Accelerated Insertion of Materials - Composites

Robust Design of Composite Structures

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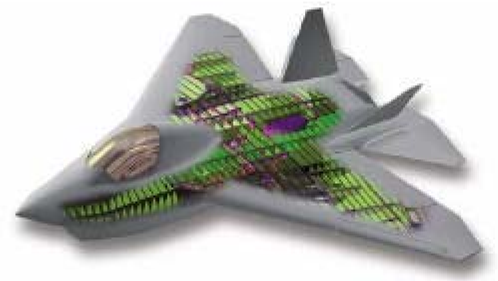
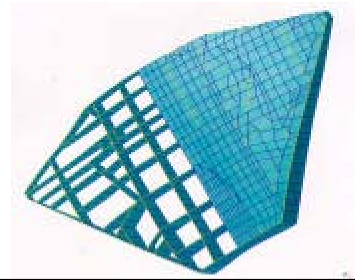
- **Introduction**
  - Goals
  - Analysis Methods and Approaches
  - Benefits of Integration with M&P and Sensitivity Tools

- **Examples**
  - Laminates (with and without holes)
  - 2D Stiffener Separation Problem
  - 3D Stiffener Termination Problem

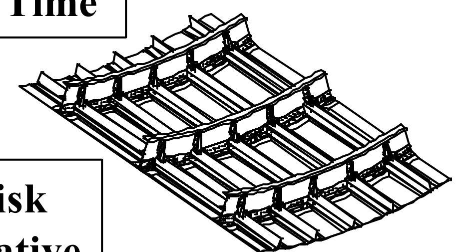
Structures Task – Long Range Goals

Increase Accuracy/Confidence





Decrease Cycle Time
Right the First Time



Supporting Technologies
Analysis

Full-Scale Tests (1 to 3)

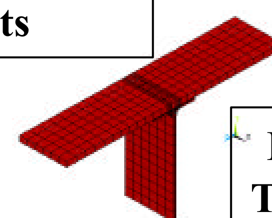
Component Tests (3 to 10)

Subcomponent Tests (~250)

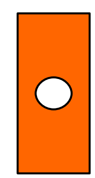
Element Tests (~2000)

Coupon Tests (~8000)

Reduce the Risk Of Using Innovative Concepts



Focus Testing



Aid Material Developers

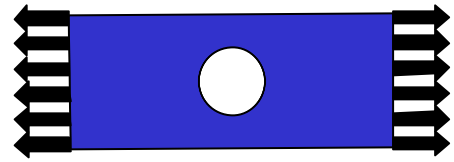
How Can We Achieve These Benefits?

- Use of Physics-Based Methods
  - Strain Invariant Failure Theory
  - Fracture Mechanics Approaches
  - Benefits of Integration with M&P and Sensitivity Tools

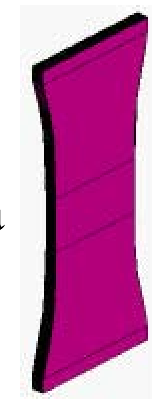
- Tight Integration with M&P Tools
  - Stress-Free Temperature
  - Manufacturing Variation and Defect Occurrence

- Integration with Statistical and Computing Tools
  - Sensitivities, DOE, Propagation of Error and Variation
  - Distributed Computing Capabilities

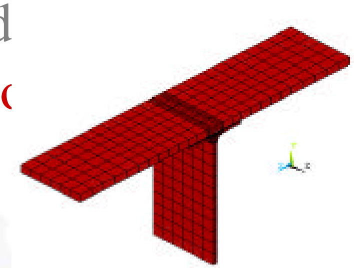
Structures Task Efforts to Reach Goals

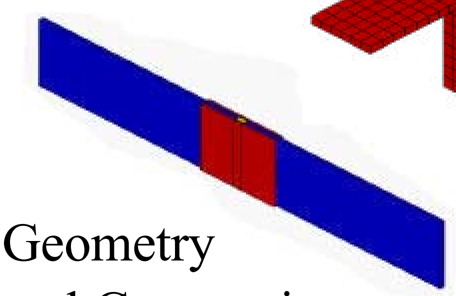


- **Progress to Date**
  - Accurately Predicted Laminate Stiffness
  - Accurately Predicted Typical Unnotched and Open Hole Strengths
  - Demonstrated Deterministic Studies and Validate Against Data
  - Demonstrated Mechanics to Perform Statistical Studies



- **Near-Future**
  - Expanding Validated Predictive Capability to Bonded and Bolted Joint Elements, and Laminates under Combined L
  - Expandeding Durability Analysis
  - Predicting Open Hole Property Scatter





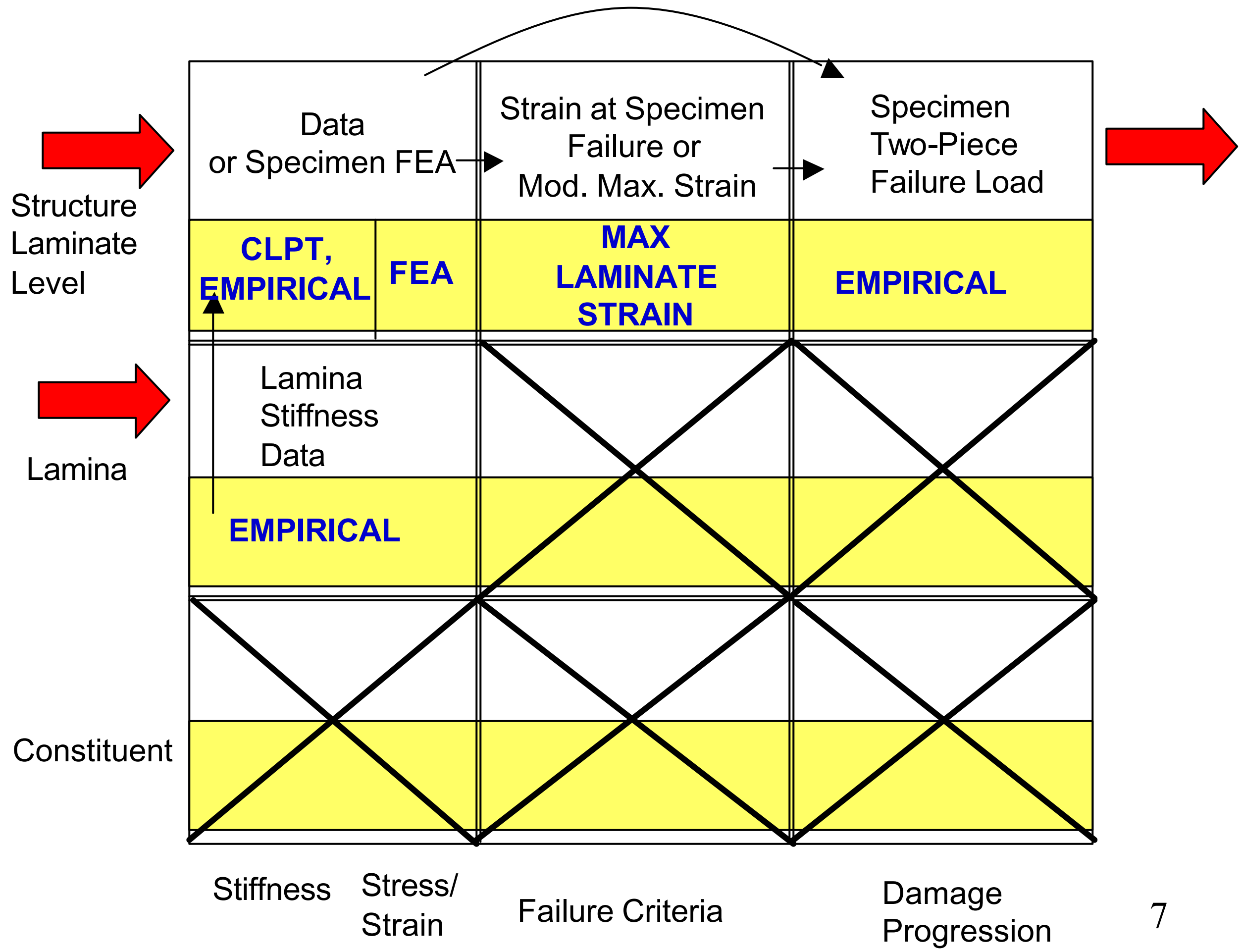
- **Beyond**
  - Accurately Predict Strength of User-Defined Geometry
  - Deterministic Study Capability for User-Defined Geometries

Use of Physics-Based Methods

The Antithesis –
Analytical Procedure For Empirical Point Design

Relies heavily on a large amount of test data at coupon level and higher

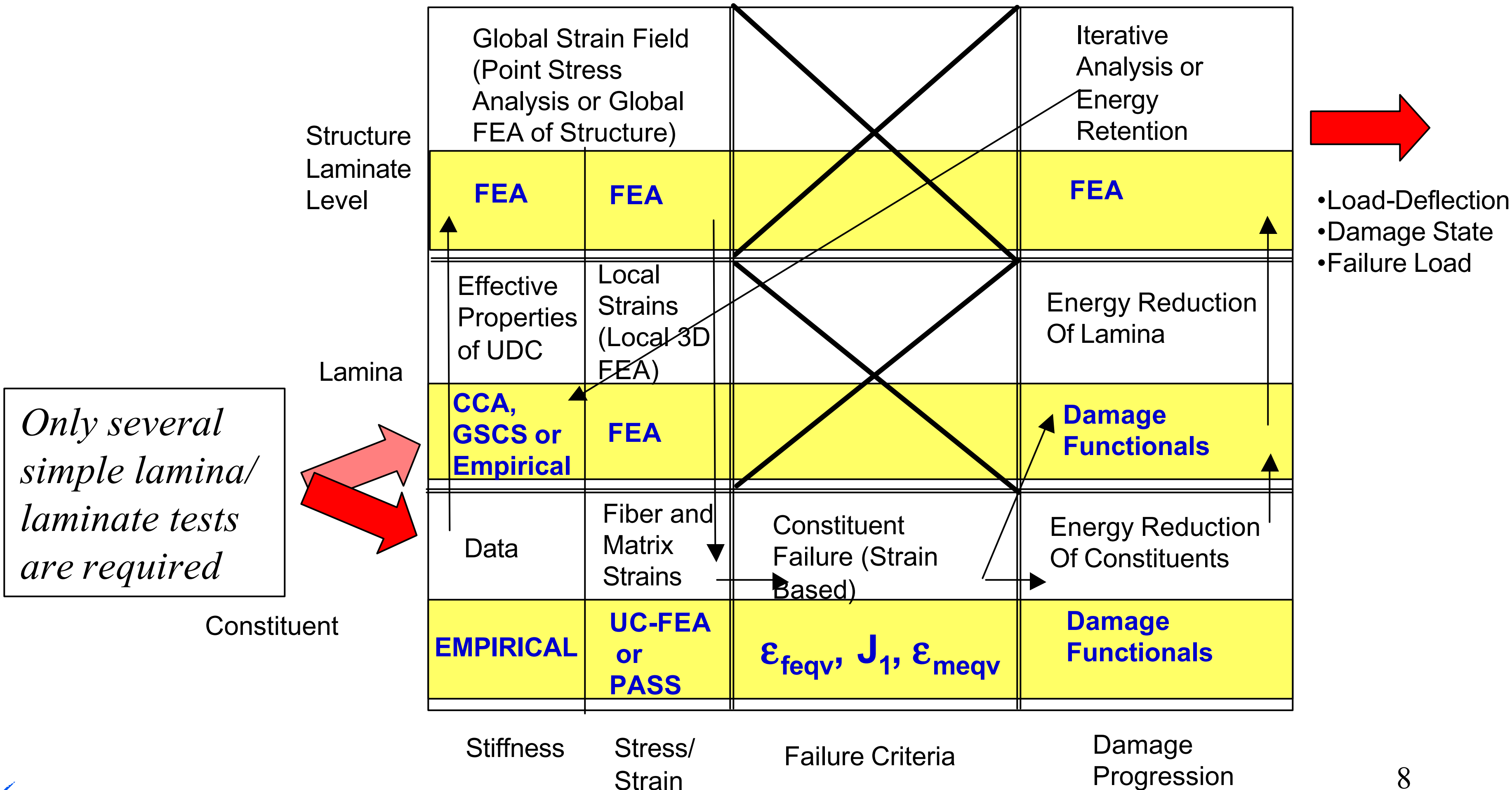
Does not take full advantage of knowledge of physics at the lamina and constituent level – Must Test Specimens very similar to those you wish to use in Design



