AMTAS: Certification of Discontinuous Composite Material Forms for Aircraft Structures

Analysis method development for Discontinuous Composite Materials, part II

Presented at AMTAS Fall Meeting 2010
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AMTAS Meeting (Spring 2010)

1. Convert previous analysis model for stochastic laminate analogy for modulus prediction from ANSYS to NASTRAN ⟸ PRESENTED TODAY
2. Applying stochastic laminate analogy approach to strength ⟸ PRESENTED TODAY
3. Predict response of more complex geometries (angle beams) ⟸ CURRENT EFFORT
4. Capture stress concentration insensitivity
5. Apply analysis method to intercostal certification test and validate against experiment

Research at UW

Beginning of year 6 of research:

- First 3 years supported by Boeing 787 Technology Integration
- Second 3 years being supported by FAA and Boeing

Key findings to date

- Notch insensitivity → "Notched behavior of prepreg-based discontinuous carbon fiber/ epoxy systems", P. Feraboli, E. Peitso, T. Cleveland, P. Stickler, J. Halpin – Composites (Part A), 40/3, 2009, pp. 289-299
- Low sensitivity to defects → "Defect and damage analysis of advanced discontinuous carbon/ epoxy composite materials", Paolo Feraboli, Tyler Cleveland, Marco Ciccu, Patrick Stickler, Composites (Part A), 41/7, 2010, Pages 888-901
- Apparent modulus variability → "Modulus measurement of prepreg-based discontinuous carbon fiber/ epoxy systems", P. Feraboli, E. Peitso, T. Cleveland, P. Stickler – Journal of Composite Materials, 43/19, 2009, pp. 1947-1965

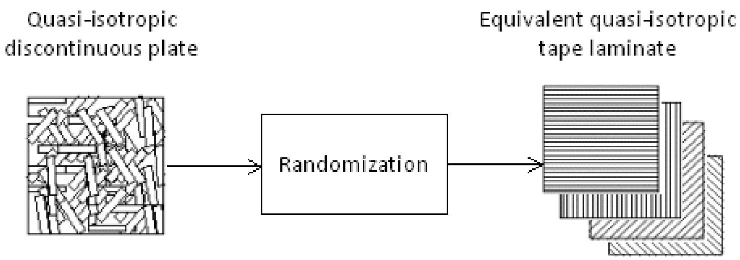
→ Traditional analysis methods do not apply

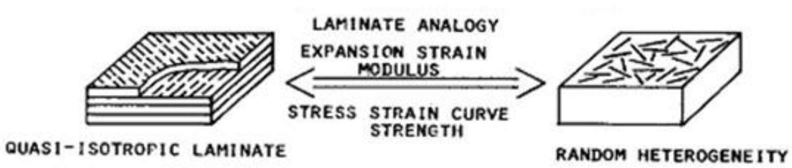
Proposed solution

- Stochastic laminate analogy approach → "Stochastic laminate analogy for simulating the variability in Modulus of discontinuous composite materials", P. Feraboli, T. Cleveland, P. Stickler, J. Halpin – Composites (Part A), 41/4, 2010, pp. 557-570

Stochastic Laminate Analogy

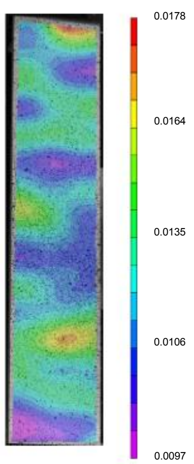
- Randomization process that generates statistical distributions of fractions and orientations of chips in order to capture the random chip meso-structure of HexMC
- Randomization process developed in Matlab environment
- Through the laminate analogy, CLPT is applied to an equivalent quasi-isotropic tape laminate to calculate its average elastic properties. THE RESULTS WERE SHOWED IN THE SPRING 2010 AMTAS MEETING
- FEM implementation in ANSYS environment



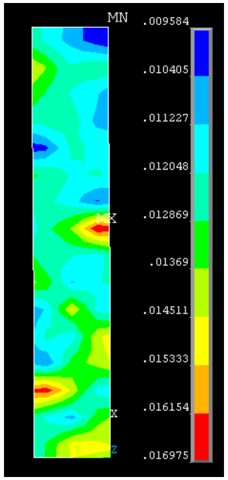


Match ANSYS-NASTRAN

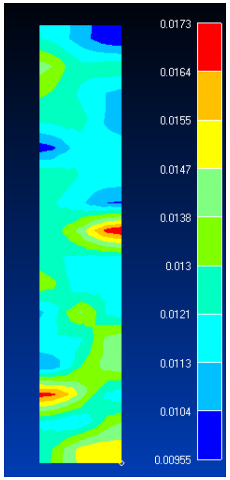
- Successful correlation between model & experiment predictions for modulus variability. New project direction required switching to Nastran (Dr. Avery)
- Automated input & output files from Matlab ➡ Femap ➡ Nastran
- Equivalency between Nastran & Ansys was successfully shown
- Nastran FEM model matches the modulus variability detected with the DIC when capturing the full size of modulus distribution



