Accelerated Insertion of Materials –

Managing Error and Uncertainty in Structures

49th International Society for the Advancement of Material and Process Engineering Symposium and Exhibition

17 May 2004

S. Eric Cregger, Boeing
samuel.e.cregger@boeing.com

Anthony Caiazzo, Materials Sciences Corporation
Perry Pugliano and Raj Rajagopal, Boeing
Stan Uryasev, American Optimal Decisions

Jointly accomplished by BOEING and the U.S. Government under the guidance of NAVAIR.

Sponsored by DARPA/DSO and administered by NAVAIR through TIA N00421-01-3-0098

Outline

- The Basic AIM-C Approach (as implemented)
  - Understand and Classify Potential Uncertainty Sources
  - Determine What's Important
  - Limit Uncertainty/Variation by Design and/or Process
  - Quantify Variation (Monte Carlo Simulation or Test)

- Data from Knowledge, Analysis, and Test
  - Previous Knowledge and Divergence Risk
  - Analysis
  - Test
  - Combined Data Approaches

Handling Uncertainty – The AIM-C Approach

- The First Step is Identifying and Understanding potential error sources
  - Maintains Visibility of potential errors
  - Forces step-by-step breakdown of the analysis/test process
  - Forces agreement on responses of interest

- Classifying them allows the team to determine appropriate strategies for addressing them.

- Types:
  - Aleatory Uncertainty (Variability, Stochastic Uncertainty)
  - Epistemic Uncertainty (Lack of Knowledge, e.g., unknown geometry)
  - Known Errors (e.g., mesh convergence, round-off error)
  - Unknown Errors (Mistakes, e.g. wrong material inputs used)

Identifying and Understanding Error Sources

	Inherent variations associated with physical system or the environment (Aleatory uncertainty) Also known as variability, stochastic uncertainty E.G. manufacturing variations, loading	Uncertainty due to lack of knowledge (Epistemic uncertainty) inadequate physics models information from expert opinions.	Known Errors (acknowledged) e.g. round-off errors from machine arithmetic, mesh size errors, convergence errors, error propagation algorithm	Mistakes (unacknowledged errors) human errors e.g error in input/output, blunder in manufacturing
Lamina Stiffness/ Thermal Properties (CCA and/or Empirical)	Variation in all fiber and resin moduli, Poisson's ratio, and CTE properties. Test uncertainties such as specimen misalignment, load/displacement measurement	Unmeasurable Constituent Properties (transverse fiber modulus, etc.) Interphase effects	CCA: Use of model outside of bounds.(e.g., woven 3D preform) Empirical: Extrapolation beyond test data (fiber volumes, temperatures, etc.)	CCA: I/O errors, code bugs Empirical:Testing machine not calibrated. Poor specimen preparation; poor strain measurement techniques.
Laminate Stiffness Calculation (CLPT)	Variations in ply-thickness, ply angles, etc.	Assumes thin plate with no shear deformation, material or geometric nonlinearity, or significant transverse strains.	Use of model outside bounds for items listed under Epistemic uncertainty)	I/O errors (ply thickness, material, layup definition), code bugs
Stress-Free Temps/ Residual Curing Strain Input (COMPRO)	Many parameters can affect residual stress: local fiber volume fraction, …	Micro-stresses are considered to be independent of meso-stresses; there are few independent measurements of residual stress.	The formulation is believed to be most accurate when the cure cycle temperature is higher than the Tg. Otherwise the residual stress calculated can be an overestimate.	Errors in material property definition, errors in coding, errors in integrating process and structural models.
Coupon Geometry and Load/BC Input (COMPRO, User-defined, Empirical)	Cured ply thickness variations, specimen dimensional tolerances, specimen curvatures due to residual stress/strain			Errors in Coupon Geometry Definition or Improper Idealization of Loading or Boundary Conditions

Handling Uncertainty – The AIM-C Approach

- Next we must know which variables are important to us

- Complex problems have hundreds of potential uncertainties. Its time-prohibitive to spend equal effort investigating each one. We must Focus on the important “few”:

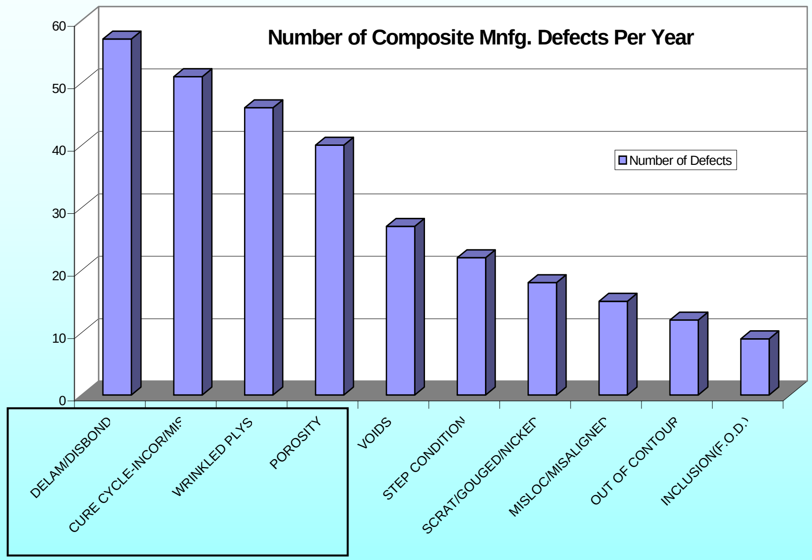
1. Uncertainties which are likely to occur
2. Uncertainties with a large influence on the response(s) of interest

(This evaluation is similar to simple Risk Analyses, assessing Probability of occurrence and consequences of failure)

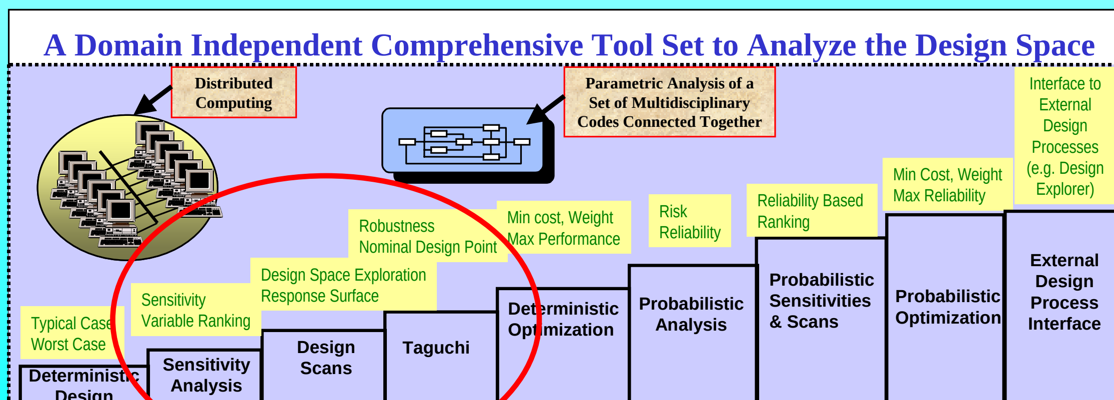
Handling Uncertainty – The AIM-C Approach

- Prior knowledge is useful in determining likelihood of occurrence.