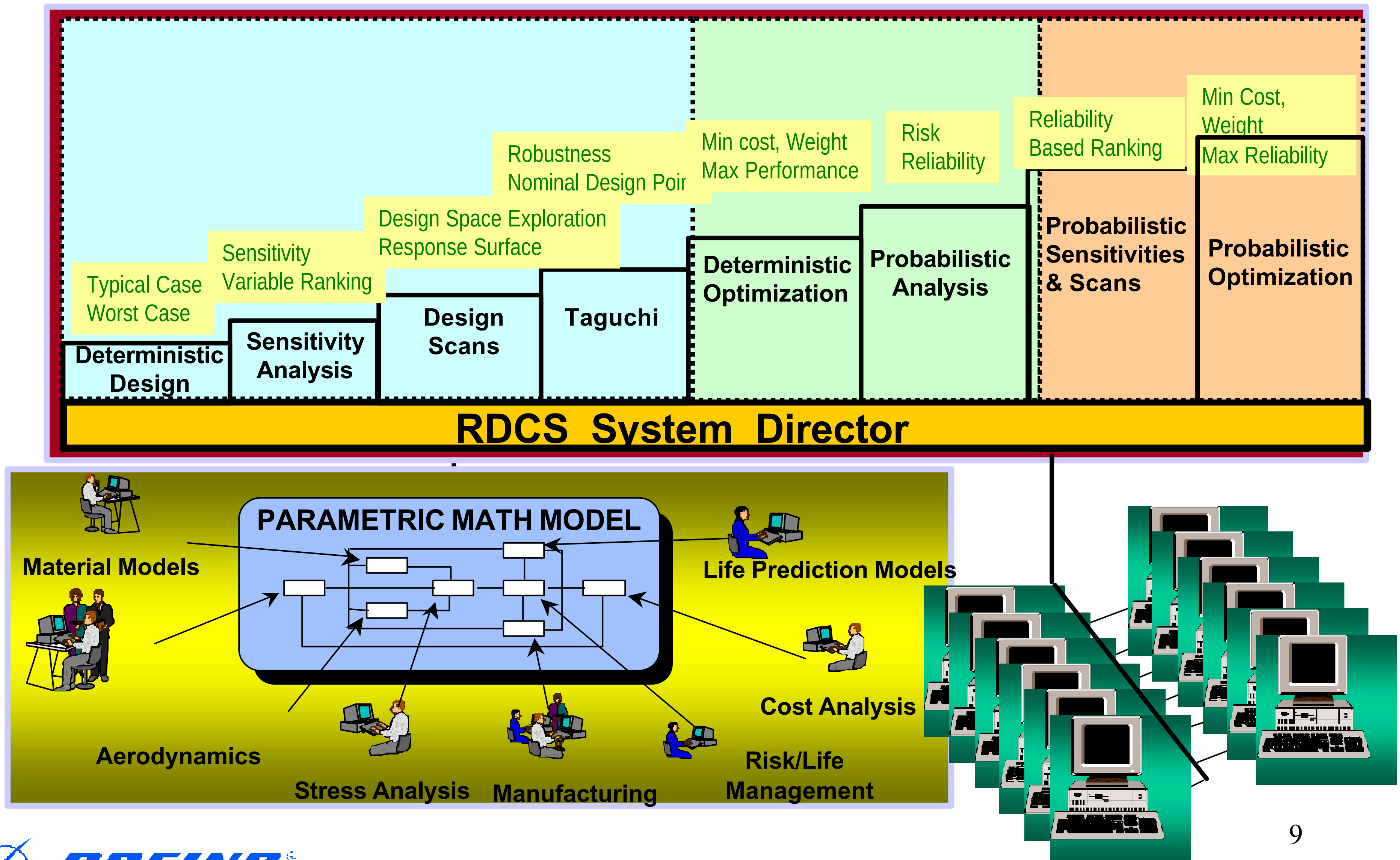
Use of Physics-Based Methods

Analytical Procedure for SIFT

Use approach which takes advantage of knowledge of physics at the lamina and constituent level



Integration With Other Disciplines In RDCS



Effects of Resin Fiber and Prepreg Properties on Failure

Purpose

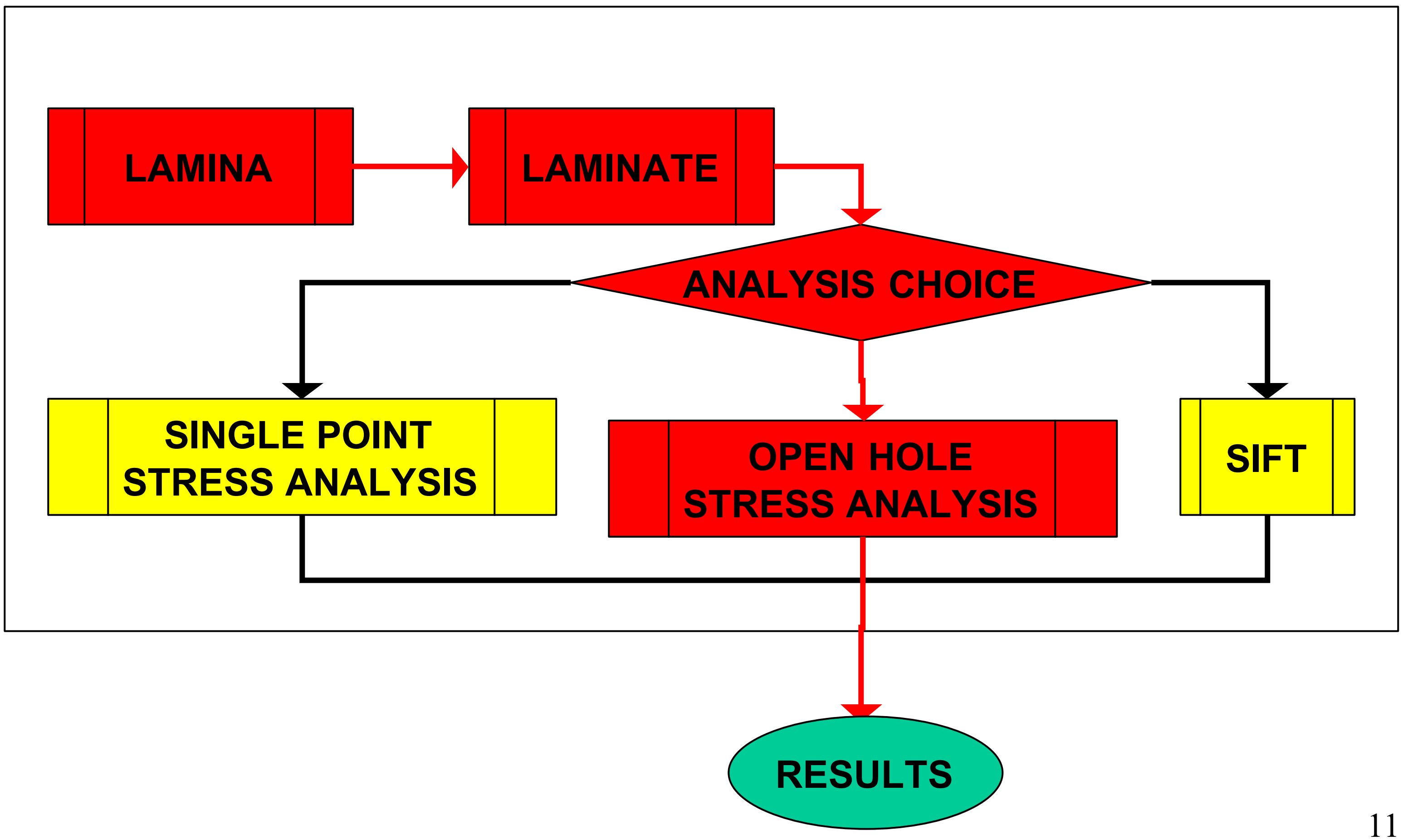
Demonstrate the effect of resin, fiber, and prepreg properties on lamina properties, laminate properties, and first ply failure in an open hole tension coupon.

Approach

Three-level RDCS sensitivity study (full factorial) showing effects of fiber volume, resin modulus, fiber axial modulus, transverse fiber modulus, and laminate orientation on lamina E_{11}, E_{22}, and G_{12}, laminate E_x, laminate 0° ply strain, and the First Ply Failure load of an Open Hole Tension specimen using Hashin, Maximum Strain, and Phase Average Stress failure criteria. This requires $3^5 = 243$ runs for each criteria.

Effects of Resin Fiber and Prepreg Properties on Failure

LAMINATE/STRUCTURES MODULE (w/Integrated Lamina)



Effects of Resin Fiber and Prepreg Properties on Failure – Experimental Design

Input/Design Variables:

	Input Variable Description/Name	Level 1 (Min)	Level 2 (Nominal)	Level 3 (Max.)
A	Cured Fiber Volume	50%	60%	70%
B	Fiber E_{11}	IM7 –20%	IM7 nominal	IM7 +20%
C	Resin E	(977-3) –20%	977-3 nominal	(977-3) +20%
D	Fiber E_{22}	IM7 –20%	IM7 nominal	IM7 +20%
E	Laminate Orientation to Load	0º (perfect alignment)	+5º	+10º

The full-factorial design with five input parameters at 3 levels provides an assessment of interactions and nonlinearities. It requires only $3^5 = 243$ runs.

Effects of Resin Fiber and Prepreg Properties on Failure – Experimental Design

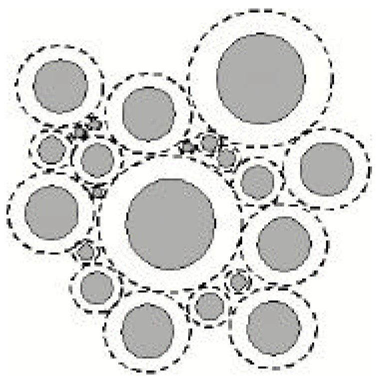
Output/Response Variables:

	Variable Name	Module
1	Lamina E11	Lamina
2	Lamina E22	Lamina
3	Lamina G12	Lamina
4	Laminate E11	Laminate
5	Strain in 0° ply	Laminate
6	Tensile Load at First Ply Failure of an Open-Hole Tension Specimen	Structures – Point Stress

Outputs show effects at multiple scales – lamina elastic constants, laminate equivalent elastic constants, laminate ply strains, and failure of an open-hole coupon.

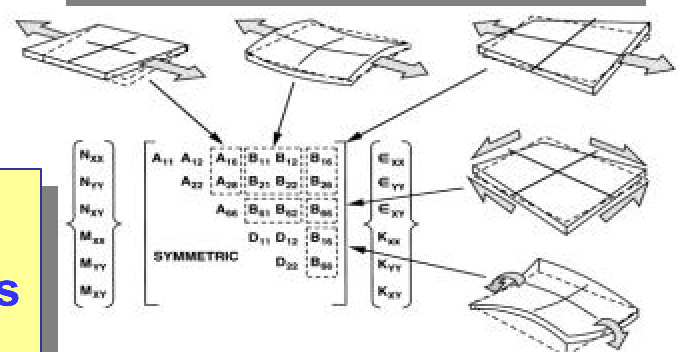
Effects of Resin Fiber and Prepreg Properties
Approach – Models

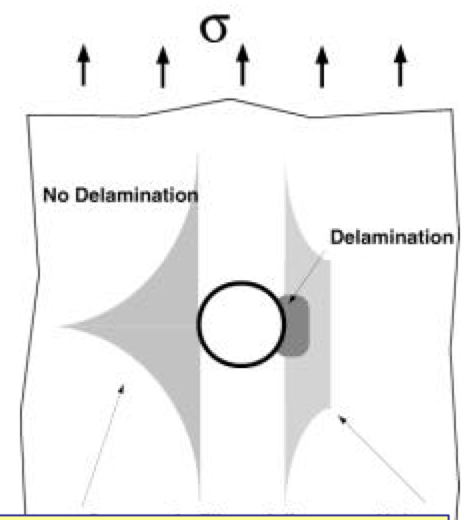
- **Composite Cylinders Assemblage used for lamina thermoelastic pro perty prediction.**
- **Laminated plate theory for $[((0/90)_S)_2]_S$ laminate level properties.**
- **Laminate analyses conducted using closed-form solution for stresses near an open hole.**
- **Various Failure Criteria (Max Strain, Hashin Interaction and PASS) can be compared.**



Models for Effective Continuum Properties

Classical Lamination Theory (CLT)





Models for Continuous Fiber Composites

Composite Cylinders Assemblage (CCA)