DIC

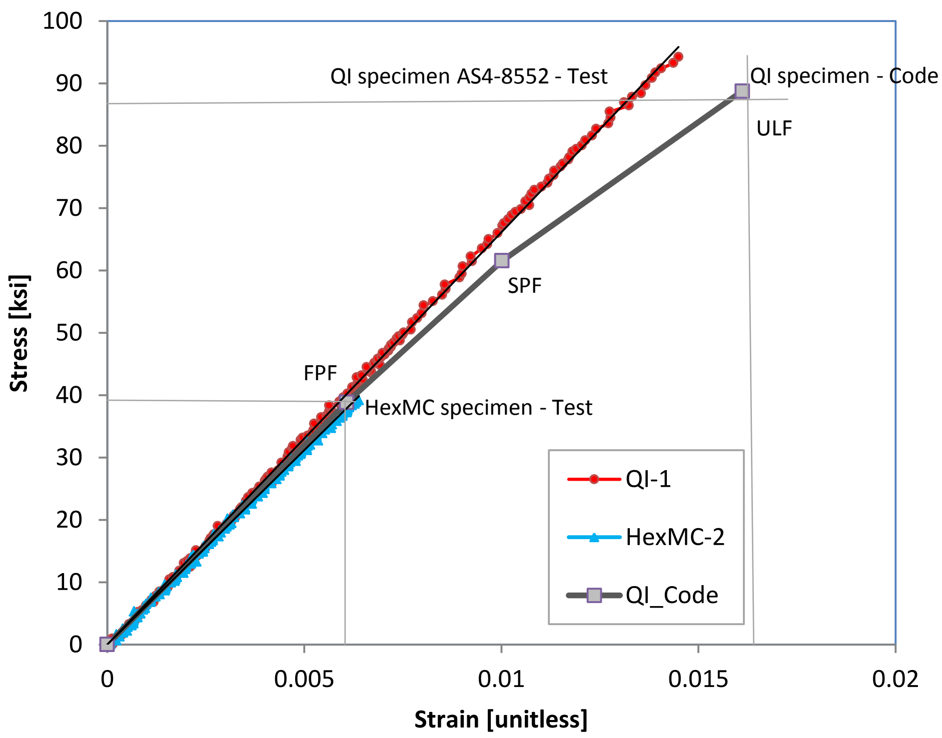


ANSYS

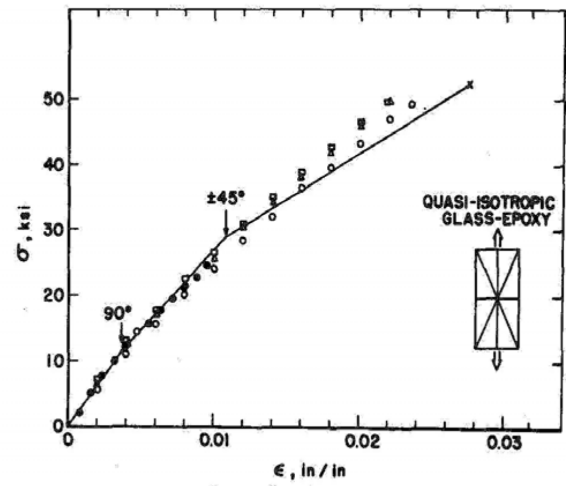


NASTRAN

Code vs Test

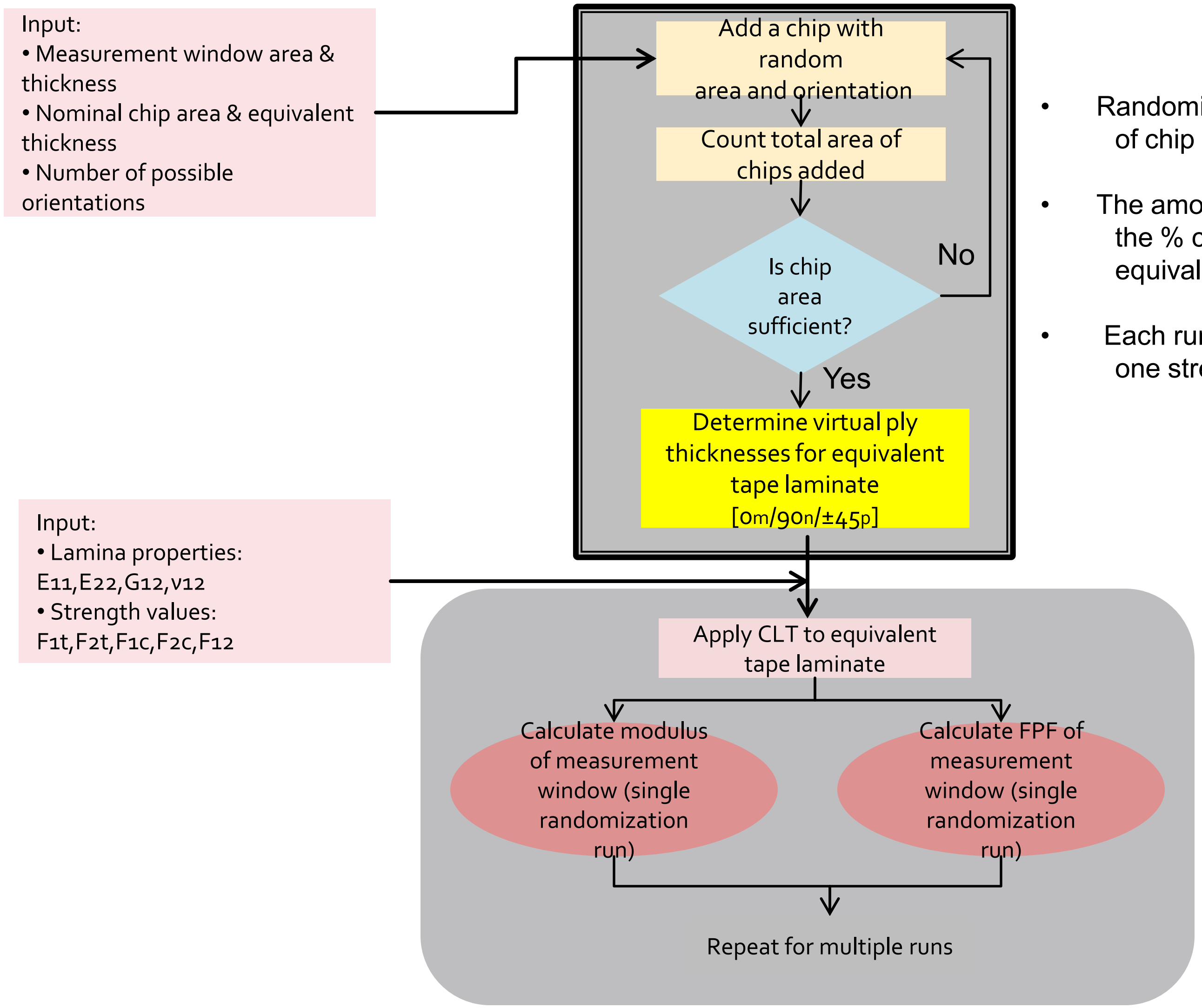


Reference image Halpin



- From experiment it is observed that first ply failure (FPF, 90-degree ply) of QI tape coincides with ultimate failure (ULF) for HexMC (same fiber and resin)
- Attempt to use stochastic laminate analogy to predict ULF of HexMC using FPF of equivalent tape laminate

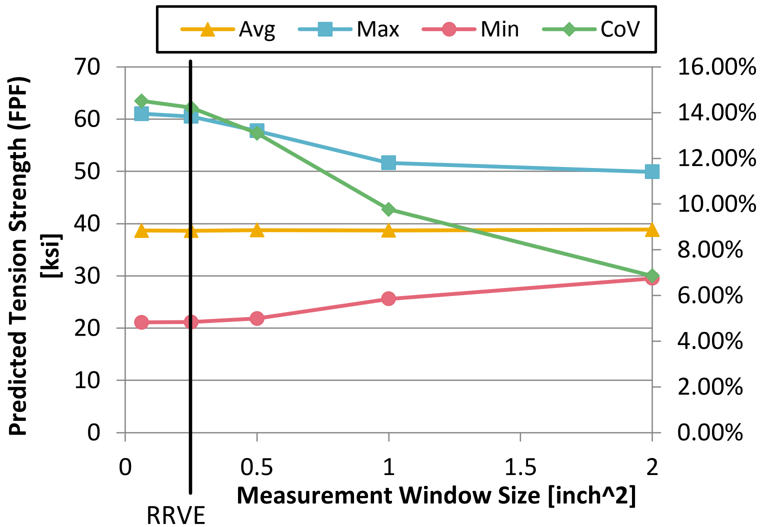
Stochastic laminate analogy approach to strength (FPF)

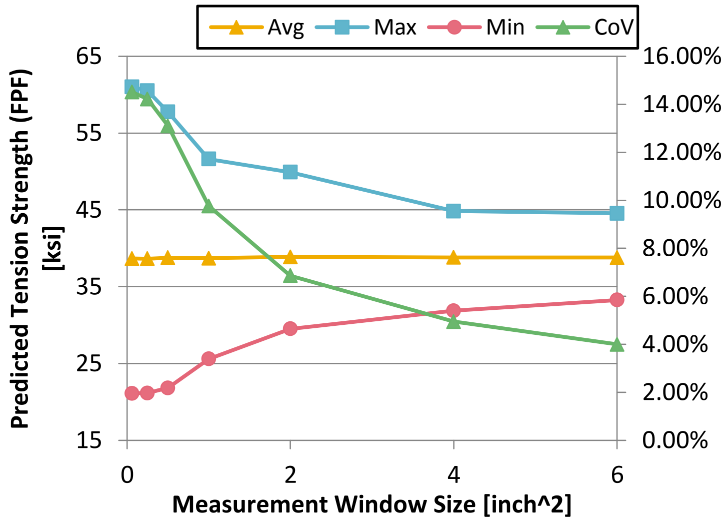


- Randomization process generates a distribution of chip orientations & quantities
- The amount of chips per orientation dictates the % content of that orientation in the equivalent tape laminate generated
- Each run generates one modulus value and one strength value (corresponding to one RRVE)

Avg, Max, Min & CoV Prediction for HexMC as a function of Measurement Window Size

- 5000 Number of Runs
- Variable Measurement Window





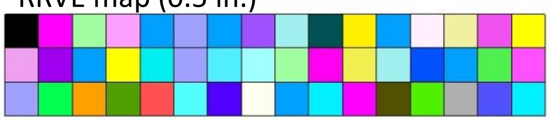
	Predicted strength [ksi] (FPF for equivalent laminate)	Experimental Strength [Ksi] (Ultimate failure for HexMC)	Predicted Modulus [Msi] (for equivalent laminate)	Experimental Modulus [Msi] (for HexMC from DIC)
Max	59.64	64.65	9.85	7.56
Avg	38.79	45.04	6.36	5.72
Min	21.11 *	34.82	3.29	4.33
CoV	14.2%	14.4%	15.2%	13.8%