Example: Past experience with Similar designs suggest that 3/4 of Stiffened panel defects are:
- Delaminations
- Cure Cycle Inconformities
- Ply wrinkles, or
- Voids/Porosity

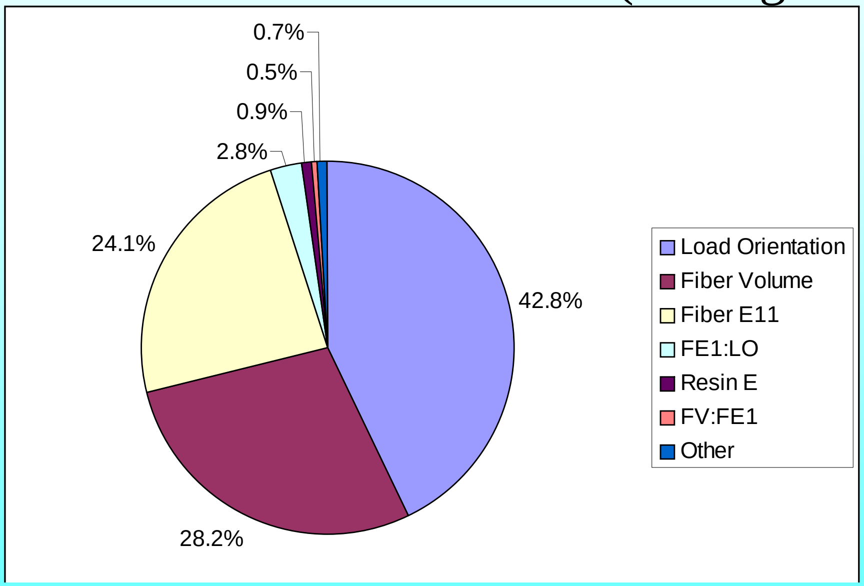


- Tools such as DOE/ANOVA and Sensitivity Analysis are useful in quantifying a variable's influence on the result.



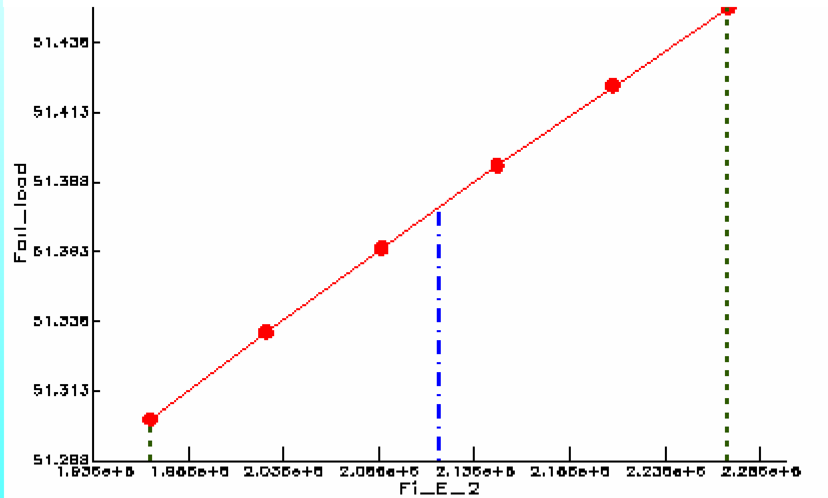
Handling Uncertainty – The AIM-C Approach

- Example – Fiber transverse modulus effect on Laminates
- Other examples:
  - Stress Free Temperature on laminates (variation was small)
  - Stiffener Pull-off (some geometric variables had little effect)



ANOVA for Laminate Axial Modulus

Design Scan for Laminate Failure Load Using PASS Criteria



- **As expected, Fiber Volume and Fiber E_{11} also have significant effects on laminate Modulus**
- Fiber E_{22} and Resin E have very little effect (<1%)

- **Transverse Fiber Modulus (E_{22}) has very little effect**

Handling Uncertainty – The AIM-C Approach

- Where possible, some uncertainties can be eliminated or limited by design choices. Pick the material and design to play to your strengths!

- Allows negotiation between competing response variables
  - E.g., Structural Performance and Producibility

- This is a major philosophical shift for Structures. Focus on Design Robustness rather than Absolute Mean Performance may generally yield a better "allowable" failure load.

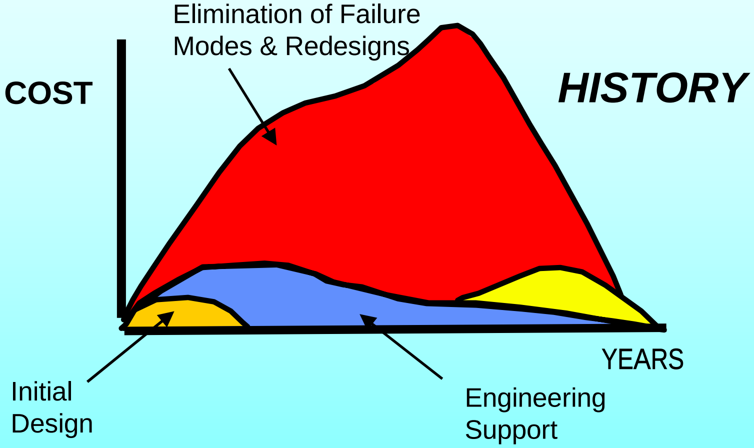
- Tools such as DOE/ANOVA and Sensitivity Analysis are again useful.

Handling Uncertainty – The AIM-C Approach

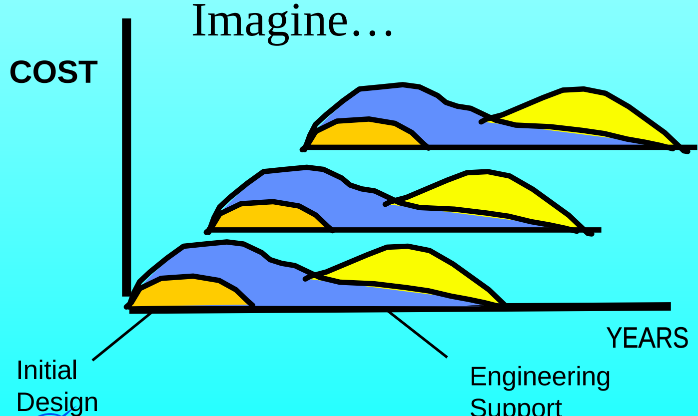
Minimizing Uncertainty by Design

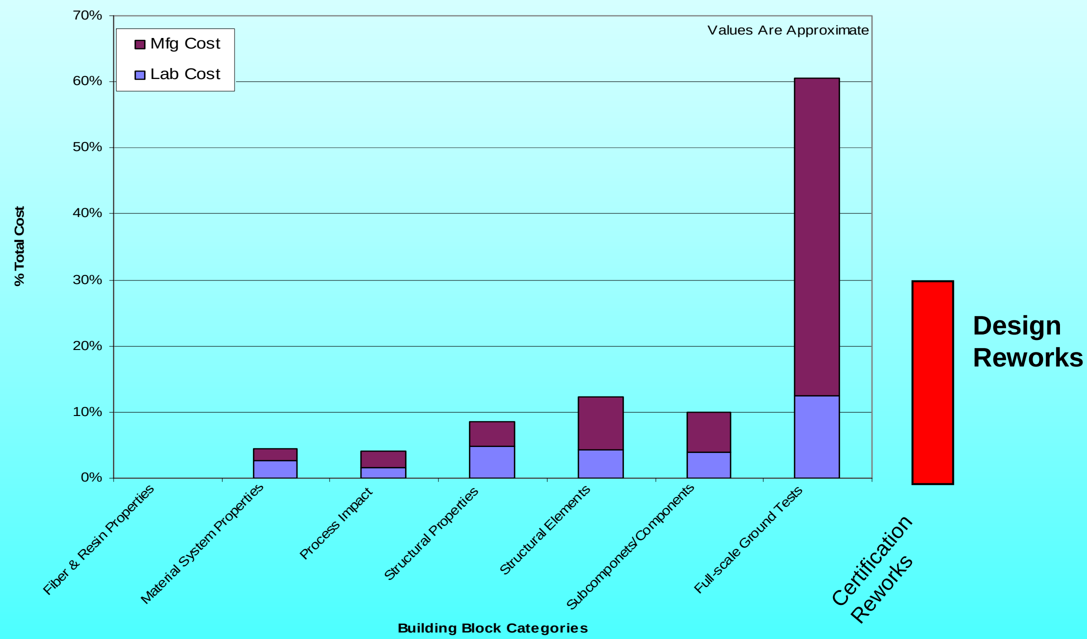
Design Robustness ➔ Avoiding Redesigns

Often, a majority of our development time and money is spent on fixing problems because we failed to choose a Robust Material, Design and/or Process the first time.