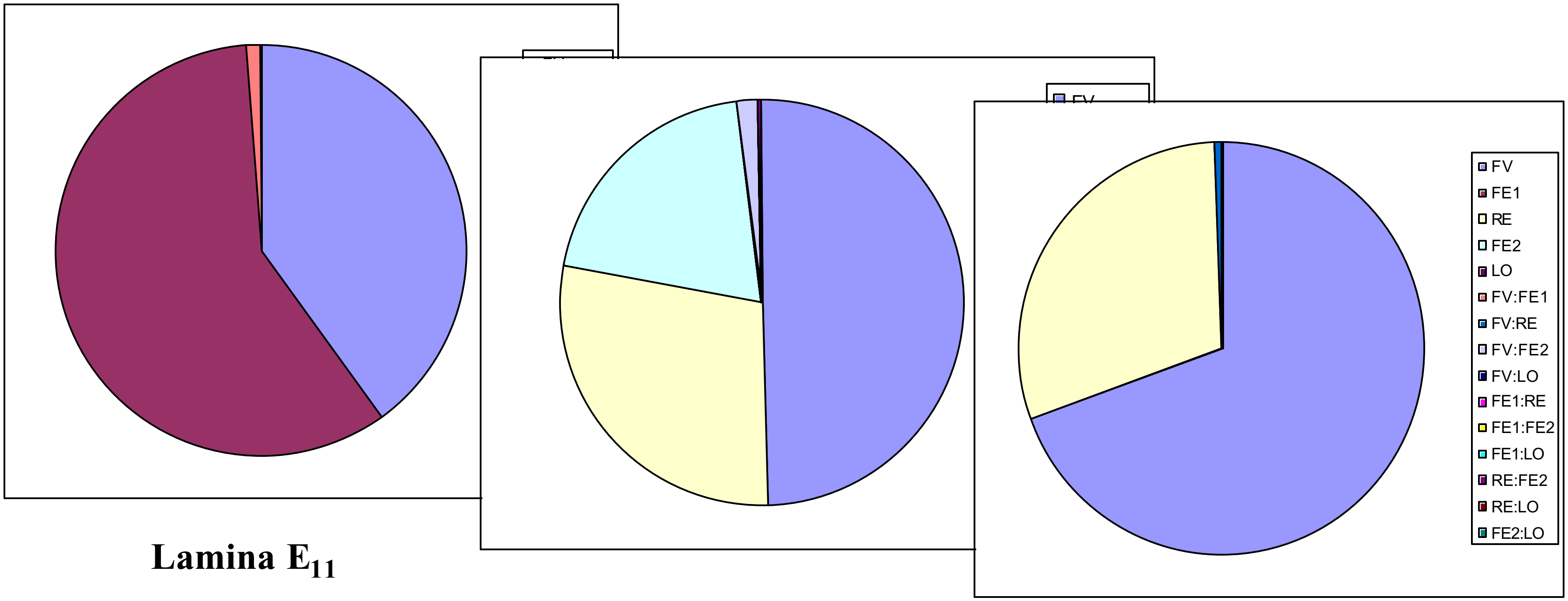
Generalized Self-Consistent Method (GSCM)

Models for Predicting Structural Response

Level 1 : Parametric Analyses; elastic laminate with approximations

Effects of Resin Fiber and Prepreg Properties
Results – Significance of Input Variables

Analysis of Variance (ANOVA) for Lamina Moduli



Lamina E_{11}

Lamina E_{22}

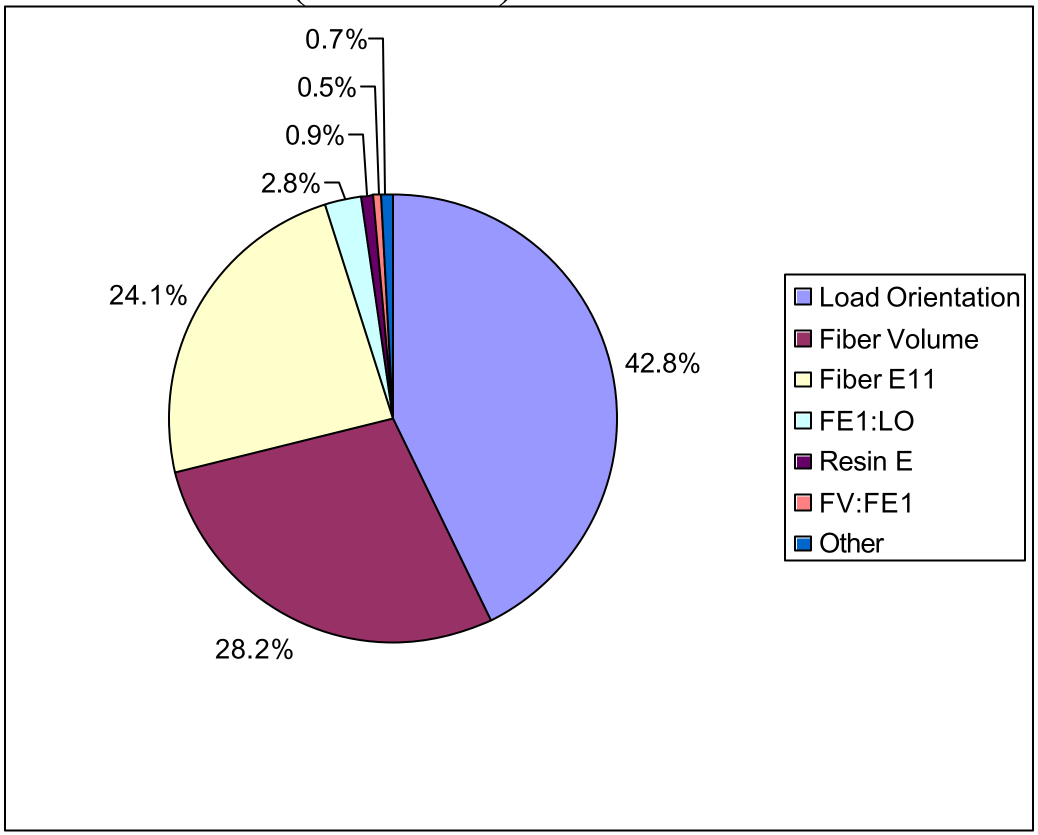
Lamina G_{12}

All Results are as expected:

- Fiber Volume and Fiber E11 are the only significant influences on the Lamina E11
- Fiber Volume, Resin E, and Fiber E22 are the only significant influences on the Lamina E22
- Fiber Volume and Resin E are the only significant influences on the Lamina G12

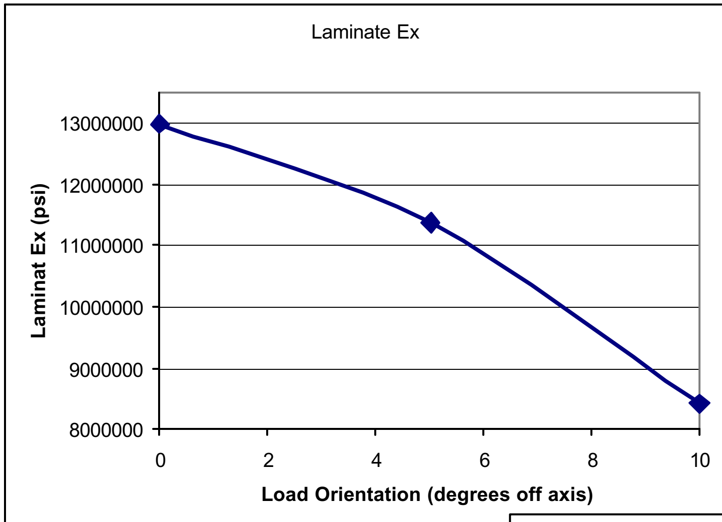
Effects of Resin Fiber and Prepreg Properties
Results – Significance of Input Variables

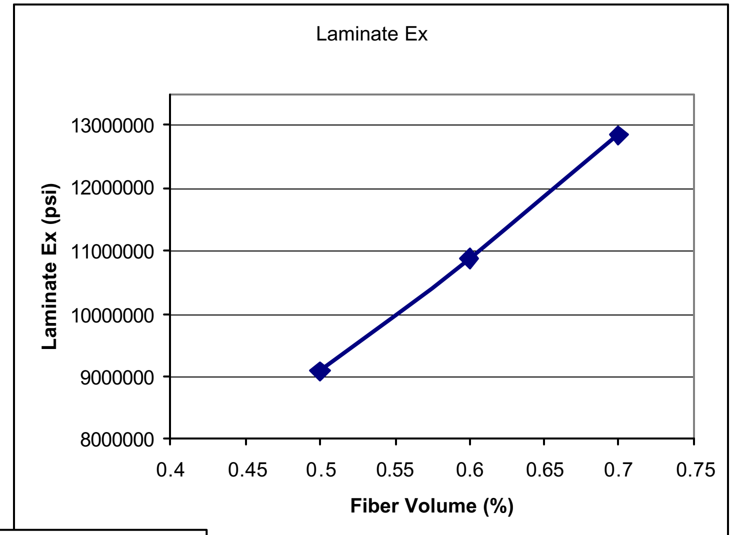
Analysis of Variance (ANOVA) for Laminate Axial Modulus (Ex)



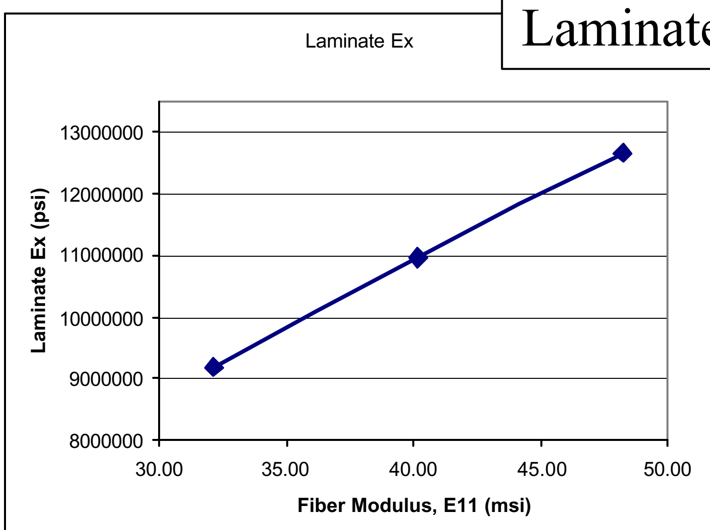
- **The Load Orientation has a large influence on the Laminate axial modulus**
- **As expected, Fiber Volume and Fiber E11 also have significant effects**
  - Fiber E22 and Resin E have very little effect (<1%)
- **Other Interactions account for the remainder (~4%).**

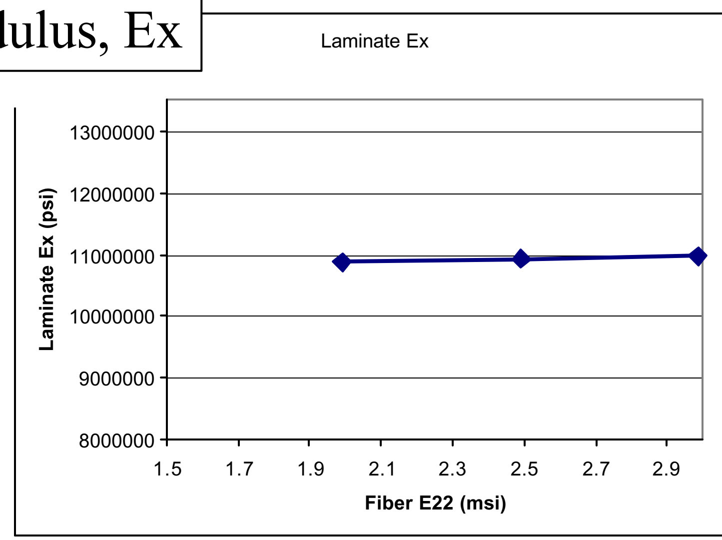
Effects of Resin Fiber and Prepreg Properties
Results – Main Effects





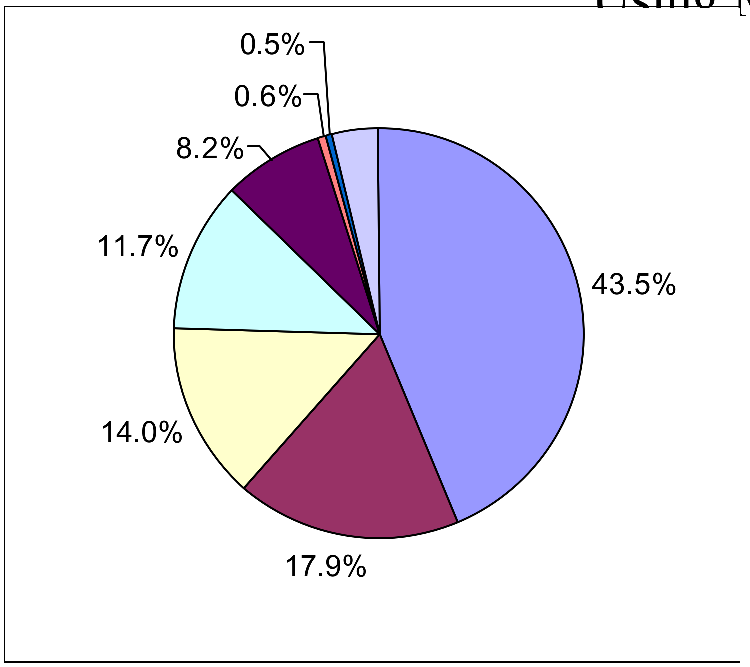
Laminate Modulus, Ex





Effects of Resin Fiber and Prepreg Properties Results – Significance of Input Variables

