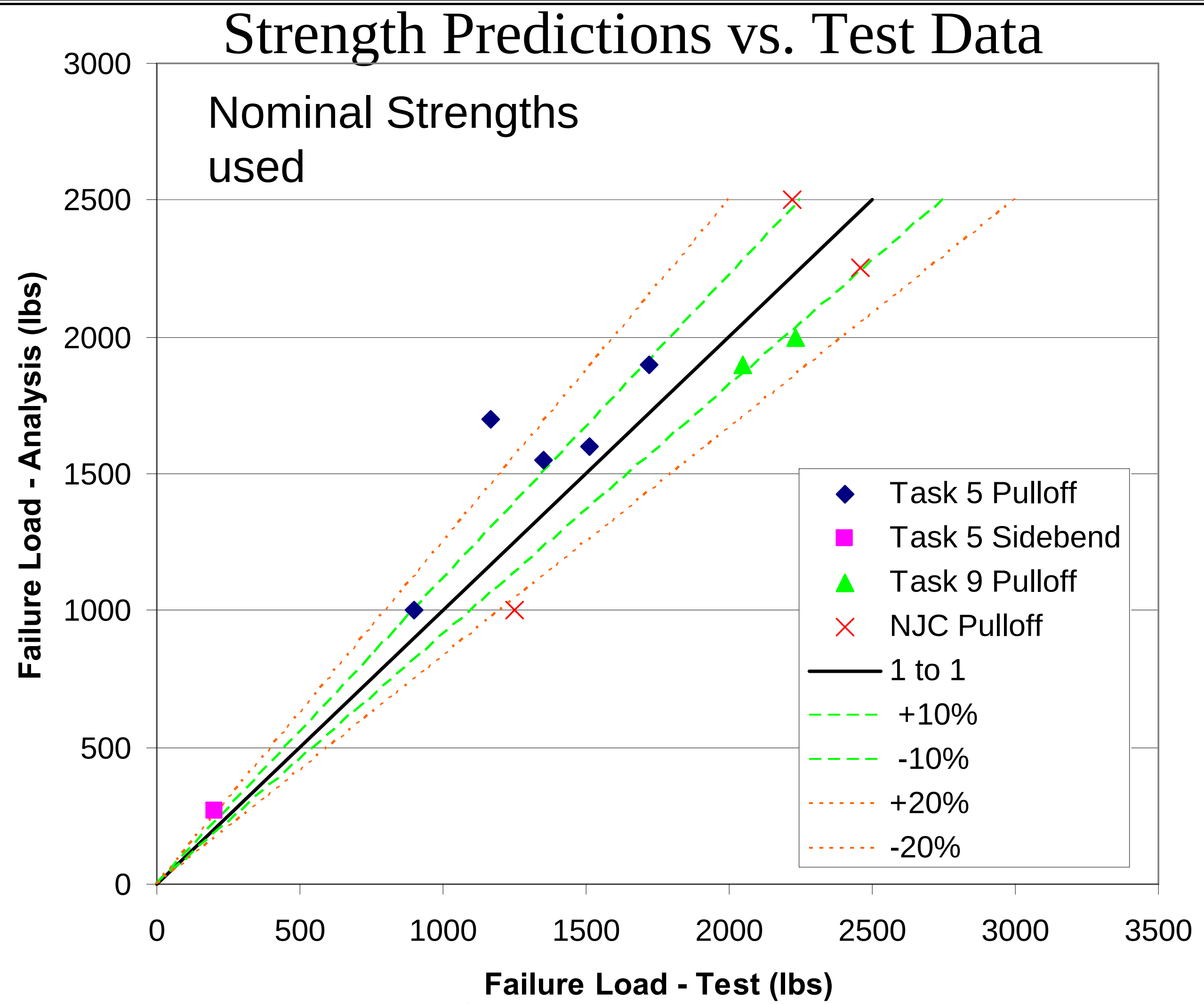


Verification of Failure Predictions with Element Testing



Combined Loads Predictions

StressCheck PI-Joint Validation Data



Strain Invariant Failure Theory (SIFT)

Two Matrix Critical Invariants

(1) $J_1 = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \geq J_{1\ critical}$ – Measured from 90ºT coupon

(2) $\varepsilon_{von\ Mises} \geq \varepsilon_{von\ Mises\ critical}$ – Measured from 10ºT coupon

One critical invariant that represents damage initiation within the fiber phase

$\varepsilon_{fiber\ von\ Mises} \geq \varepsilon_{fiber\ von\ Mises\ critical}$ - Measured from 0ºT coupon

where $\varepsilon_{\ von\ Mises} = 1/2[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_1 - \varepsilon_3)^2 + (\varepsilon_2 - \varepsilon_3)^2]^{1/2}$