Imagine…





Approved for Public Release, Distribution Unlimited

Handling Uncertainty – The AIM-C Approach

Minimizing Uncertainty by Design

- Example – Hat-Stiffened Panel Design

Problem 1:
- Bondline delaminations are commonly occurring defects
- They occur at structurally-critical locations
- The failure load can be very sensitive to bondline delaminations

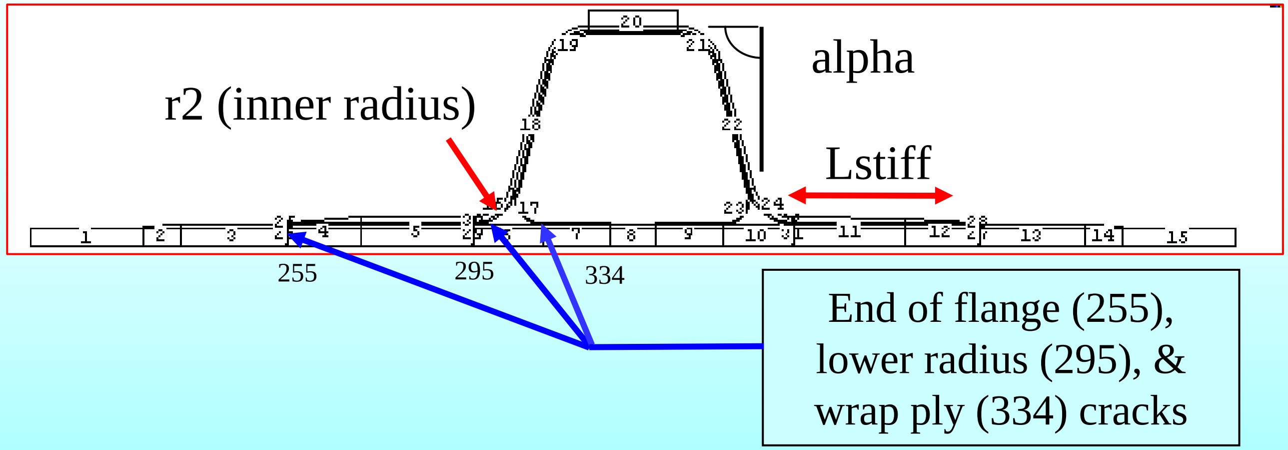
Problem 2:
- All dimensions have manufacturing tolerances
- In some cases, failure can be very sensitive to off-nominal dimensions

Questions:
Can we formulate a design that is much less sensitive to delaminations?
Can we minimize the effect of off-nominal dimensions on the failure load?

Minimizing Uncertainty by Design

HSP Pull-off Modeling with Defects

- Utilizes the following modules within AIM-C
  - Fiber
  - Resin
  - Lamina
  - Fabric



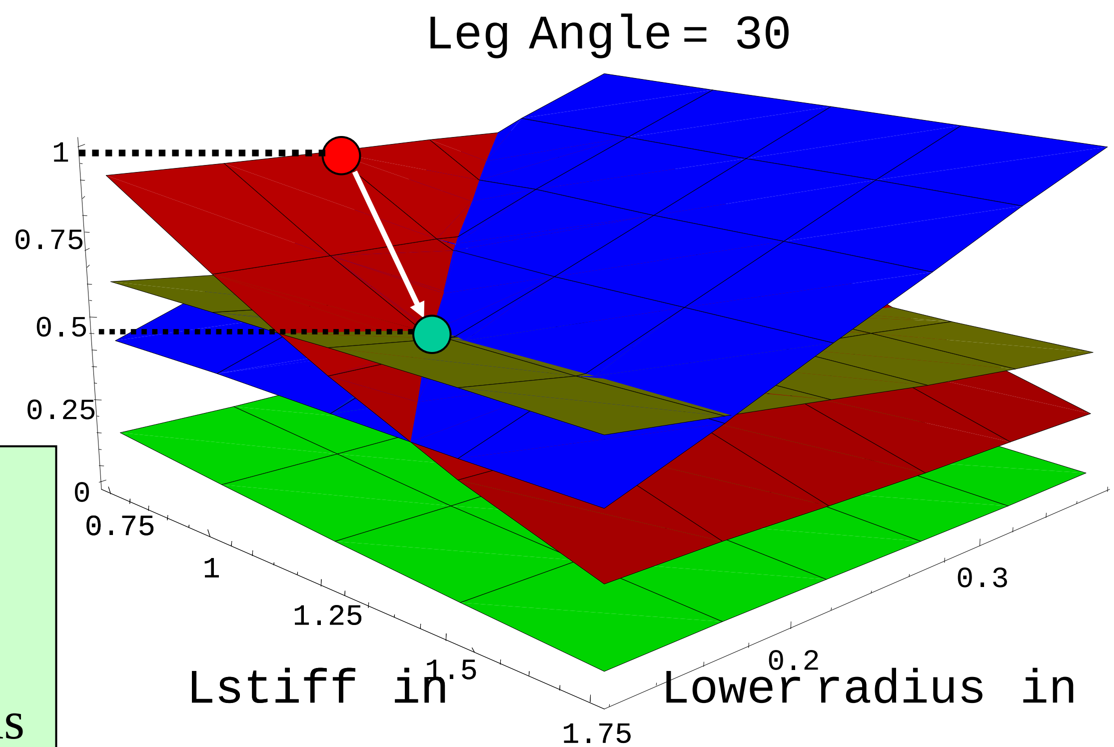
- Allows for both material and geometric variability
  - Focused on length of stiffener, leg angle, and lower radius
- RDCS aided in the following tasks:
  - Determining the sensitivity of embedded flaws to geometric parameters
  - Pinpointing optimal geometric parameters that minimize SERR in
    - Lower radius (multiple delamination locations at "nugget")
    - Length of horizontal stiffener section

Minimizing Uncertainty by Design

Geometry Effect on Radius and Edge-of-Flange Delaminations

SERR Data, Leg Angle = 30 degrees

Large Lstiff and smaller lower radius minimizes energy available to propagate a crack