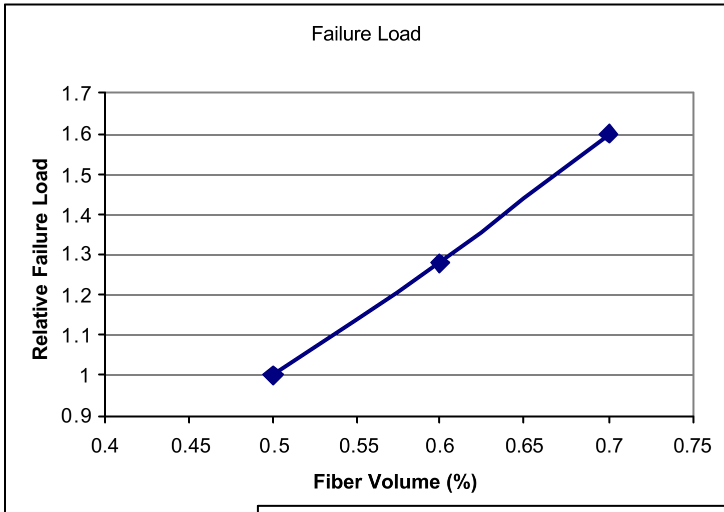
Analysis of Variance (ANOVA) for First Ply Failure Using Maximum Strain Criteria

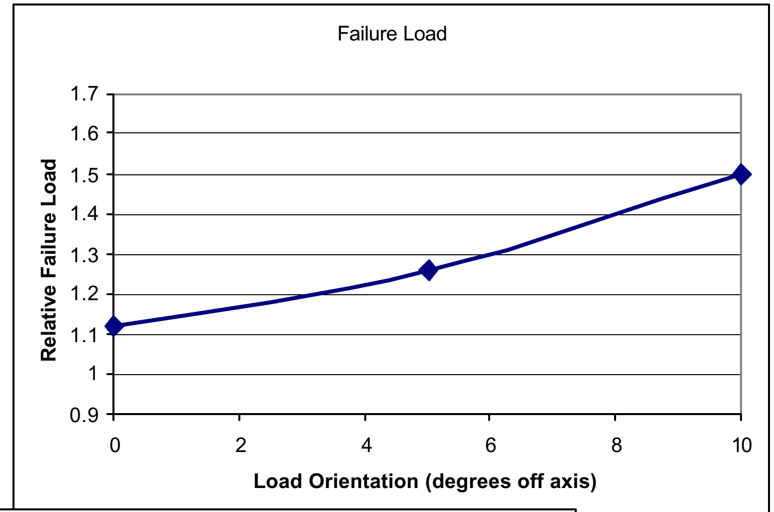


	Df	SS	F	%Contrib
Fiber Volume	2	14.663	7.331	43.5%
Load Orientation	2	6.037	3.019	17.9%
Resin E	2	4.707	2.354	14.0%
Fiber E22	2	3.953	1.977	11.7%
Fiber E11	2	2.763	1.382	8.2%
FV:RE	4	0.202	0.051	0.6%
FE1:RE:LO	8	0.154	0.019	0.5%
Other	220	1.218	0.005537	3.6%
Total	242	34		100%

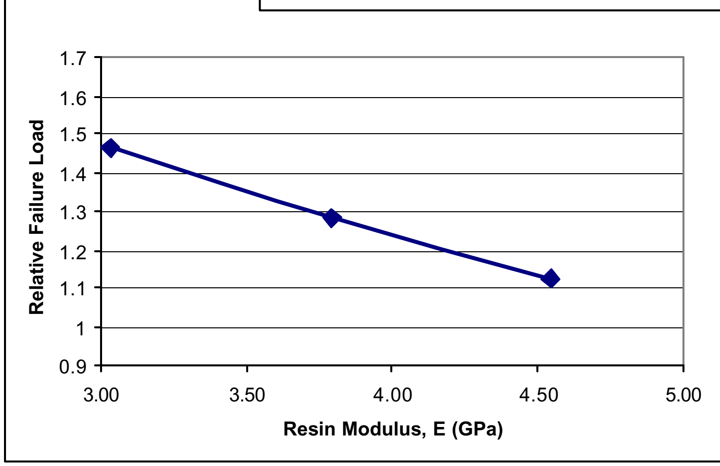
- **The Fiber Volume and Constituent Moduli have significant influence on Strain at Failure**
  - These four variables account for 77% of the effect!
  - Load Orientation also has a large effect (about 18%)

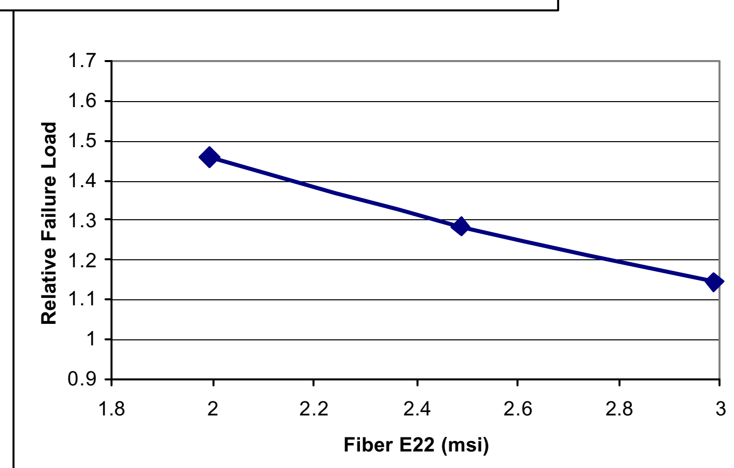
Effects of Resin Fiber and Prepreg Properties
Results – Main Effects





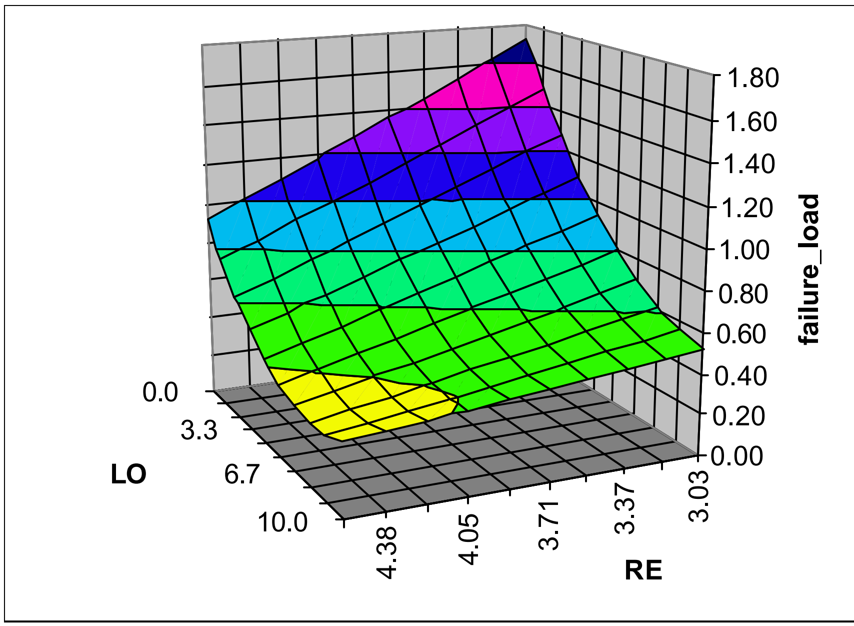
First Fiber Failure Using Maximum Strain Criteria

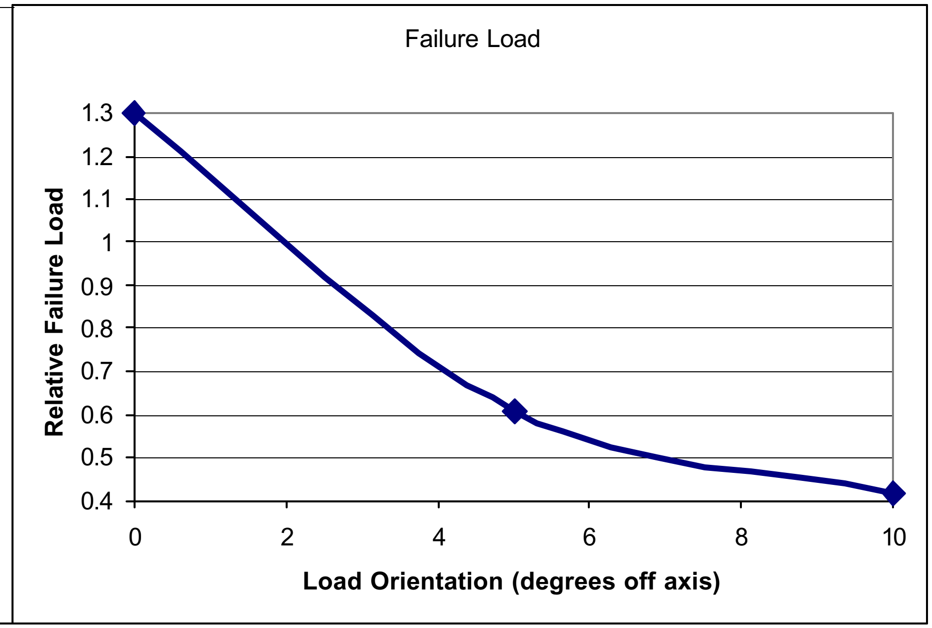




Effects of Resin Fiber and Prepreg Properties
Results – PASS Criteria

Failure Response Surface and Main Effect – PASS Criteria



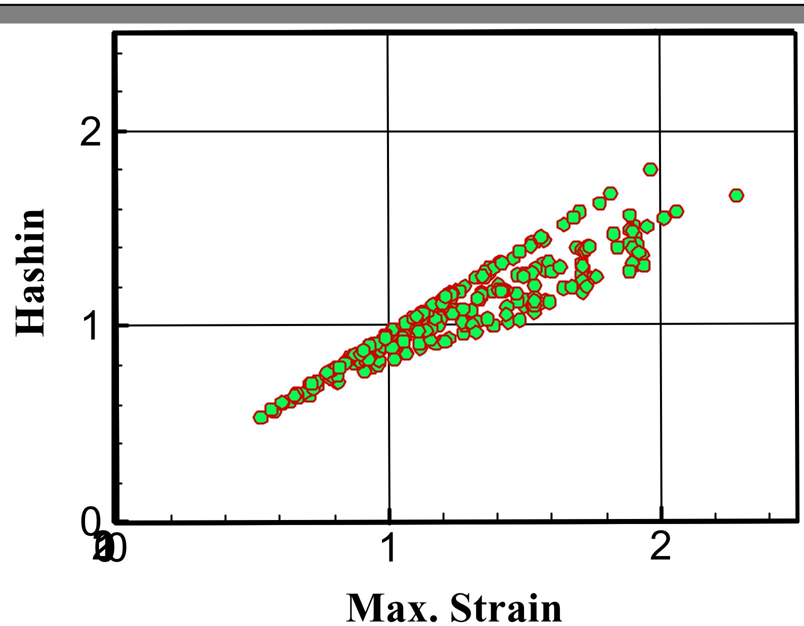


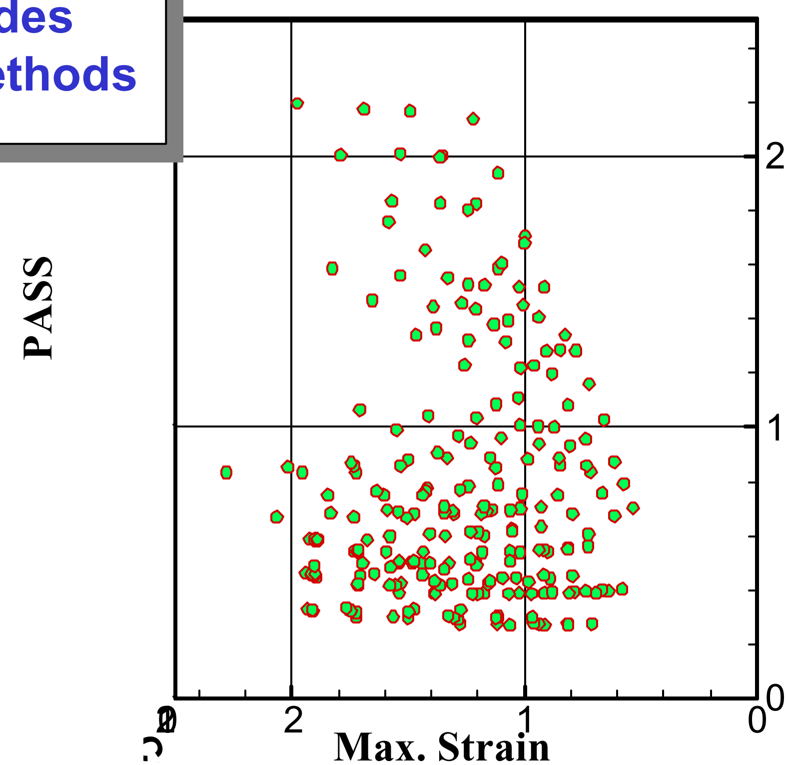
- **ANOVA and most Main Effect Trends Similar to Max. Strain Criteria, except…**
- **Load Applied Off-axis DECREASES Failure Load**
- **A Significant Interaction exists between Resin Modulus and Load Orientation**
  - When the load is well-aligned with fiber direction, Resin Modulus has much more influence