- Strength predictions are acceptable with the exception of minimum strength
- RRVE “Stiff” are also RRVE “Strong”

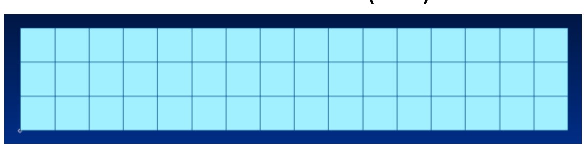
FEM / Investigated Elementsize

- FEM implementation is performed in NASTRAN to simulate a specimen under uniaxial tension
- Identical approach was successfully used for modulus prediction
- The model discretizes the coupon (8.0 in. x 1.5 in. x 0.165 in.) in 48 RRVE's (0.5 in. x 0.5 in. x 0.165 in.) having elastic orthotropic material properties assigned independently from the neighboring ones and generated by running the stochastic laminate analogy code.
- The discretization of the specimen into RRVE's has no relation with the mesh size. The nodes of neighboring elements are merged to ensure displacement compatibility

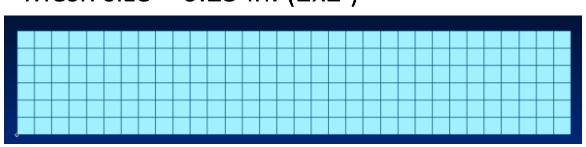
RRVE map (0.5 in.)



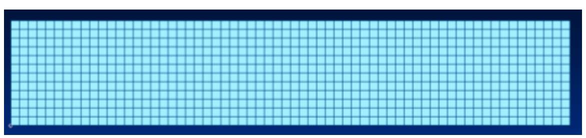
Mesh size = RRVE = 0.5 in. (1x1)



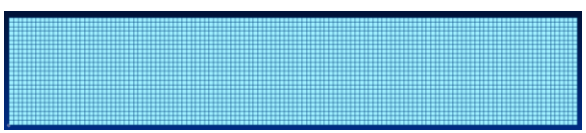
Mesh size = 0.25 in. (2x2)



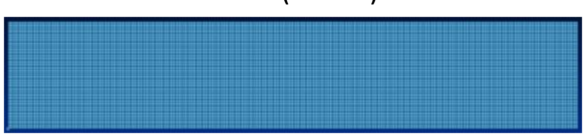
Mesh size = 0.125 in. (4x4)



Mesh size = 0.0625 in. (8x8)

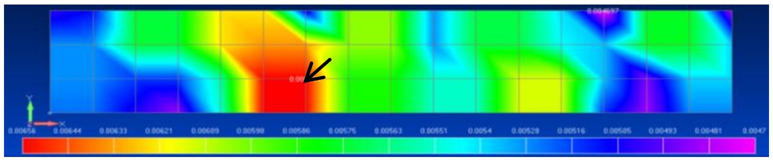


Mesh size =0.02 in. (25x25)

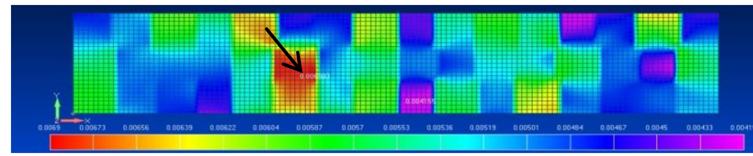


Strain Contours

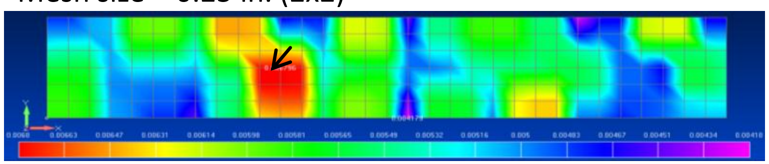
Mesh size = RRVE = 0.5 in. (1x1)



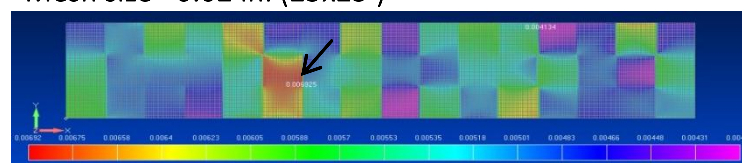
Mesh size = 0.0625 in. (8x8)



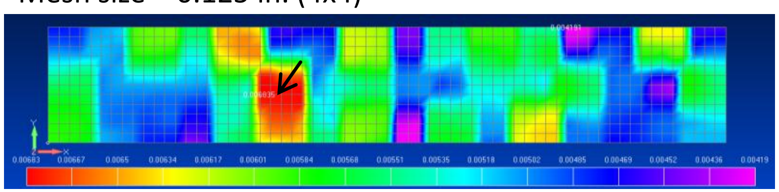
Mesh size = 0.25 in. (2x2)



Mesh size =0.02 in. (25x25)



Mesh size = 0.125 in. (4x4)

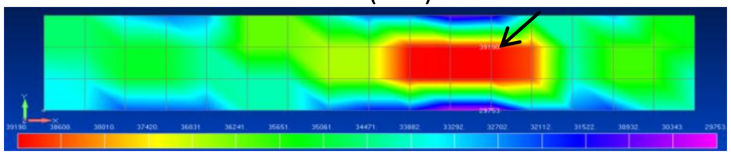


Elementsize [in.]	0.5	0.25	0.125	0.0625	0.02
Max Normal Strain in x-dir []	0.0065	0.0068	0.0068	0.0069	0.0069