Red: G_I EOF

Blue: G_I Lower Radius

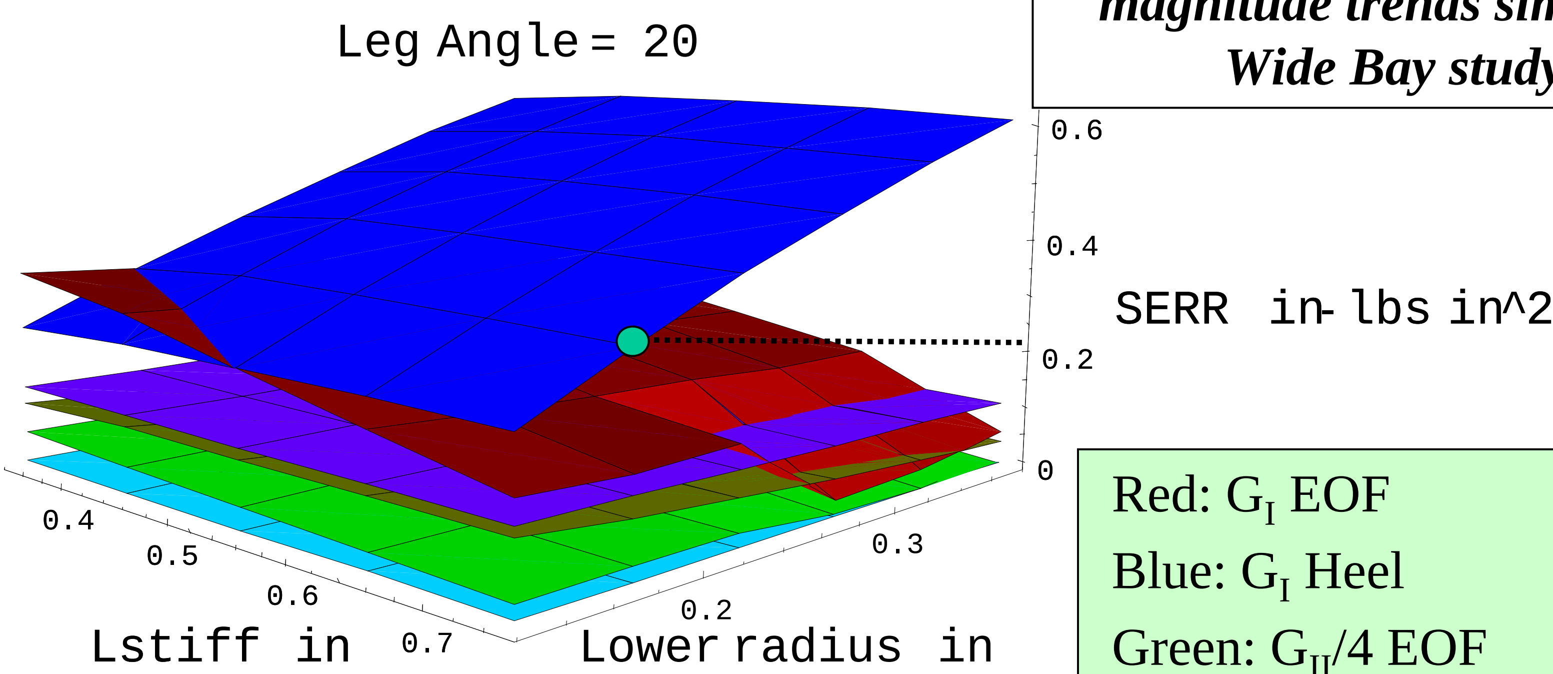
Green: $G_{II}/4$ EOF

Brown: $G_{II}/4$ Lower Radius

A local SUBLAM model run suggests that the lower radius and stiffener leg angle could be designed to minimize the effect of potential radius delaminations. Sufficient stiffener Leg length controls Edge-of-Flange Delamination

Minimizing Uncertainty by Design

SERR – Short Bay Width



Adding wrap and shortening bay width reduces SERR magnitude trends similar to Wide Bay study.

Red: G_I EOF

Blue: G_I Heel

Green: $G_{II}/4$ EOF

Brown: $G_{II}/4$ Heel

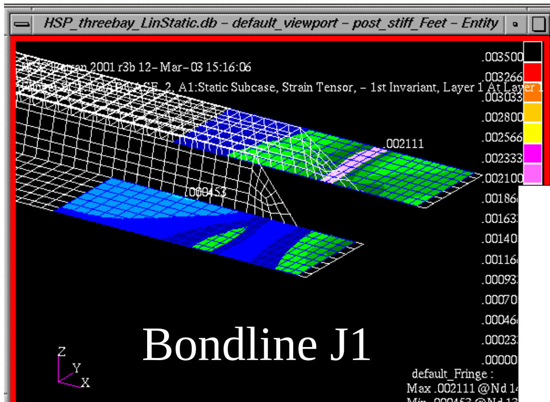
Light Blue: G_I Wrap/Plank

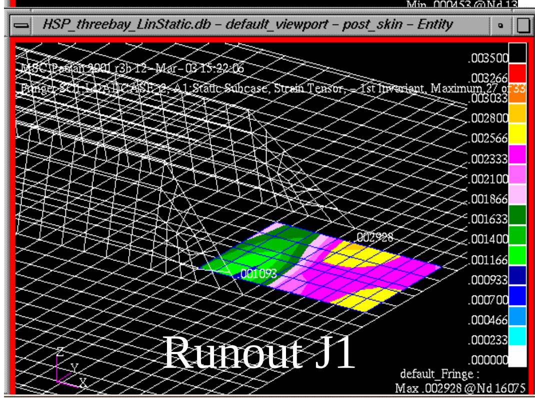
Purple: $G_{II}/4$ Wrap/Plank

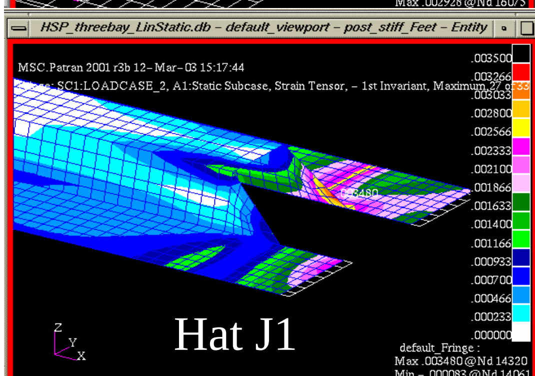
With reduced bay width, wrap plies, and leg angle of 20º, G_{II} is no longer critical and SERRs are all generally reduced.

Minimizing Uncertainty by Design

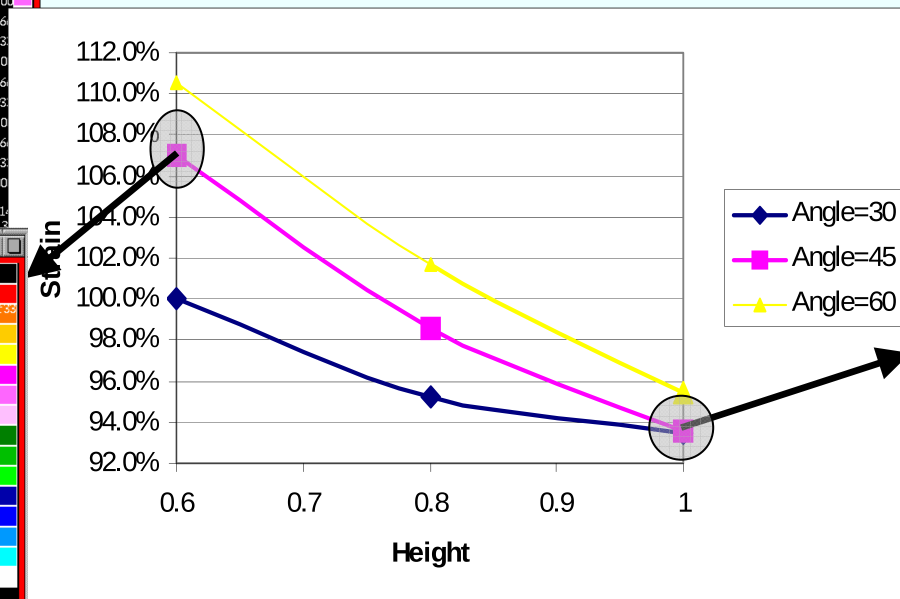
Hat Height, Width, and Runout Angle Study