Effects of Resin Fiber and Prepreg Properties – Conclusions and Lessons Learned

- Failure Criteria give significantly different results
  - Effective way to find tests to discriminate between criteria
  - Resin vs. Fiber Failure– different drivers

Integration of Structures Tools Provides Comparison of Different Criteria and Methods





Sensitivity of OHT Strength to Uncertainties

Purpose and Setup

- Purpose
  - Determine the effects of Material and Manufacturing Variation and Analysis Uncertainty on Failure of an Open Hole Tension Specimen

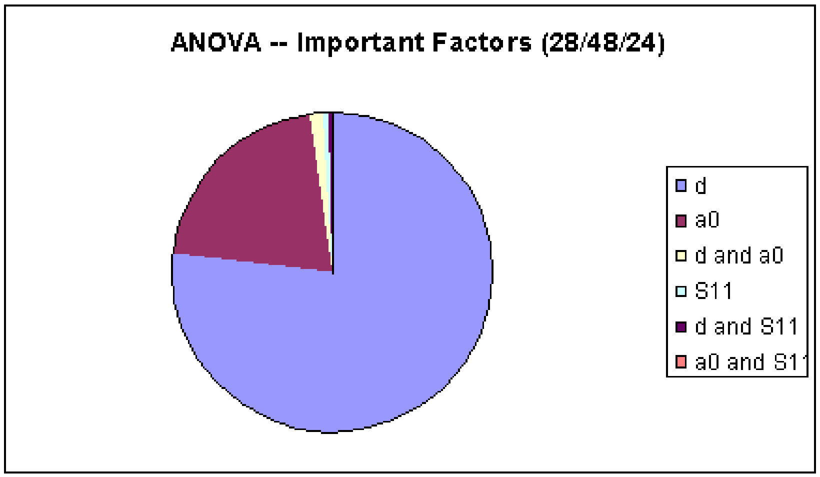
- Setup:

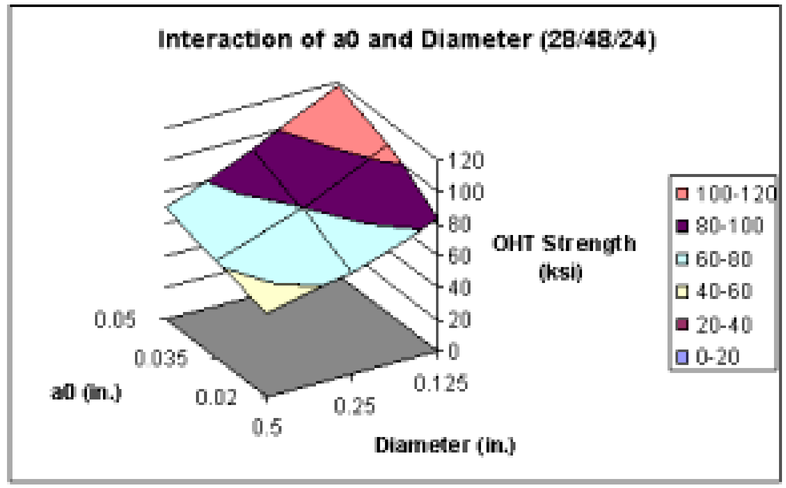
Case	Descriptor	Input/Design Variables (3 Levels)		
		L1	L2	L3
A	Hole Diameter – d mm (inches)	5.72 (0.225)	6.35 (0.250)	6.99 (0.275)
B	a_0 mm (inches)	0.000 (0.000)	0.889 (0.0350)	1.207 (0.0475)
C	Tensile Strength -S_{11}^{+} Mpa (ksi)	2324 (337)	2551 (370)	2779 (403)

- Similar Methods as Study 1, Hashin Failure Criteria
- Four Laminate Architectures (Stacking Sequences)

Sensitivity of OHT Strength to Uncertainties

Important Variables – ANOVA Results



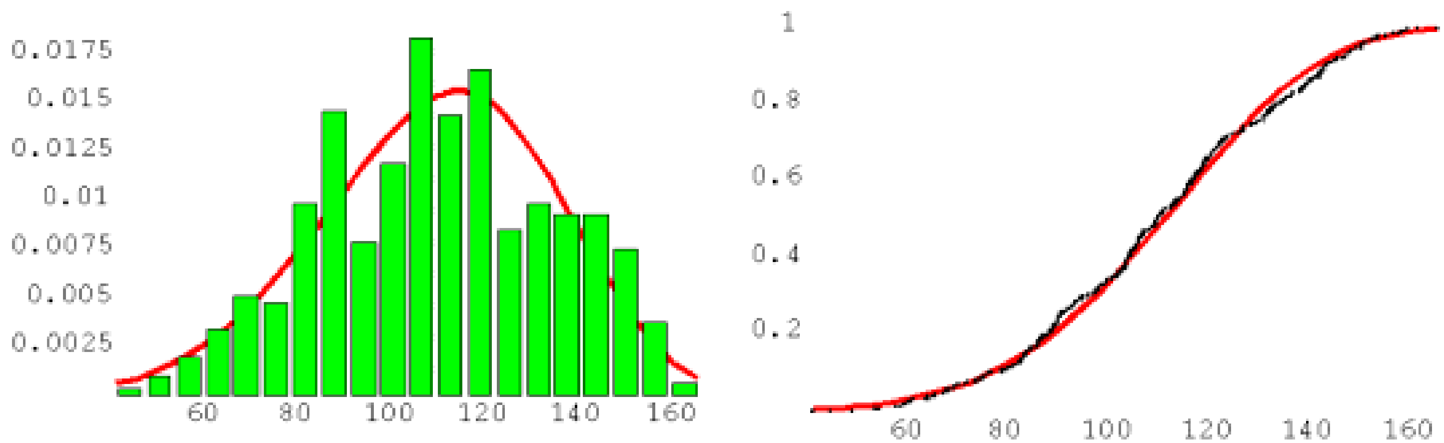


- Hole Diameter and Choice of a_0 are much more important than Lamina Tension Strength!

- Choice of a_0 is much more important for small hole diameters

Sensitivity of OHT Strength to Uncertainties

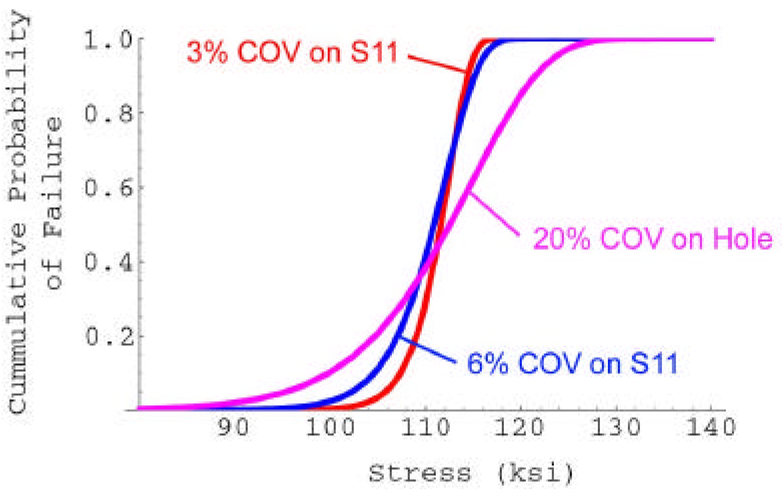
Uncertainty Propagation – Monte Carlo Analysis



- Effect of Large Variations (Study Ranges) on Failure Strength
  - Weibull PDF Fit (Left)
  - CDF Fit versus Data Points (Right)

Sensitivity of OHT Strength to Uncertainties

Uncertainty Propagation – Monte Carlo Analysis



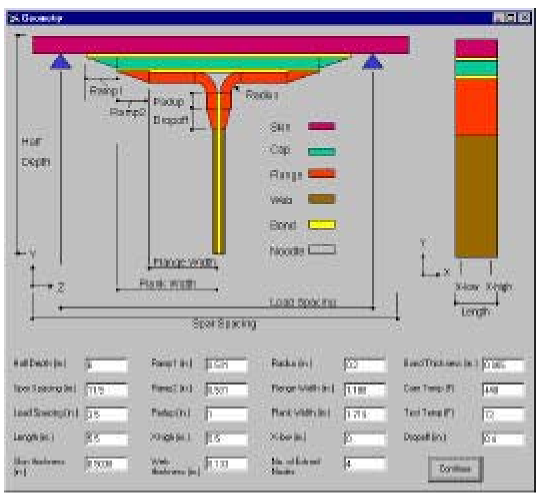
Case	Probability of Failure at 80 ksi (0.60% strain) 0.68xMean	Probability of Failure at 90 ksi (0.67% strain) 0.77xMean	Probability of Failure at 100 ksi (0.75% strain) 0.85xMean
3% COV on S11	1 / 15 x 10^6	1 / 51,000	1 / 303
6% COV on S11	1 / 53,000	1 / 1,200	1 / 41
Including 20% hole diameter variation	1 / 310	1 / 50	1 / 10

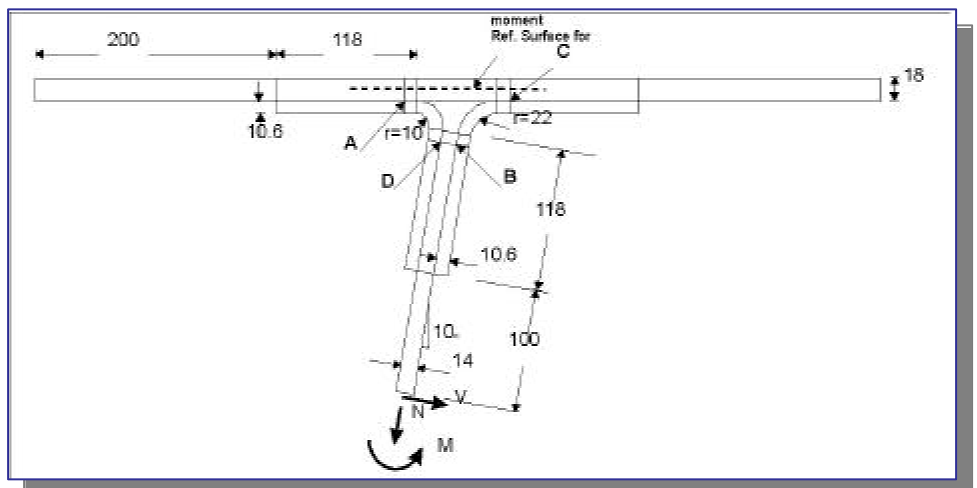
- Effect of Small Manufacturing and Material Variations on Failure

- Variations have a large effect on Failure Probabilities (and, therefore, allowables)

2-D Bonded Stiffener Separation

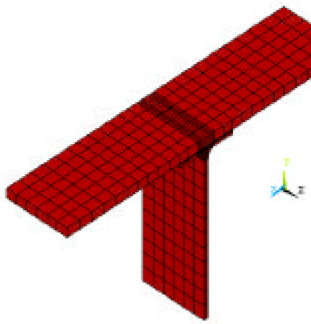
- Simple Strength Tools (SIFT Handbooks) and Fracture Tools (e.g. beam and/or stacked plate solutions, such as SUBLAM) exist to perform this Analysis for Pressure Loading
- Material Property Data exists to perform this solution for <u>multiple materials</u>.
- Fresh Validation Data available from other programs
- Typically two primary failure modes (noodle and edge of flange)
- Solutions are easily expandable to z-pin or stitched reinforcements