Methods Beyond Initiation are Beyond the Scope of this Program

Application of SIFT

- Two problems solved:
  - Thermal residual strains from curing
    - Utilize mechanical portion of thermal strains

$$\varepsilon_{i\ mech} = \varepsilon_{i\ total} - \alpha_i\ \Delta T$$

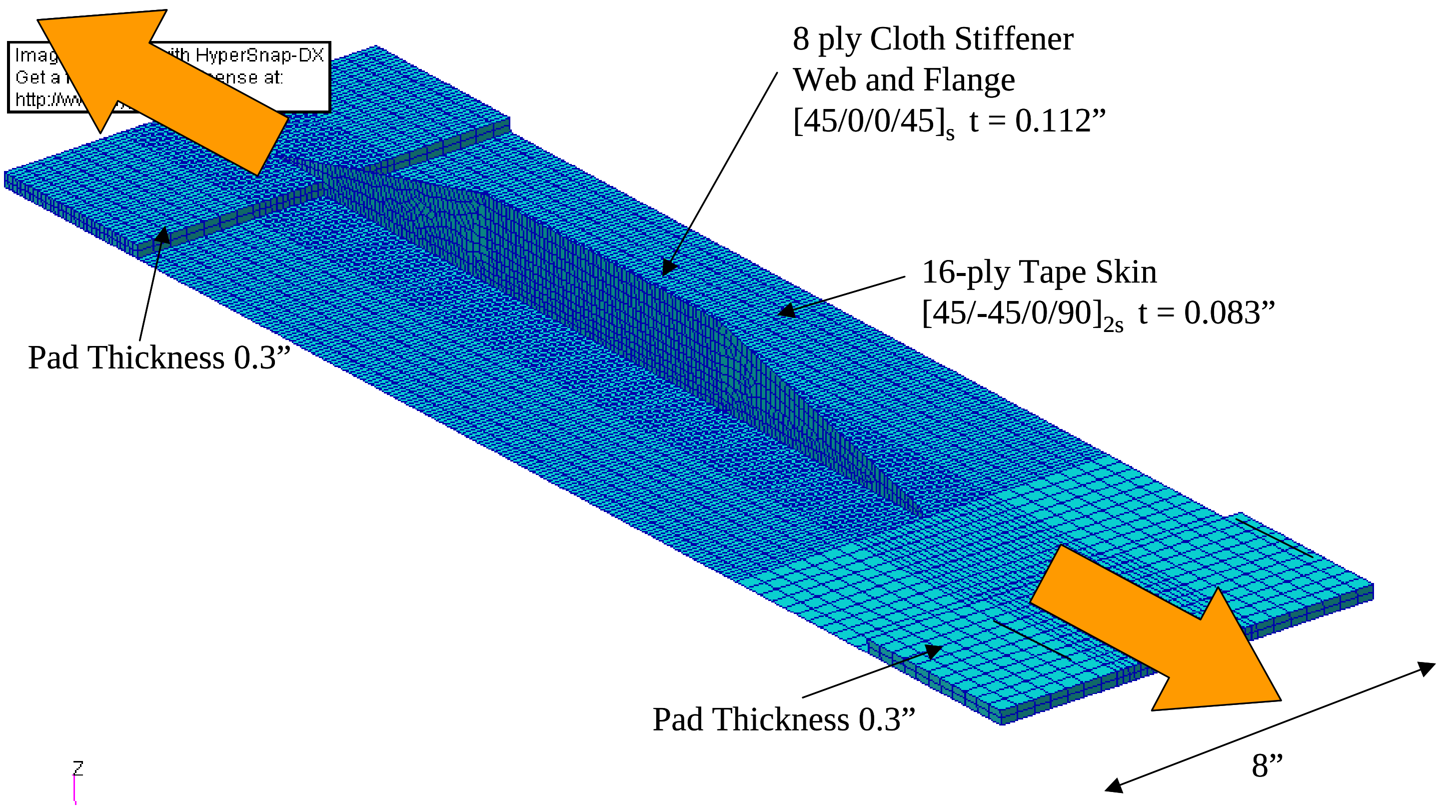
$$J_{1\ thermal} = \varepsilon_{1\ mech} + \varepsilon_{2\ mech} + \varepsilon_{3\ mech}$$

  - Mechanical Loading

$$J_1 = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$$

- Results superimposed

Stiffener Termination Test Problem Definition



Stiffener Termination Test Summary

- **Correlation – Initiation load and failure mode**
  - SIFT Failure mode predictions very accurate
  - SIFT-Initiation Load Predictions (without distance rule empiricism)
    - Generally predicts well below scatter bands on measurable initiation loads except bonded no taper series (modeled large spew)
    - A progressive damage algorithm needed

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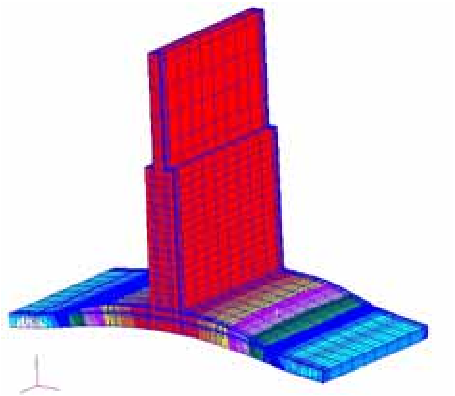
Background