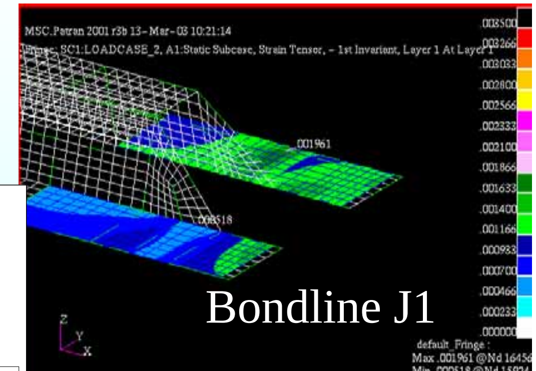


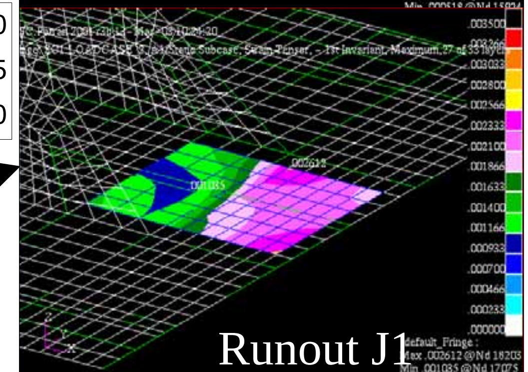


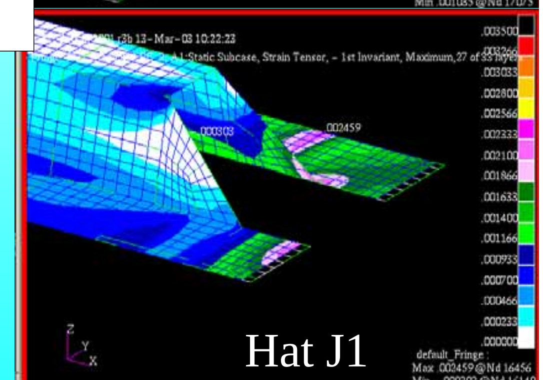


Critical Load Case: 2









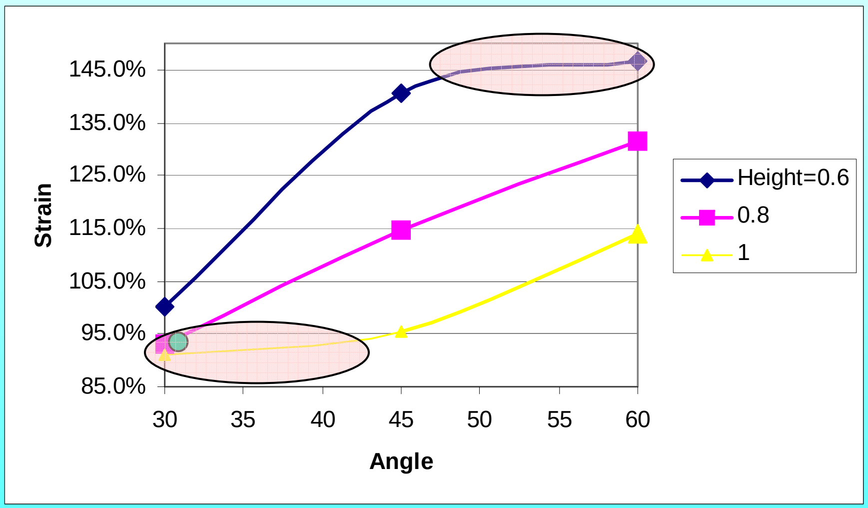
- Tall hats have lower J_1 in all regions
- Shallow runout angle is better
- Tall hats are less sensitive to runout angle
- Shallow runout angles make design less sensitive to hat height

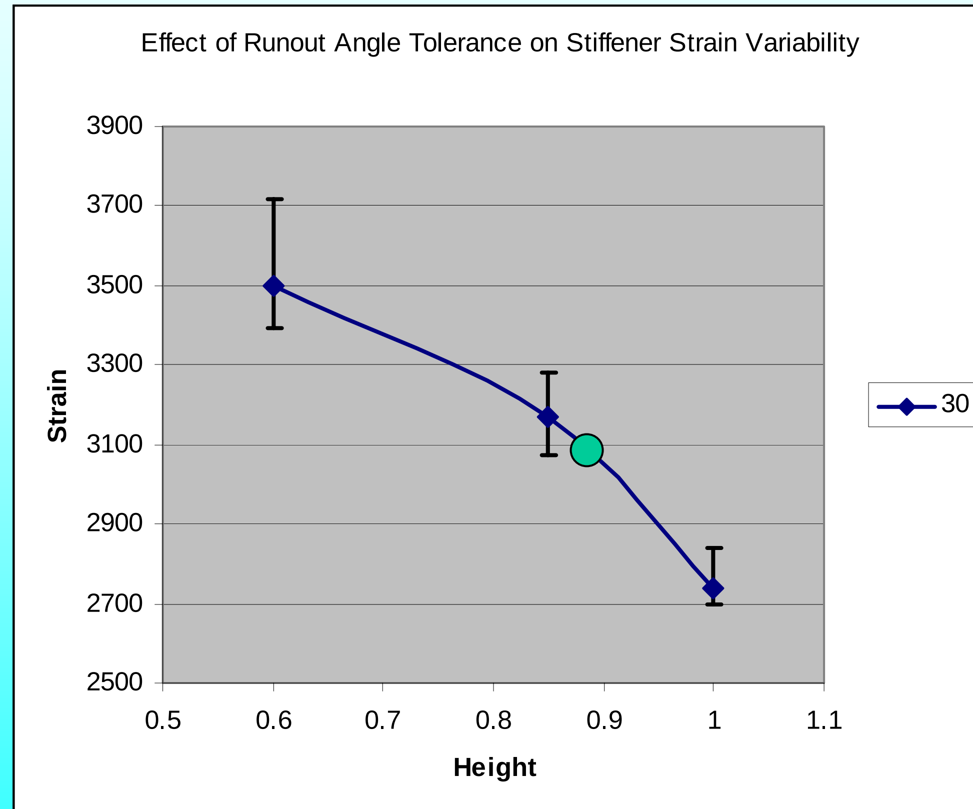
Minimizing Uncertainty by Design

Robustness to Geometric Variability – Hat Height, Width, Runout

Design on the Flat!

Tall Hats with shallow runouts or short hats with steep runouts
are less sensitive to runout angle tolerance