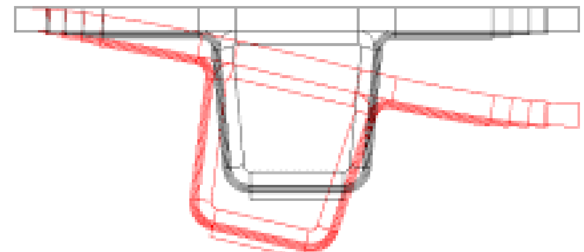


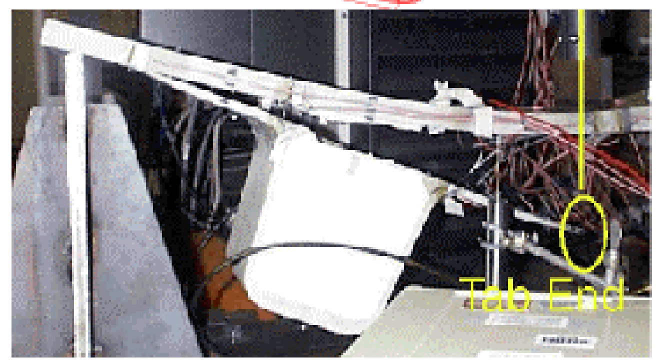


2D Disbond Analysis Methods

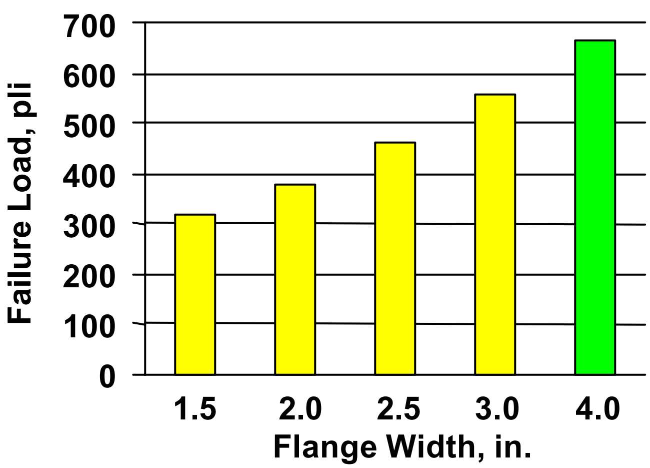
SIFT and Fracture Methods have been Successfully Applied to 2D Bonded Joints

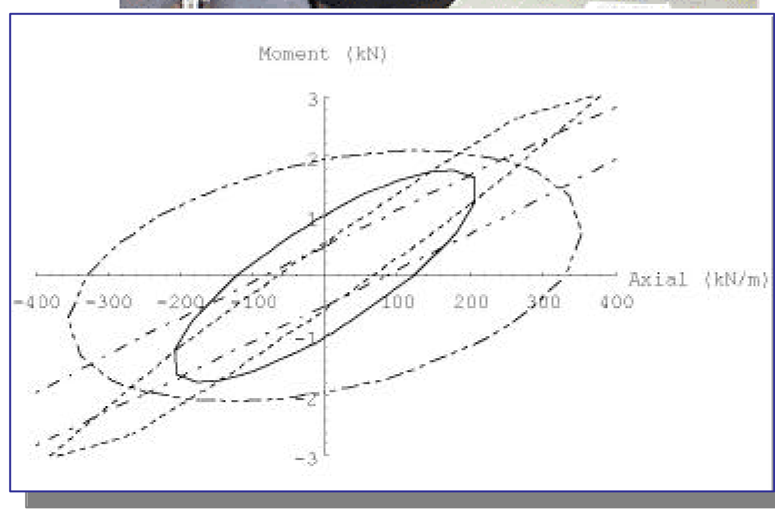






J_{1crit} = 0.012
COV = 0.0427





RDCS Edge of Flange Disbond Study

The Problem

Application Objective

- Investigate the effect of skin-stringer panel geometric parameters on maximum moment at the flange and margin of safety for stringer pull-off
- To aid in the selection of appropriate stiffener geometry and spacing

High Level Description

- **Design variables:** Skin Thickness, Flange Thickness, Stiffener Height, Total Flange Width
- **Response Variables**: Maximum Flange Moment, Pull-off Margin
- **Solvers/Methods:** RDCS, ANSYS/LEFM

Solution Scope

- **RDCS:** Sensitivity analysis, Factorial Design Space Explorations
- **ANSYS**: Static non-linear large deflection analysis
- **Solution Cases**: 81 Large Scale FEM Solutions

Experimental Setup

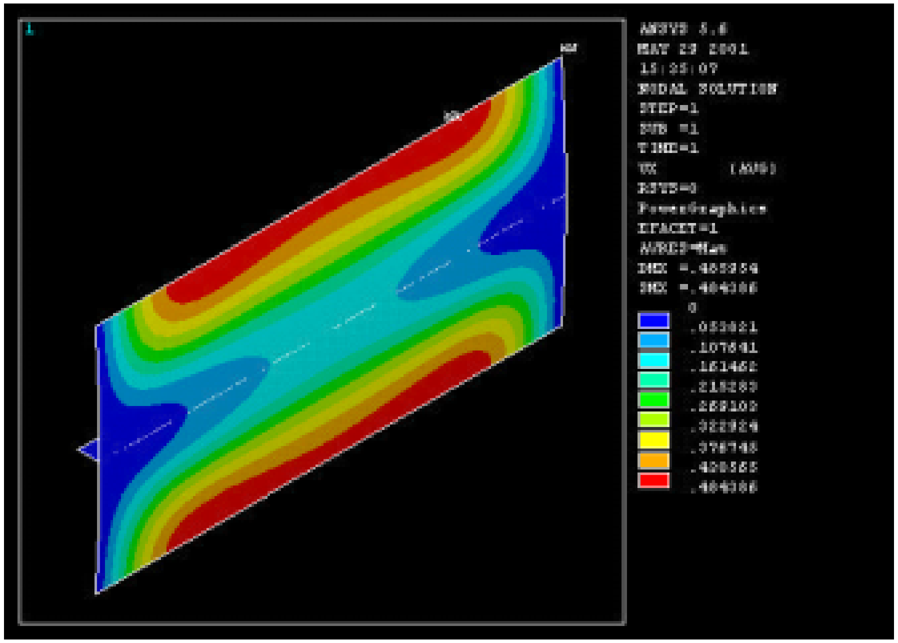
	Variable Name	ANSYS® Variable	Level 1 (Min)	Level 2	Level 3 (Max.)
A	Skin Thickness, mm	tskin	2.03	3.05	4.06
B	Flange Thickness, mm	tflan	2.03	3.05	4.06
C	Stiffener Height, mm	Hhat	25.4	38.1	50.8
D	Total Flange Width, mm	wbot	50.8	101.6	152.4

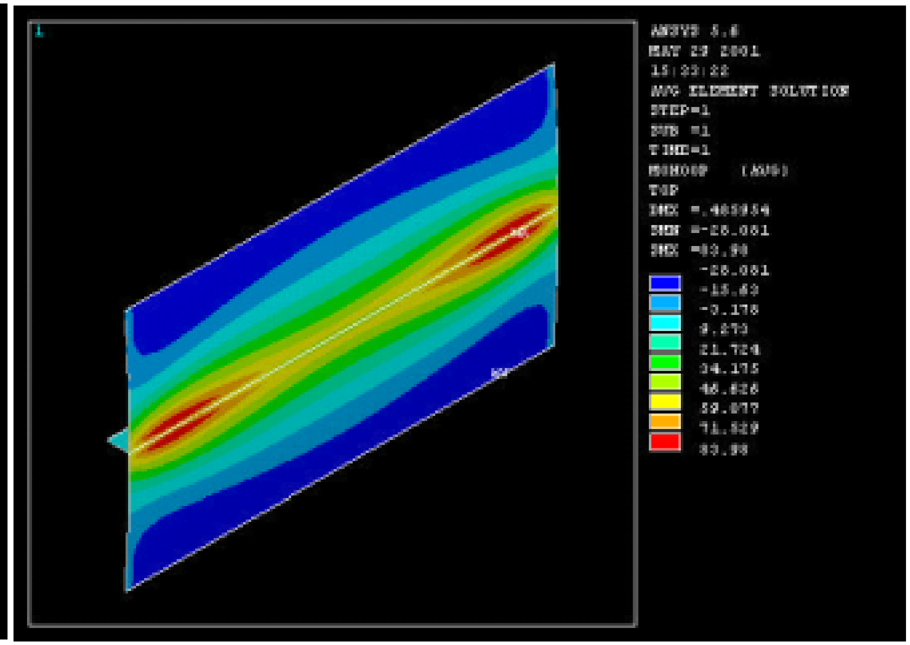
RDCS Application Benefits

- **Rapid factorial design calculations for external ANOVA study and response surface with significant cycle time reduction**
- **ANOVA helps identify critical factors and interactions**
- **Accurate surrogate response surface model helps simplify the design process**

RDCS Edge of Flange Disbond Study

The Problem





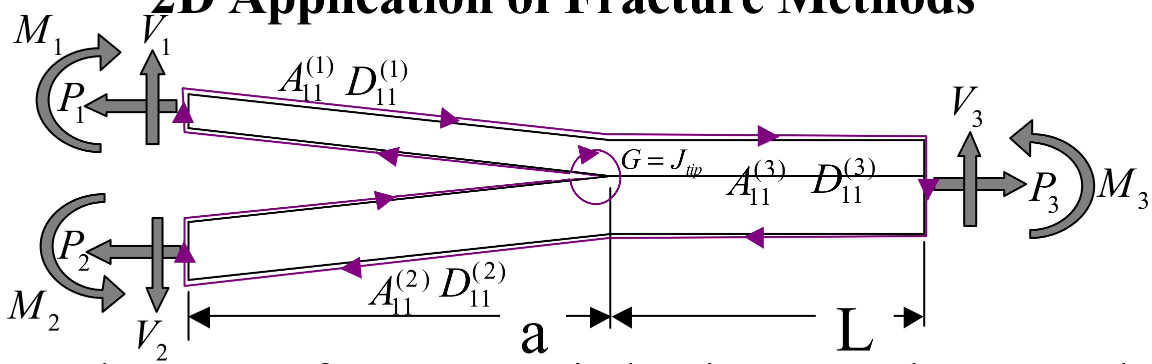
Internal Pressure (or postbuckling) create large pillowing deflections between stringers

These deflections create high moments at the skin-to-stringer bondline. The loads don’t vary tremendously along the length – can be analyzed as a 2D problem using the maximum loads (conservative)

RDCS Edge of Flange Disbond Study

2D Application of Fracture Methods

- J-integral

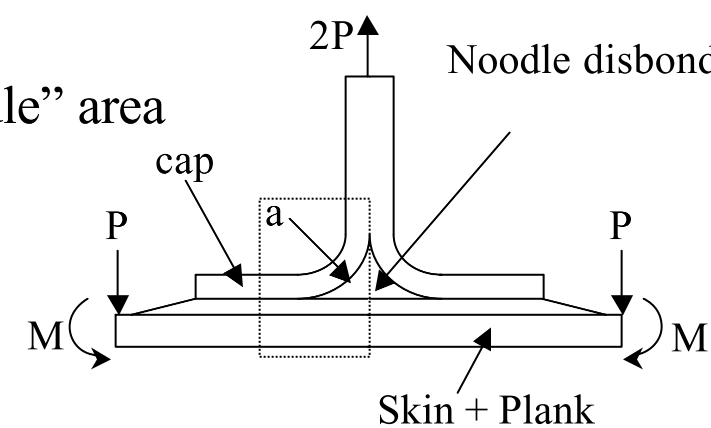


- Strain energy release rate for symmetric laminates under general loading, unequal stiffness

$$G = \frac{1}{2}\left\{ \frac{P_1^2}{A_{11}^{(1)}} + \frac{(M_1 + V_1 a)^2}{D_{11}^{(1)}} + \frac{P_2^2}{A_{11}^{(2)}} + \frac{(M_2 + V_2 a)^2}{D_{11}^{(2)}} - \frac{P_3^2}{A_{11}^{(3)}} - \frac{(M_3 + V_3 L)^2}{D_{11}^{(3)}} \right\}$$