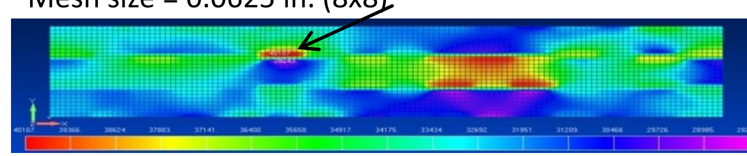
- Strain variation is independent from mesh size
- Modulus prediction is accurate even for coarse mesh (2x2)

Stress Contours

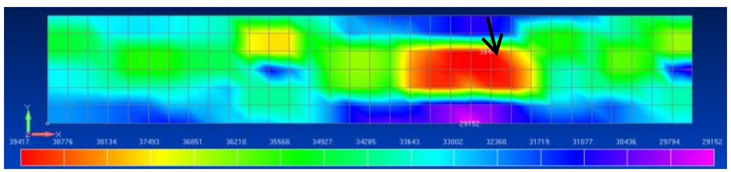
Mesh size = RRVE = 0.5 in. (1x1)



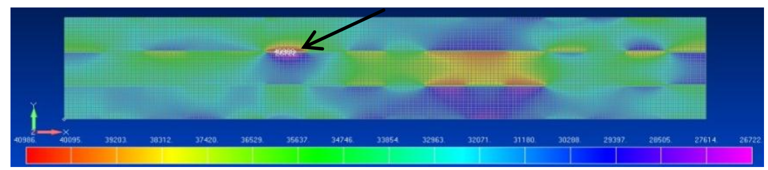
Mesh size = 0.0625 in. (8x8)



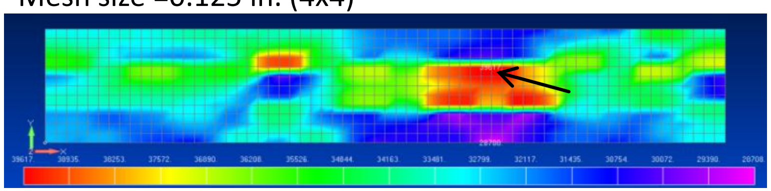
Mesh size = 0.25 in.(2x2)



Mesh size =0.02 in. (25x25)



Mesh size =0.125 in. (4x4)

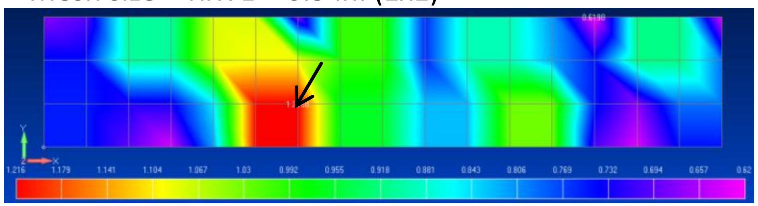


Elementsize [inch]	0.5	0.25	0.125	0.0625	0.02
X-Normal Stress [ksi]	39.19	39.41	39.61	40.10	40.98

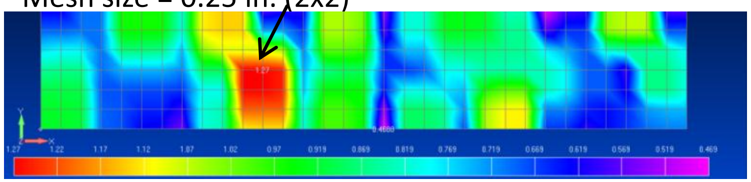
- Averaged (thru the thickness) stress follows different distribution than strain
- Peak stress varies in location and partly in magnitude based on mesh and overall distribution is significantly effected

Failure Index Contours

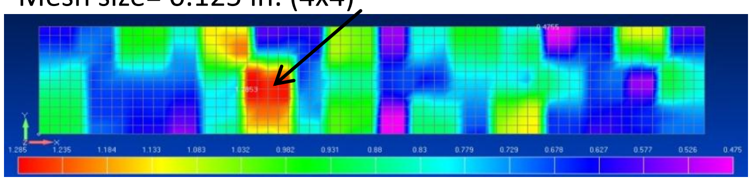
Mesh size = RRVE = 0.5 in. (1x1)



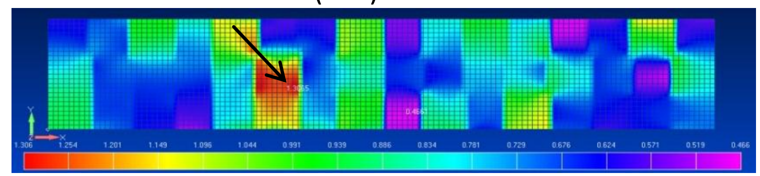
Mesh size = 0.25 in. (2x2)



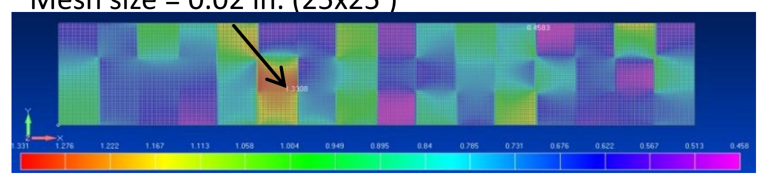
Mesh size= 0.125 in. (4x4)