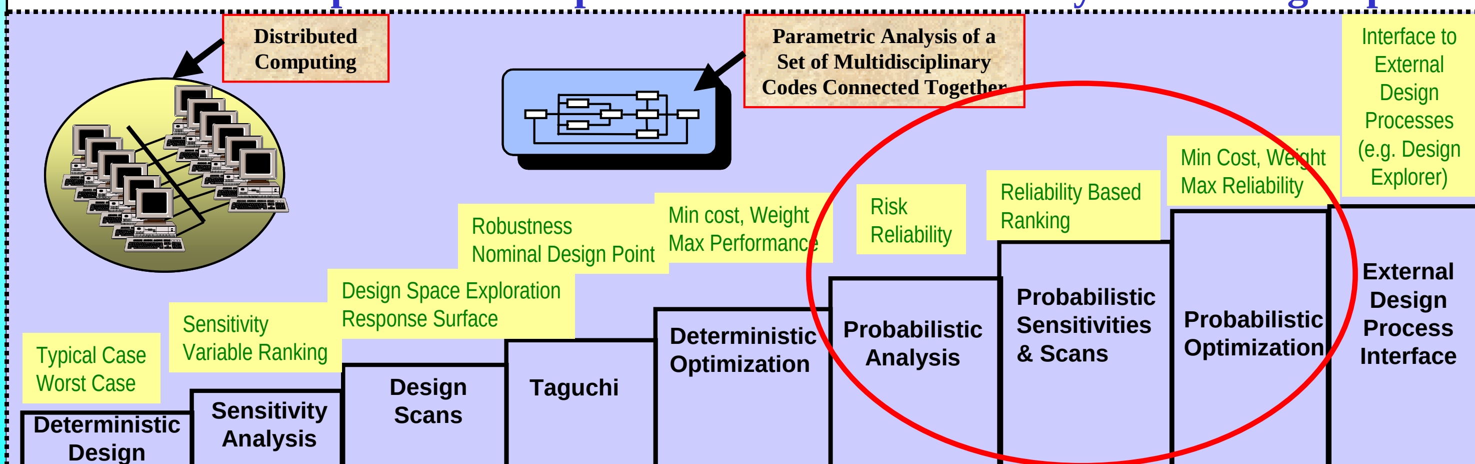


Approved for Public Release, Distribution Unlimited

Handling Uncertainty – The AIM-C Approach
Quantifying Uncertainty

- If its important, and you can't design it out, quantify it.
- Another change from current philosophy. Currently only done with coupon allowables. Other variation is considered covered in "material scatter", covered by factors, or worst-case assumptions.
- Testing or Probabilistic Analysis Tools are applied.

A Domain Independent Comprehensive Tool Set to Analyze the Design Space



Handling Uncertainty – The AIM-C Approach
Quantifying Uncertainty

Recent Enhancements

- Greatly expanded the operating space of uncertainty analysis
  - Continuous, discrete and enumerated variable types
  - Sensitivity analysis on mixed space and constrained design space exploration
- Integration of external uncertainty analysis plug-ins with RDCS
    - Advanced design of experiments – Design Explorer
- Probabilistic (Robust) Optimization
    - A capability to define statistical parameters as design variables
    - One of the tools for use in the current on-going model-test integration task

Handling Uncertainty – The AIM-C Approach
Quantifying Uncertainty

- Example – OHT Laminate Monte-Carlo Simulation

Design Process VisualizerSimula

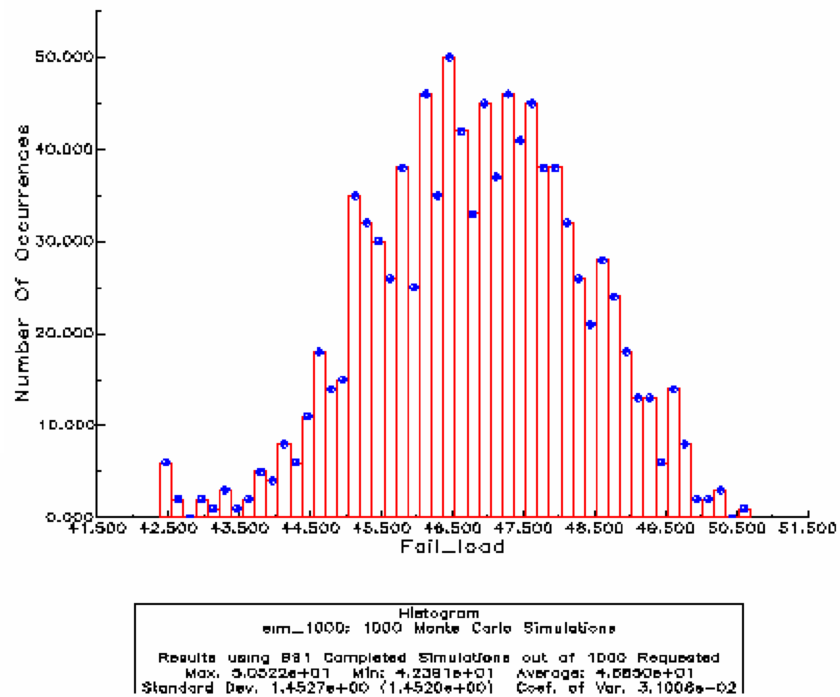
Effect of Aleatory Uncertainty due to variations in:

- •Resin Modulus
- •Fiber Elastic Properties
- •Fiber strength
- •Ply angles
- •Fiber Volume
- •Load Orientation
- •Hole diameter

Parameter	Value
DocumentRes	yes

Close Print Help

OHT - PASS criteria



Page: 1/4 Refresh

Handling Uncertainty – The AIM-C Approach

- Example – OHT Laminate Monte-Carlo Simulation

Design Process VisualizerSimula

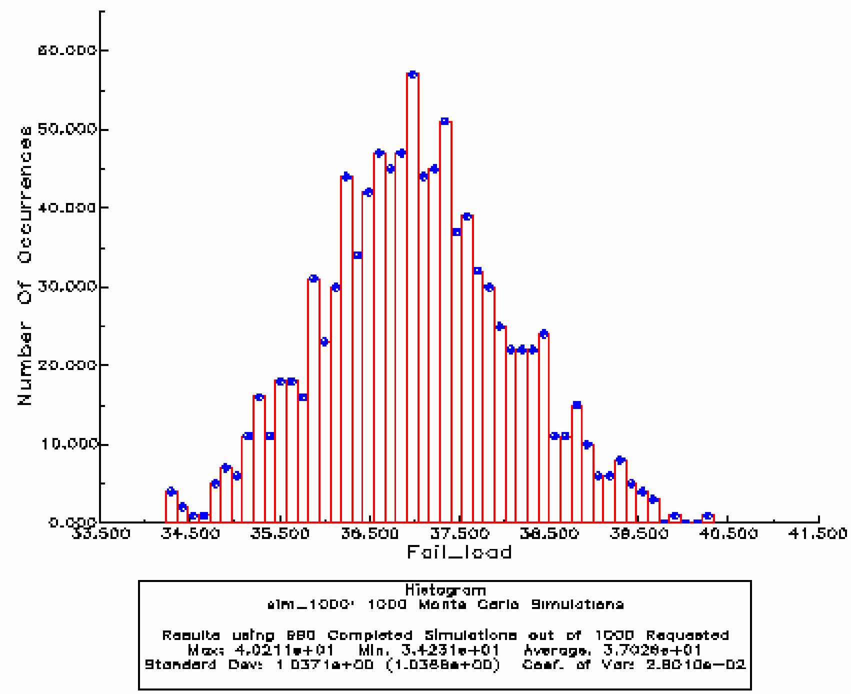
Effect of Aleatory Uncertainty due to variations in:

- Resin Modulus
- Fiber Elastic Properties
- Fiber strength
- Ply angles
- Fiber Volume
- Load Orientation
- Hole diameter