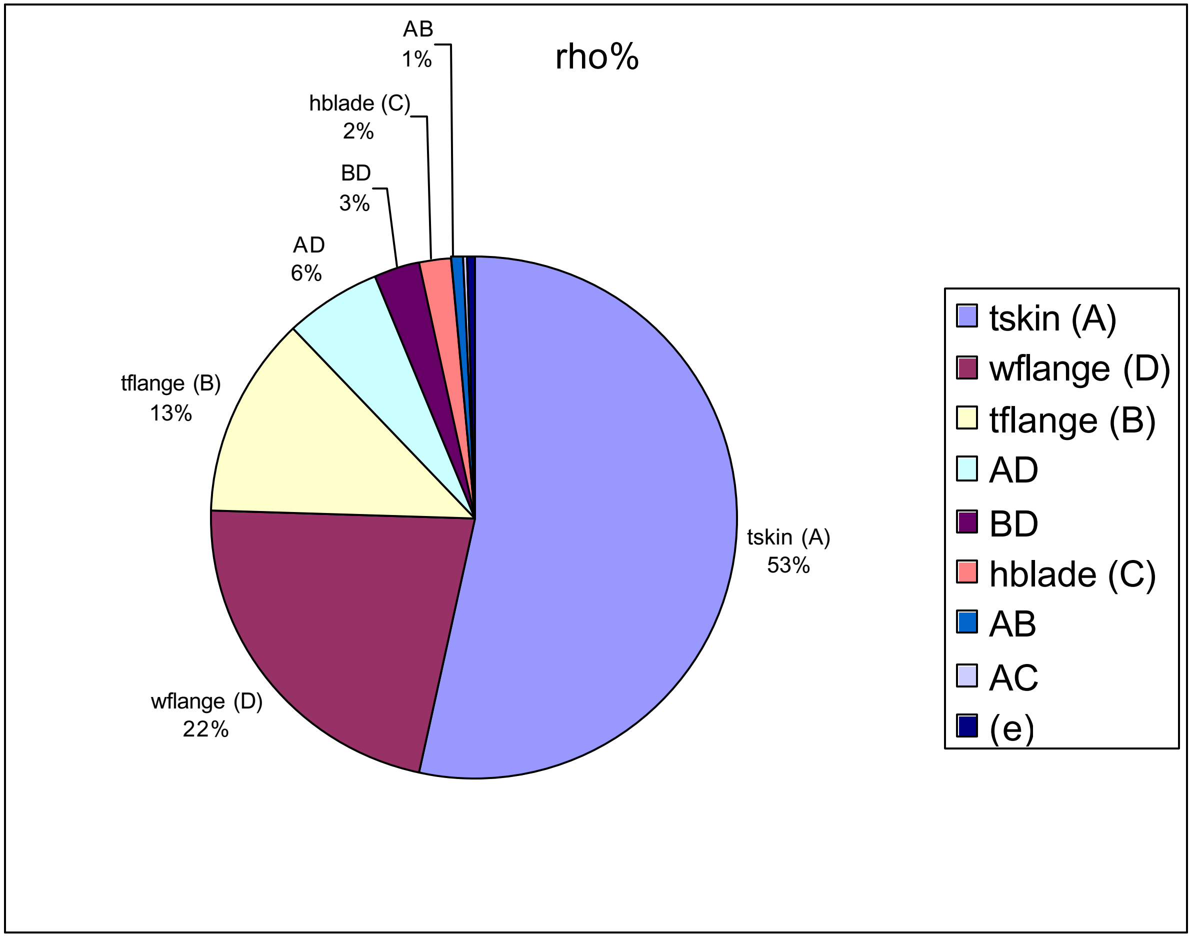
- Solution by J-integral, expandable to z-pin or stitched reinforcements

- Similar Solutions avaliable for “noodle” area



RDCS Edge of Flange Disbond Study

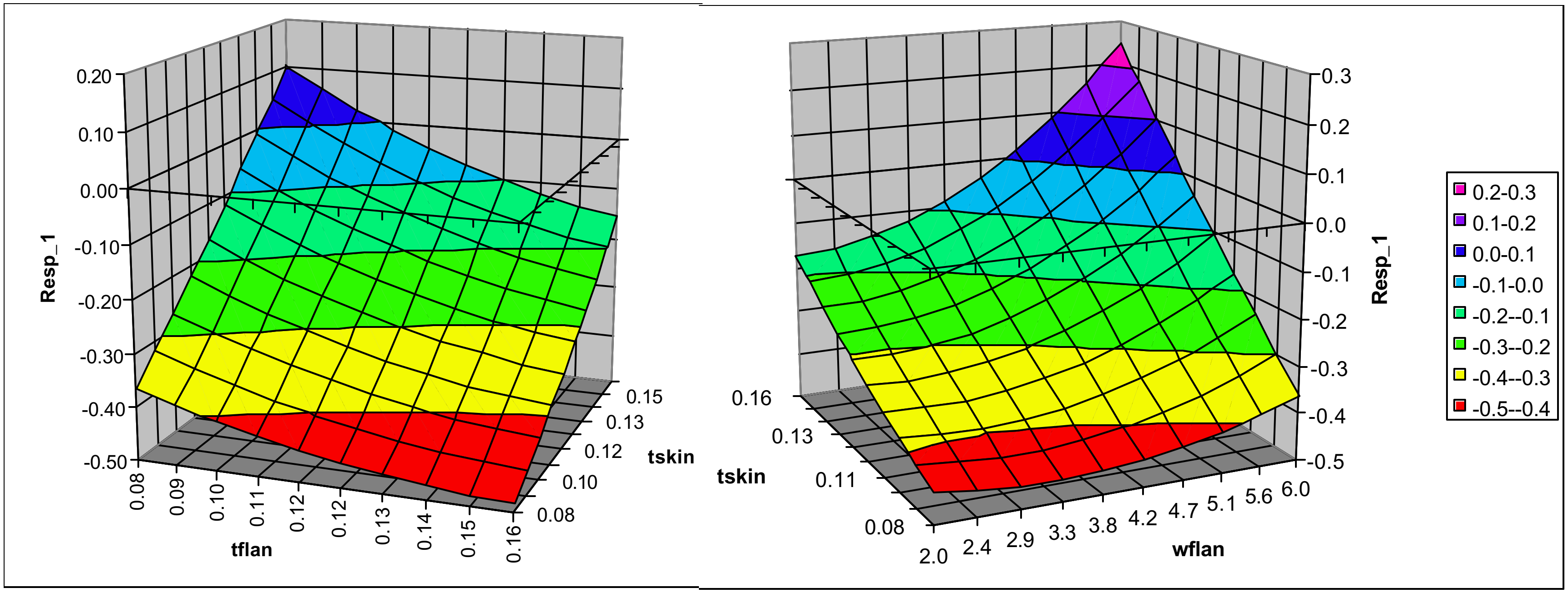
ANOVA Results



The major influences are skin thickness, flange width, flange thickness, and their interactions

RDCS Edge of Flange Disbond Study

Interaction Results

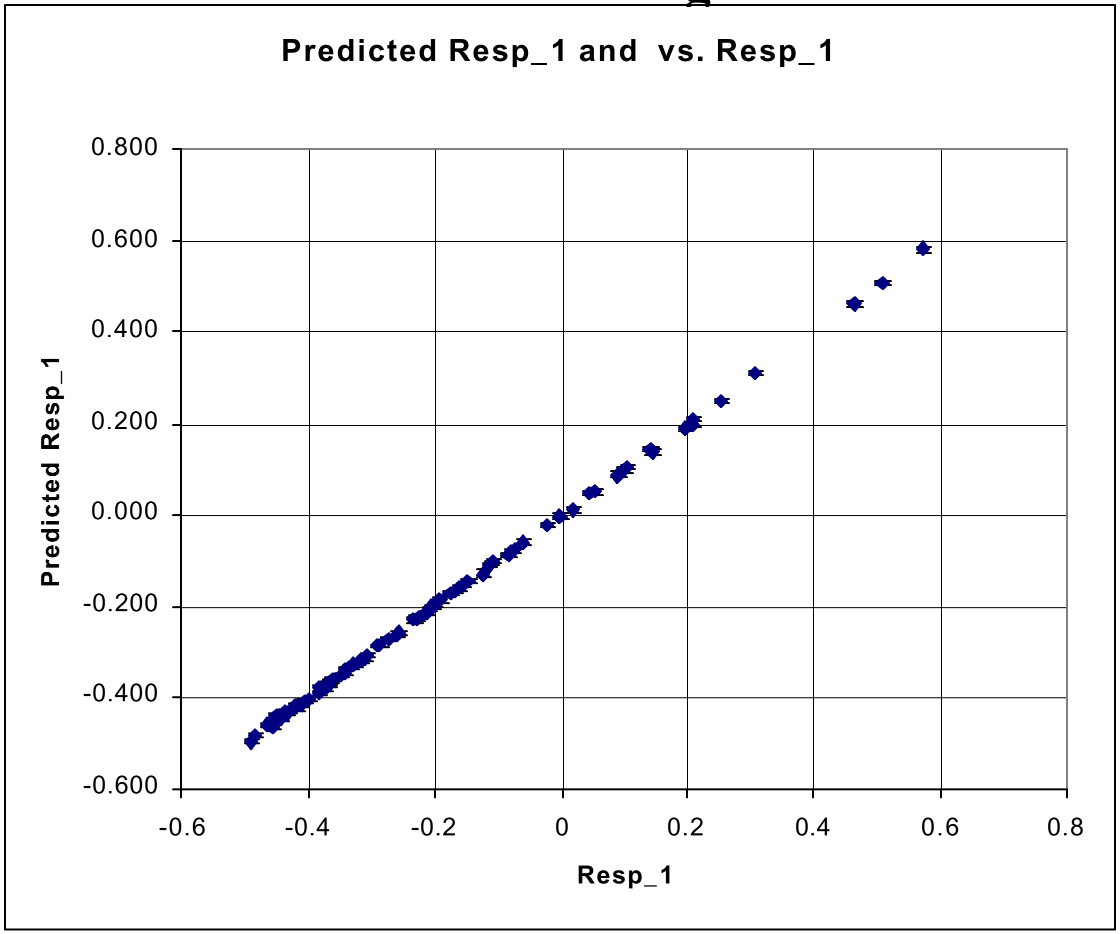


- **Best edge-of-flange peel margin of safety is when skin is thick and flange is thin**

- **Flange width has a much greater effect on the margin when skins are thick. The effect is highly nonlinear.**

RDCS Edge of Flange Disbond Study

Closed-form Regression fit



A quadratic regression fit to the response surface captured this failure mode nearly perfectly. Errors are on the order of ±1%.

Edge of Flange Disbonds

Some Analysis Issues

Fracture Property Input Tests (Data Scatter/Method Dependency)

Mode Mixture (Often assume values near Mode I – Conservative)

Validation Pending (Simple Pull-off through 7-Stringer Panels)

2D Approximation – Okay for Pressure? Not for some loadings.

Definition and Location of Initial Flaw

Fiber Bridging

Simplicity of Propagation of Damage

Modeling and Interpreting Free Edges

Accuracy of Input Values (e.g., Stress-Free Temperature)

Convergence/Detailed Models/DOF

Other Sensitivity Studies

- Error Propagation Study.
  - Demonstrated use of Lamina and Laminate Module tools to help understand how material and manufacturing variability (moduli, cured ply thickness, ply angle) propagates from the lamina to the laminate. (Aleatory Uncertainty).
- Effects of Processing Variables on Laminate Cracking.
  - Demonstrated the effect of cure parameters on the propensity for a laminate to exotherm and examined residual stresses resulting from various cure cycles and tooling material combinations and their effect on the initiation of matrix damage under subsequent loading. Discovered suspect input data and coding errors which would only be apparent by exercising linked models.

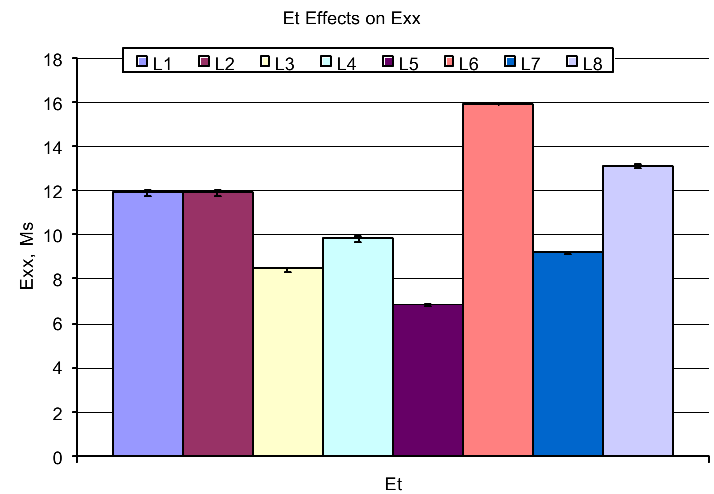
Material Sensitivity Study

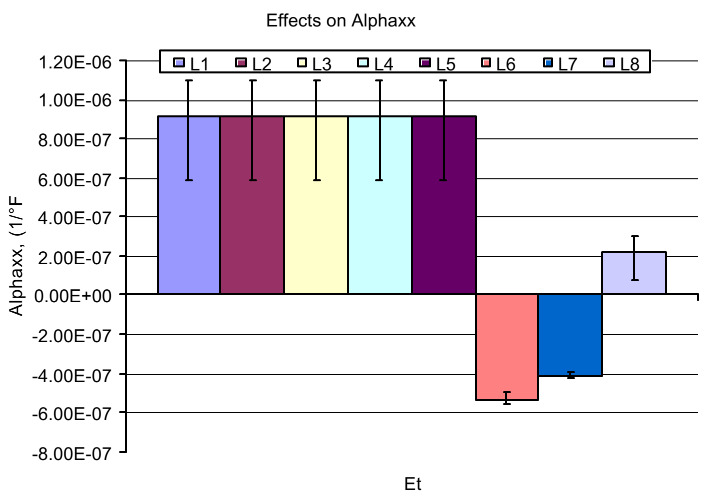
- Effect of "Unmeasurable" Properties.
  - Use Lamina and Laminate Module tools to quantify the sensitivity of laminate level properties to large (50%) variations in micro properties that can not reliably be measured (Epistemic Uncertainty).
- Findings.
  - *Unmeasurable* fiber properties have little effect on laminate mechanical properties, i.e., stiffness and fiber dominated (ultimate) strength.
  - Some parameters can significantly effect thermo-elastic properties, e.g., thermal expansion coefficients.