Mesh size = 0.0625 in. (8x8)



Mesh size = 0.02 in. (25x25)



Elementsize [in.]	0.5	0.25	0.125	0.0625	0.02
Failure Index []	1.216	1.27	1.28	1.30	1.33

$$FI = \left(\frac{1}{x_t} - \frac{1}{x_c}\right)\sigma_1 + \left(\frac{1}{y_t} - \frac{1}{y_c}\right)\sigma_2 + \frac{{\sigma_1}^2}{x_t x_c} + \frac{{\sigma_2}^2}{y_t y_c} + \frac{{\tau_1}^2}{S^2} + 2F_{12}\sigma_1\sigma_2$$

- Failure index using Tsai-Wu shows strong dependency on mesh size

FPF randomized orthotropic material properties

100 (specimens) of FEM with different combinations of 48 RRVE per run

	Tests	Matlab	FEA
Max [Ksi]	64.65	59.64	30.55
Avg [Ksi]	45.04	38.79	27.09
Min [Ksi]	34.82	21.11	21.49
CoV	14.4%	14.2%	11.9%

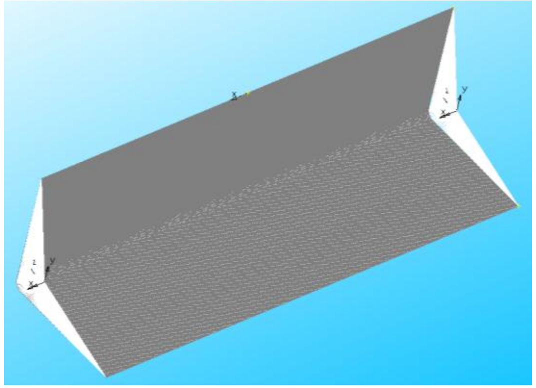
- Matlab predictions are acceptable
- FEM greatly underestimates strength
- Stochastic laminate analogy for strength applies well in principle but cannot be used for FEM (if 1 of 48 RRVE is low, failure is predicted regardless of other 47 values) ⇒ Failure is dictated by the weakest link

Current Research

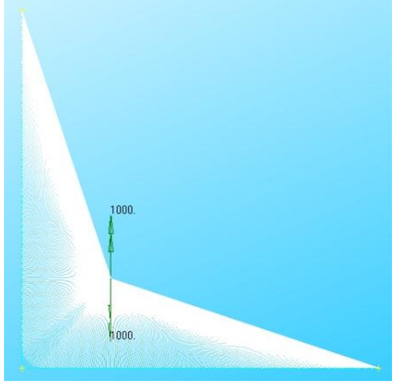
- Angle Beam: immediate future dedicated to generate FEM predictions for 3 shapes under 6 loading conditions (18 models) and to verify against experimental results by Shifman & Tuttle

- NASTRAN model developed successfully in terms of boundary and loading conditions