Parameter	Value
DocumentRes	yes

Close Print Help

OHT - Hashin criteria



Page: 1/1

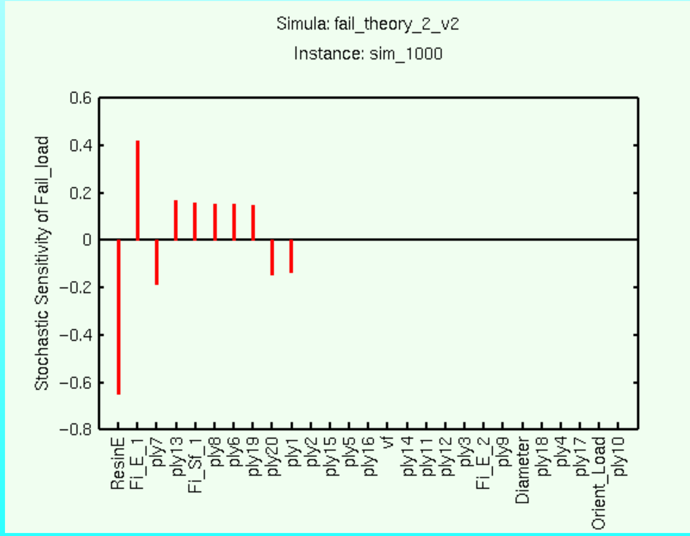
Refresh

Approved for Public Release, Distribution Unlimited

Handling Uncertainty – The AIM-C Approach

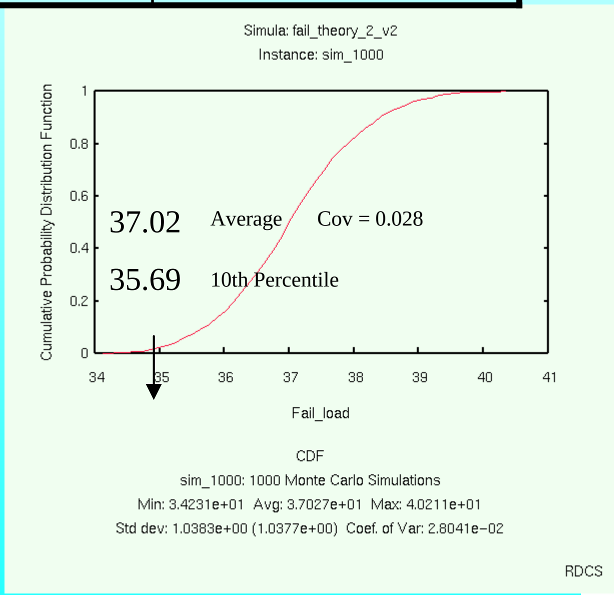
- Example – OHT Laminate Monte-Carlo Simulation

	Test	Hashin	Phase Avg.
Mean	37.274	34.231	42.39
Std.Deviation	1.683	1.0371	1.4527
Coefficient of Variation	.04517	.02801	.031



10/80/10

Layup



Approved for Public Release, Distribution Unlimited

Handling Uncertainty – The AIM-C Approach
Quantifying Uncertainty

HSP Robustness to Flaws, Geometric and Material Variability

Probabilistic Analysis – Monte Carlo Simulation

Problem Definition: Random variables listed below, all other parameters same as Study 09.

Geometry *only*

- Length of stiffener flange (Mean = 1.25”, SD = 0.015”)
- Leg angle (Mean = 20º, SD = 1.5º)
- Lower radius (Mean = 0.2”, SD = 0.015”)

Geometry + Material

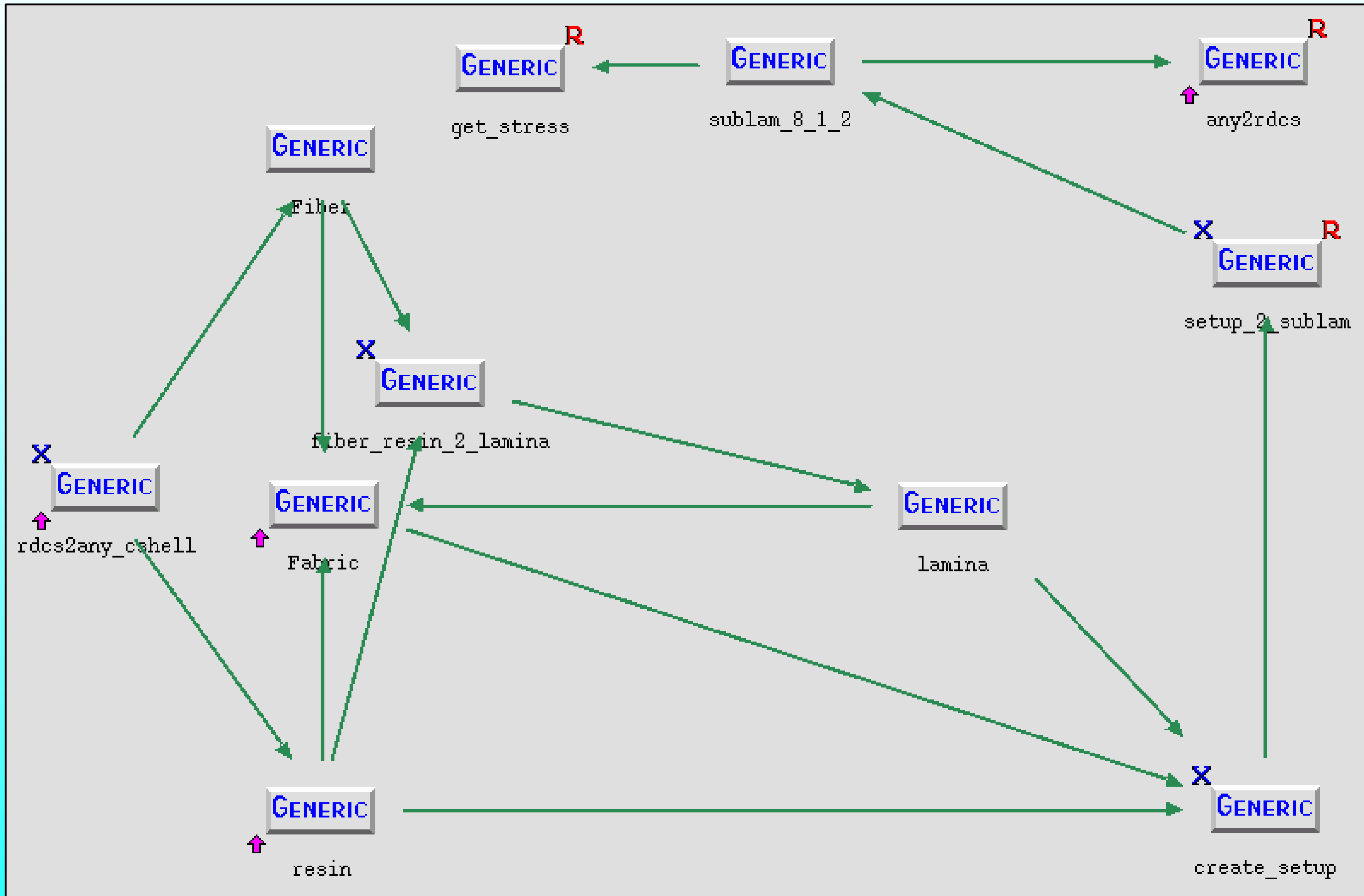
- Length of stiffener (SD = 0.015”)
- Leg angle (SD = 0.015”)
- Lower radius (SD = 1.5º)
- Fiber volume (5% COV)
- Fiber modulus (5% COV)
- Resin modulus (5% COV)

Normal distributions were used for all input parameters,

Quantifying Uncertainty

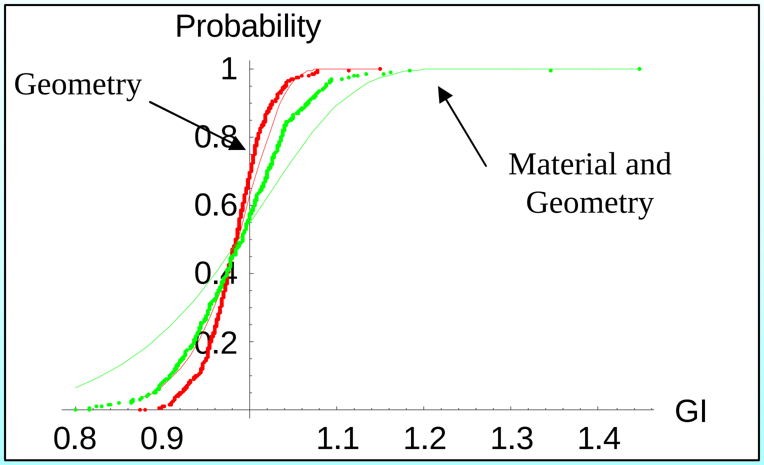
Robustness to Flaws, Geometric and Material Variability