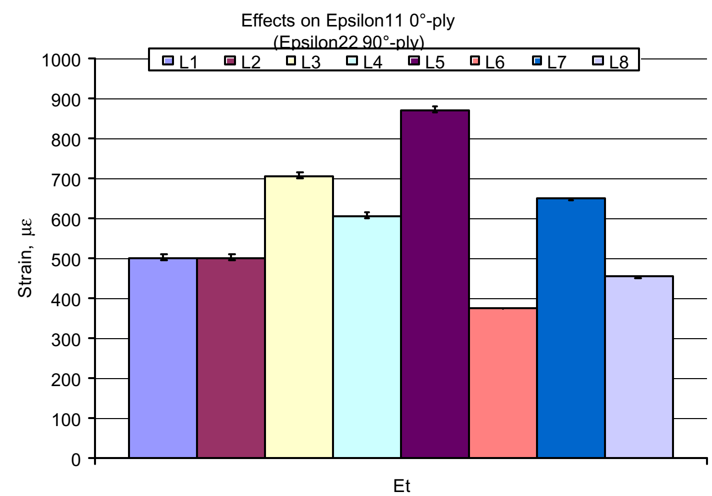
The models being assembled to form the Structures Module can be used to aid the design of experiments to quantify the effects of lack of knowledge of material input parameters (Epistemic Uncertainty).

Material Sensitivity Study
Effect of "Unmeasurable" Properties

Case	Laminate
L1	$(0/90/0/90/0/90/0/90/0/90/0/90)_s$
L2	$(0/0/90/90/90/0/0/90/90/90/0/0)_s$
L3	$(+45/-45/0/90/+45/-45/0/90/+45/-45/0/90)_s$
L4	$(+45/-45/0/90/0/90/0/90/0/90/+45/-45)_s$
L5	$(+45/-45/+45/-45/0/90/0/90/+45/-45/+45/-45)_s$
L6	$(+45/-45/0/0/0/0/0/0/0/0/+45/-45)_s$
L7	$(+45/-45/+45/-45/0/0/0/0/+45/-45/+45/-45)_s$
L8	$(+45/-45/0/0/0/90/90/0/0/0/+45/-45)_s$







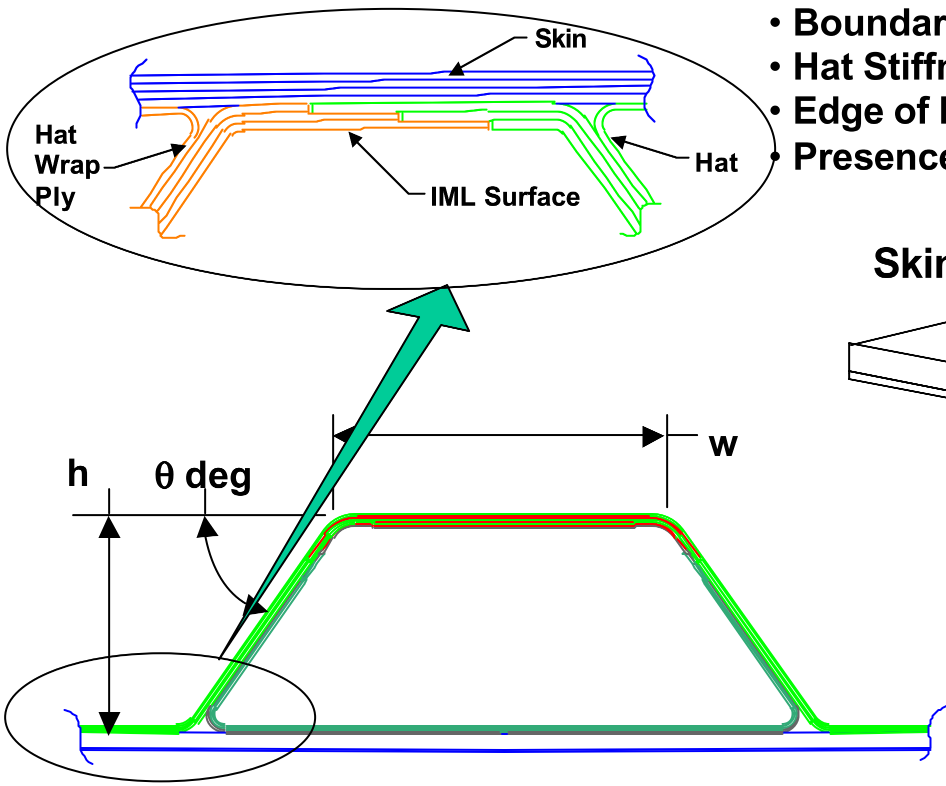
Conclusions and Lessons Learned

- RDCS Provides a Framework for Quickly and Easily:
  - Allowing Statistical Calculations
  - Determining Which Inputs are Critical
  - Helping Establish Mfg Thresholds
  - Comparing Methods
  - Developing Design Curves
  - Investigating Design Improvements
  - Exposing Poor Data and Inconsistencies
- Ability to Analyze using mixed English and SI Units
  - Mars Climate Orbiter Issue
- Beware of Type III Error
  - Failure to ask the right question – Right Answer to Wrong Question
- Answers are only as Valid as Input Data and Analysis Methods
- Significant Integration Effort Still Required
- Significant Time Required to Analyze Data from Large Studies
- Large RDCS benefit – Often over a 50% Decrease in Required Time

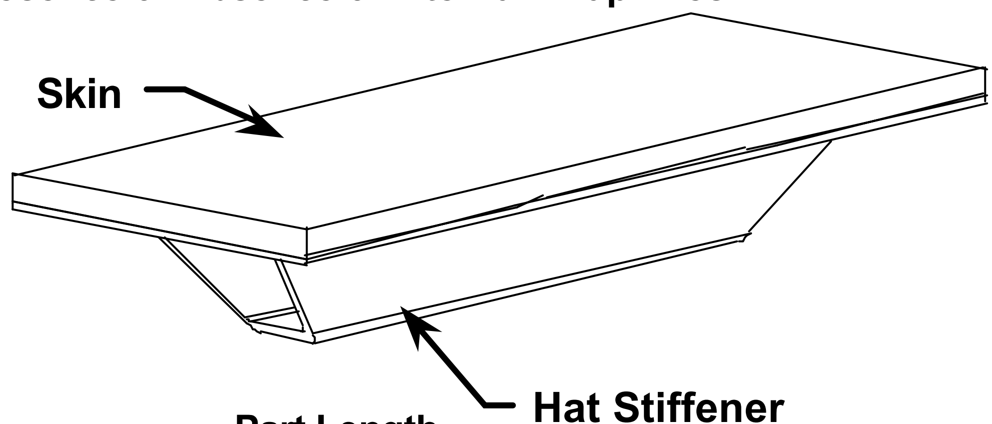
Next Steps

Understanding The Mechanics of a Stiffener Runout
A True 3D Problem with Hundreds of Variables

- Runout Shape and Angle
- Boundary Conditions/Edge Reinforcement
- Hat Stiffness Tailoring at/near Runout
- Edge of Flange Configuration (Tapered, Square-edged)
- Presence or Absence of Internal Wrap Plies



Sect A-A

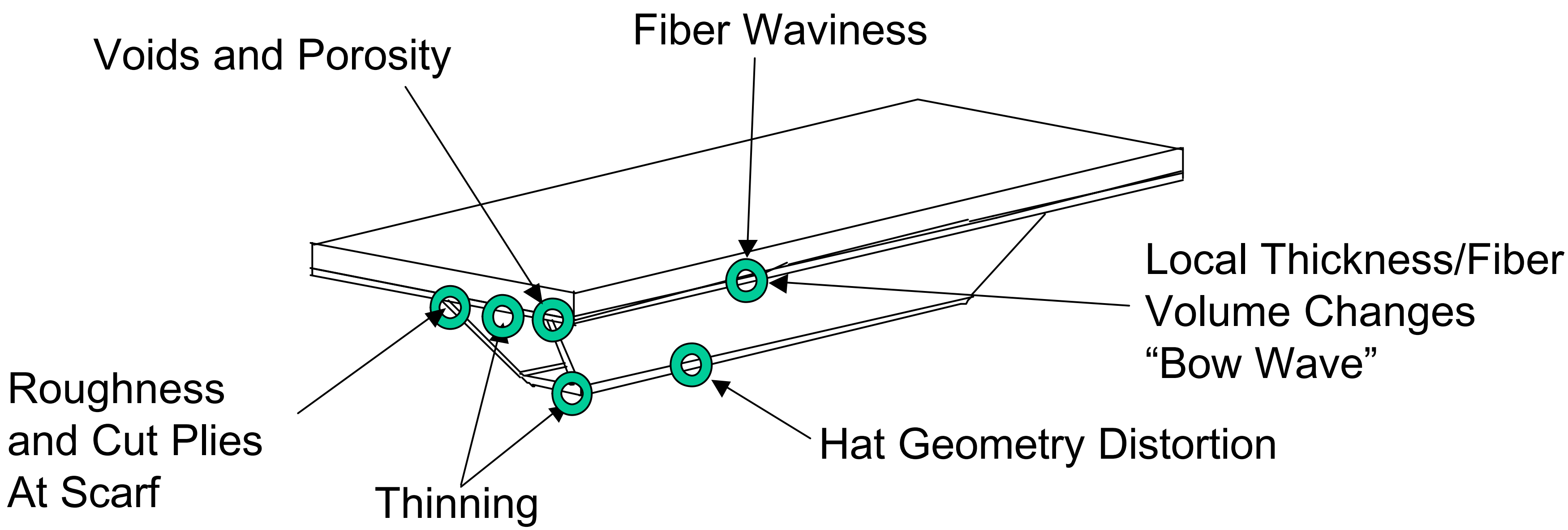


- Part Length
- Skin Thickness
- Spanwise/Chordwise ply dropoffs
- Hat Geometry (e.g., h, w, and θ)
- Layups
- Taper?

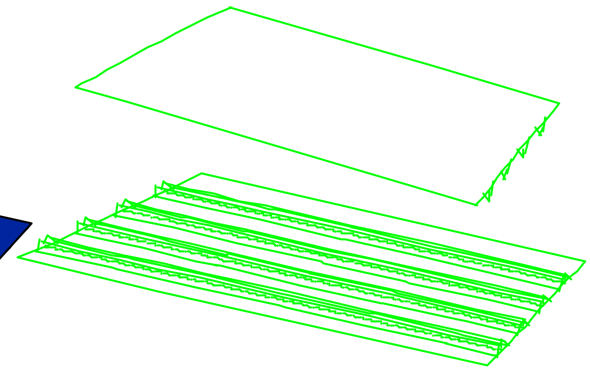
Next Steps

Failure Analysis Must Account For:

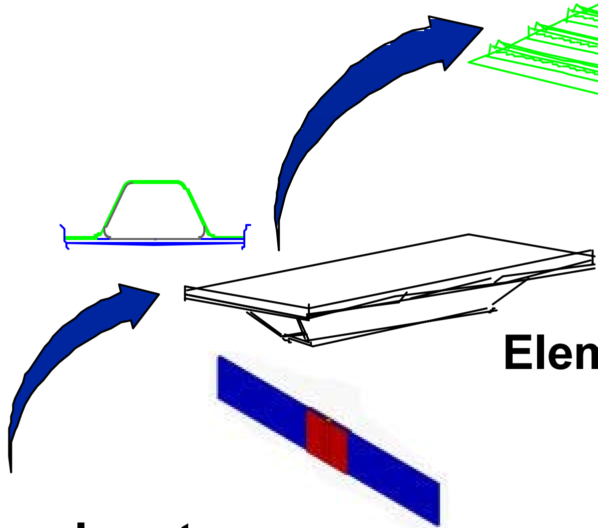
- **Effects of Common Critical Defects**
- **Tooling and Processing Effect on Residual Stresses**
- **Skin, Stiffener, and Adhesive Material**
- **Tape and Fabric Product Forms**



Next Steps
Validation Testing

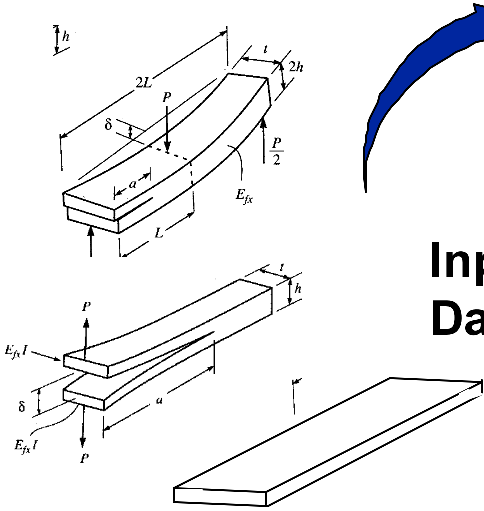


Analysis Validation Tests



Elements

- Static Strength
- Durability
- Damage Tolerance?



Input Data

- DCB and ENF
- J_1 and ε_{eqv} Laminates/Joints