Angle beam geometries



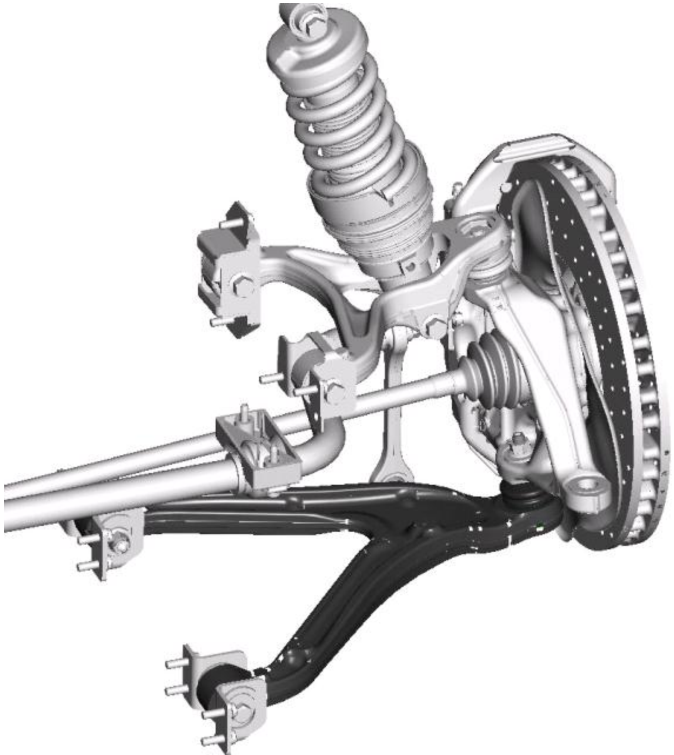
Model with constraints



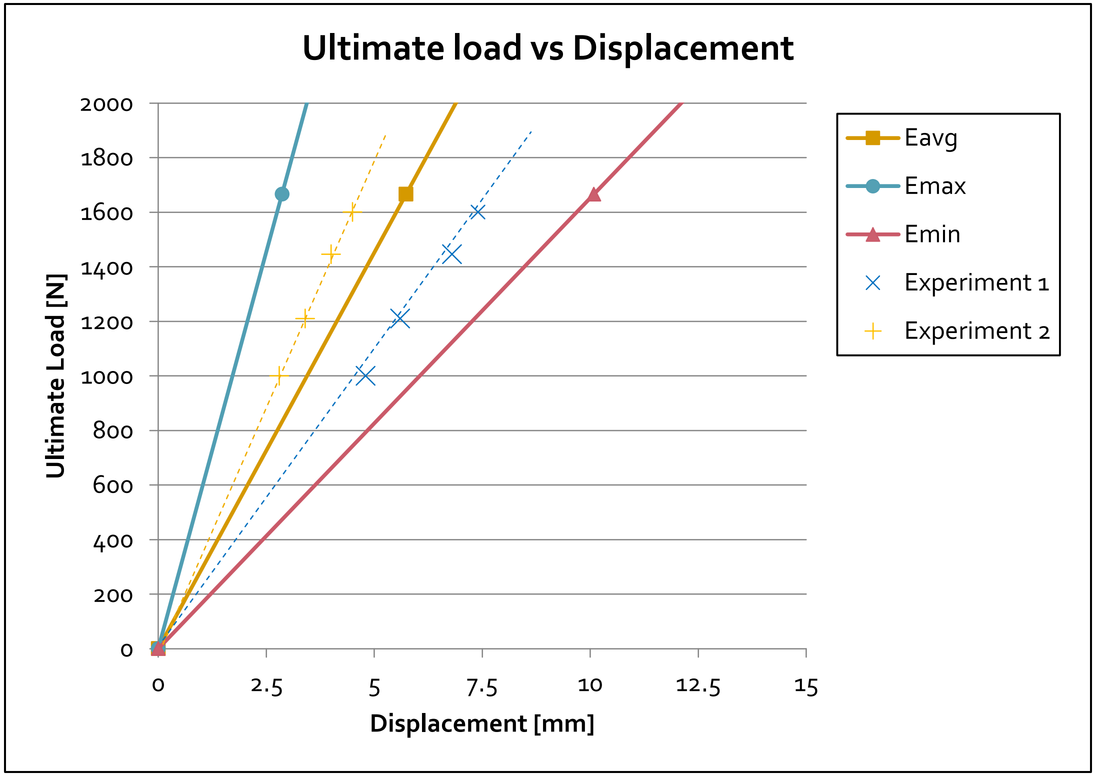
MPC: Multi Point Constraint

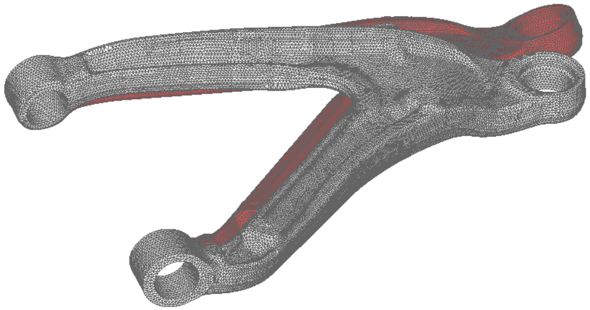
Example Application

- Different material system, identical behaviors:
  - → Notch insensitivity
  - → Modulus variability
  - → Defect insensitivity
- Current wishbone suspension (control arms) in Aluminum
- Redesign using “Forged Composite” technology (chopped carbon fiber for compression molding)



Example Application





- Stiffness (deflection) prediction based on stochastic laminate analogy to account for modulus variation
- Experiment results are in line with predictions

Discussions and Future Work

- CONCLUSIONS:
  1. Stochastic laminate analogy successfully integrated into NASTRAN
  2. From experiment FPF of equivalent laminate coincides with ultimate failure of HexMC
  3. Stochastic strength prediction based on Tsai-Wu FPF works for independent runs (Matlab) but doesn't apply to FEM (are not independent from each other)
  4. Global response of the model (modulus) is averaged over the 48 RRVE's thus modulus variability is successfully predicted
  5. Global response of the model (strength) cannot be averaged but is given by localized peak within the 48 RRVE's

- ONGOING WORK
  A. Build a shell 2D model for angle/crippling element predicting the elastic behavior through the use of stochastic modulus analogy
  B. Notch insensitivity modeling thru stochastic laminate analogy for elastic behavior
  C. Validate intercostal (long term)

References

[1] ASTM D3039/D3039M-00, Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, *Volume 15.03,2006.*

[2] ASTM D7078/ D7078M-05, Standard Test Method for Shear Properties of Composite Materials by V-notched Rail Shear Method.

[3] Boeing Test Method, Boeing Test Method for Unnotched Compressive Properties – Laminate