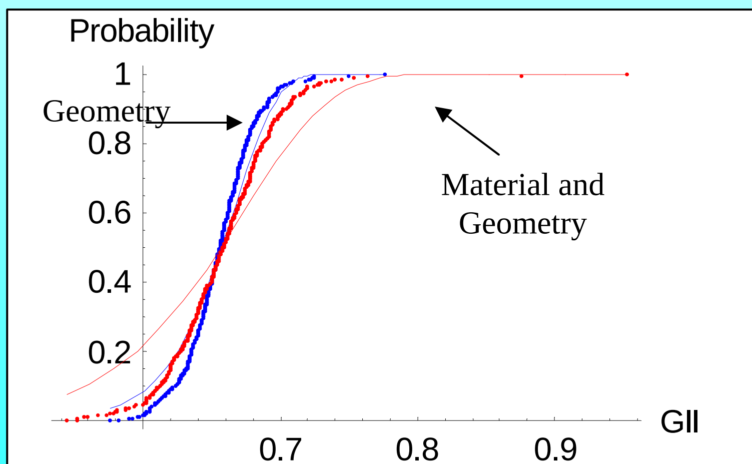
Probabilistic Analysis – RDCS Math Model



Quantifying Uncertainty

Robustness to Flaws, Geometric and Material Variability
RDCS Results



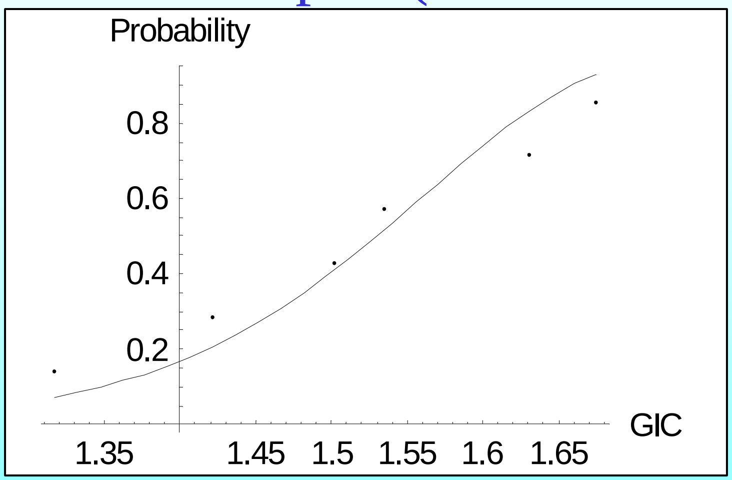


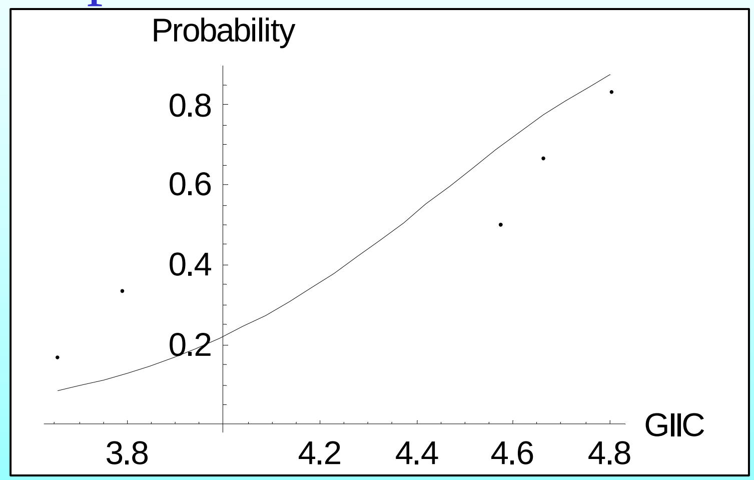
- Numerical values reported for 90 lb/in pull off load
- Mode I and II SERR at end of flange drives failure results
- Variations in crack driving force increase significantly when variability in material elastic constants are added:
  - SD_{GI} 0.036 → 0.068
  - SD_{GII} 0.026 → 0.041

Quantifying Uncertainty

Robustness to Flaws, Geometric and Material Variability

Variation in Critical Failure Properties by Test Coupon (DCB and ENF) Experimental Results





Mean = 1.51

St. Dev. = 0.132

No. of Specimens = 6

Weibull B-Value = 1.0

Mean = 4.30

St. Dev. = 0.533

No. of Specimens = 5

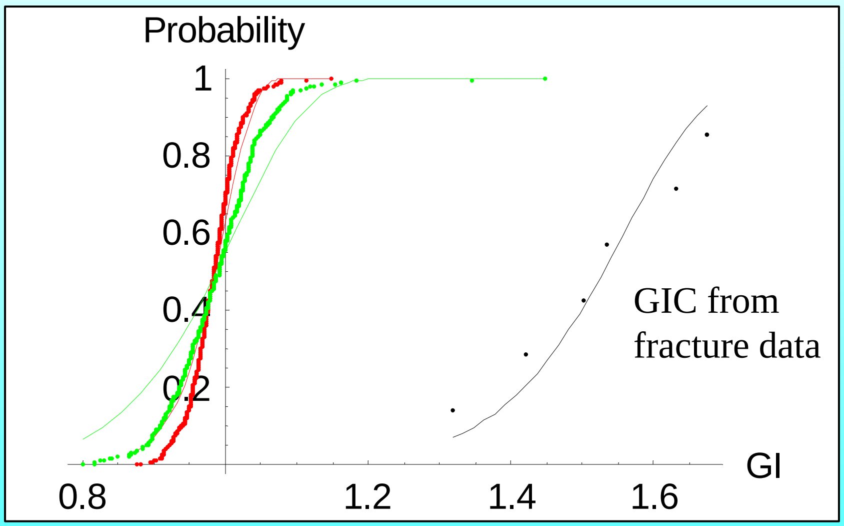
Weibull B-Value = 2.24

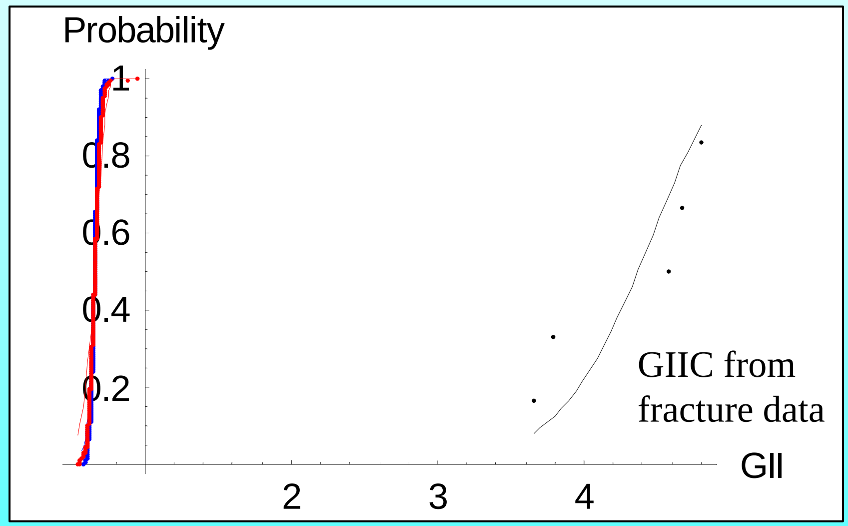
Quantifying Uncertainty

Robustness to Flaws, Geometric and Material Variability

Comparison of Variabilities

CDFs of SUBLAM SERRs and critical SERRs
from experimental fracture data





Note: Materials measured resistance to crack growth (Critical SERR) is MUCH more variable than computed variations in crack driving force due to other Material/Geometry variation