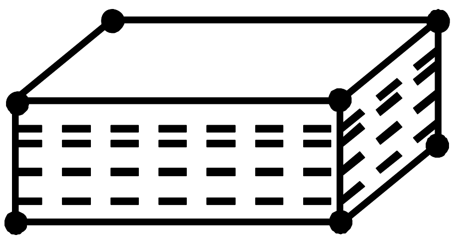
- **Zig-Zag Elements are Specially Designed COMPOSITE Solid Elements Integrated Into ABAQUS Commercial Software**
  - **Composite Solid Elements Designed to Handle Composite Layering, Without Requiring Individual Elements for Each Layer**
  - **Utilize Robust Capabilities of Commercial Code (Element Library, Nonlinear Analysis)**
  - **Utilize Pre- and Post-processing**
- **ZIG-ZAG Solid Elements, Developed by Dr. Ron Averill Have Been Selected for Implementation As User-defined Elements in ABAQUS**



Background (Cont.)

- Higher-order Kinematic Behavior
  - Zig-Zag (Piecewise Linear in-plane displacements)
  - Brick Elements With Rotations at Each Node
- Handles Multiple Layers Per Element & Bending Behavior
- Bricks Relatively Insensitive to Aspect Ratio Problems
- Bricks Do Not Shear Lock in Bending
- Shell-to-brick Transition Elements Included
- Discretization of Each Layer Not Required and Large Element Aspect Ratios Are Not a Problem
- Accuracy of Interlaminar Stresses Retained
- Implemented as ABAQUS user element subroutines
- PATRAN Pre- and Post-processor specialized for Zig-Zag elements

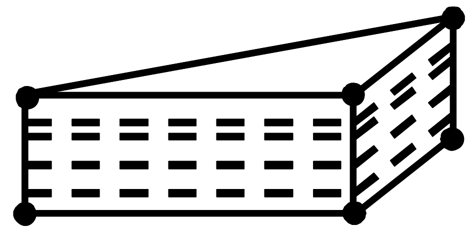
A Family of Composite Solid Elements



ZZ-Layered Brick

Nodal DOFs:

$u \;\; v \;\; w \;\; \theta_x \;\; \theta_y \;\; (\theta_z)$



ZZ- Layered Wedge

Nodal DOFs:

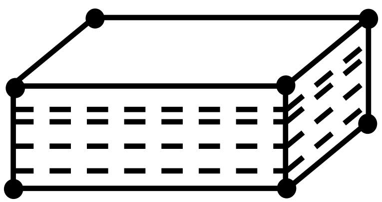
$u \;\; v \;\; w \;\; \theta_x \;\; \theta_y \;\; (\theta_z)$

Zig-Zag Elements Commercialization

- In Fall of 2003, ABAQUS, Inc. released a close "cousin" to the Zig-Zag element
- LM Aero evaluated this new ABAQUS element, and identified shortcomings
  - Not reporting/computing interlaminar stress/strain
  - Postprocessing/visualization
  - Made request for improvements in Vs 6.5 to be released in Fall of 2004
- CAI decided to halt all Zig-Zag element development, and focused on the new ABAQUS element called the "SC8R" element

Zig-Zag vs. SC8R

- **Zig-Zag & SC8R Similarities**
  - Handles Multiple Layers Per Element & Bending Behavior
  - Bricks Relatively Insensitive to Aspect Ratio Problems
  - Bricks Do Not Shear Lock When in Bending
- **Differences**
  - Zig-Zag
    - Higher-order Kinematic Behavior (Piecewise Linear)
    - Brick Elements With Rotations at Each Node
    - User Element
  - SC8R
    - New ABAQUS native element
    - Called a "Continuum Shell"
    - Mindlin Shell Theory
    - Brick element Topology with only displacements at each node



Layered Hex Element

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Summary

- StressCheck
  - StressCheck ability to provide detailed interlaminar stress/strain information has been validated
  - Analysis methods for modeling various composite bonded joints has been demonstrated
  - Stress-based failure theory successfully demonstrated using an empirical distance rule
  - Strain Invariant Failure Theory (SIFT) was evaluated without distance-rule empiricism
    - Pi-joints, Lap joints, and Stiffener Termination
    - “Onset of irreversible damage” initiation predictions do not coincide with measurable load events
    - Failure mode predictions are very accurate

- Zig-Zag Elements
  - Element theory was initially explored, and ABAQUS user elements developed and validated
  - Accuracy of Zig-Zag interlaminar stress/strain predictions was verified
  - Work was halted in lieu of evaluation of ABAQUS Continuum Shell Element (SC8R)
  - Global/local Zig-Zag and SC8R applications were successful

Use of CAI Developed StressCheck Analysis Capabilities

Original Objective

To develop improved analysis tools to support the timely analysis of bonded/cocured joints and IRC structures including structural trade studies, detailed stress analysis and failure prediction

Success

- **StressCheck is widely viewed as the needed next-generation composite joint strength analysis tool**
- **StressCheck usage has dramatically caught on, with usage spreading to LM/JSF and other Boeing & Bell programs**
- **CAI is receiving a lot of "Credit" for this technology development, as it is recognized that much of the composites capability in StressCheck was initiated and paid for by CAI**

StressCheck Analysis Capabilities for Composites and Bonded Joints is a CAI Success Story