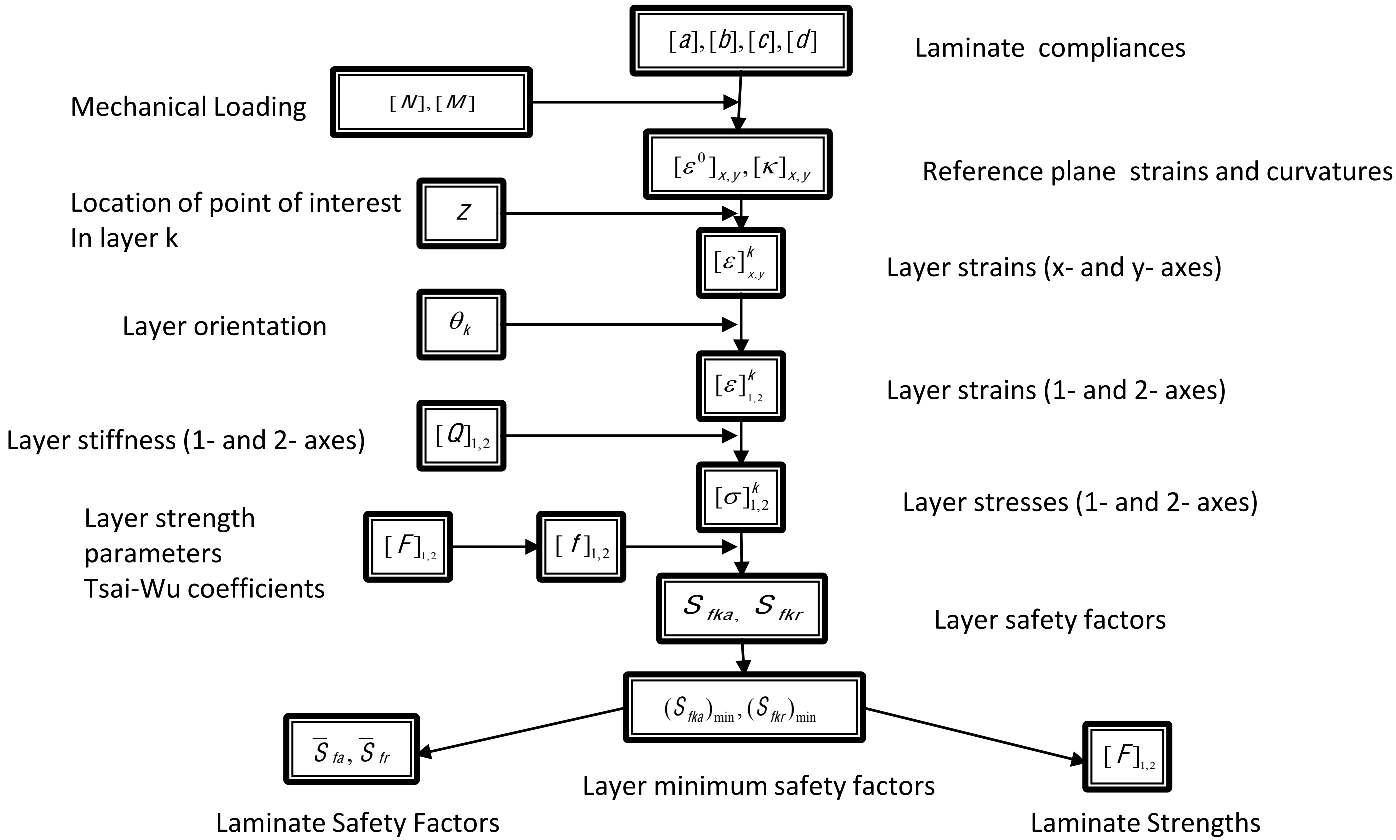
[4] Feraboli, P., Peitso, E., Deleo, F., Cleveland, T., Stickler, P.B., ''Characterization of pre-preg based discontinuous carbon fiber/ epoxy systems: Part1*", J. Reinf. Plastics and Composites, 28/10,2009, pp.1191-1214*

[5] Feraboli, P., F., Cleveland, T., Stickler, P.B., Halpin, J., "Stochastic Laminate Analogy for Simulating the Variability in Modulus of Discontinuous Composite Materials"

[6] Isaac, M. D., Ori, I., "Engineering Mechanics of composite materials", *Oxford University Press*, (2006).

- Il mio modello simulando il comportamento di fibre discontinue ha proprieta’ elastiche/leggi costitutive diverse da punto a punto quindi il picco di stress si trova in una location diversa da quella dove trovo il picco di strain!
- Il FI e’ stress based perche’ calcolato tramite Tsai-Wu. Egli ha quindi lo stesso andamento dello stress in una ply. Il problema e’ che qui non ho il valore di stress ad una ply ma ho un valore mediato sullo spessore del mio laminato. Apparentemente quindi il FI ha lo stesso andamento dello strain, questo avviene solo perke’ lo strain del laminato e’ uguale a quello di una singola ply….cosa che non si puo’ dire relativamente al valore di stress mostrato nel plot!

First Ply Failure (Tsai-Wu)



- The Tsai-Wu failure criteria used for the two-dimensional state of stress assumed in the code is $f_1\sigma_1 + f_2\sigma_2 + f_{11}{\sigma_1}^2 + f_{22}{\sigma_2}^2 + f_{66}{\tau_6}^2 + 2f_{12}\sigma_1\sigma_2 = 1$
- A reasonable approximation of $f_{12} \cong -0.5\sqrt{(f_{11}f_{22})}$

Experimental Tests

- Experimental tests were accomplished on specimens cut out from panels made in the lab with Hexcel AS4-8552 UD tape prepreg in order to obtain material properties and strengths values needed as inputs for the code. $[0]_{8T}$ and $[0/+-45/90]_S$ laminates were tested to measure both UD and QI properties.

- Tests:
  - ASTM Standard D 3039 (Tension) [1]
  - Boeing Test Method for Unnotched Compressive Properties (OHC fixture) [3]
  - ASTM Standard V Notch Shear D 7078 (Shear) [2]

- 60 Specimens Tested:
  - Tension (0 ° direction), E_{11} and F_{1T}
  - Tension (90 ° direction), E_{22} and F_{2T}
  - Compression (0° direction), F_{1c}
  - Compression (90 ° direction), F_{2c}
  - Shear, ν_{12}, G_{12} and F_{12}
  - QI, tension strength only

Material Properties and Strengths

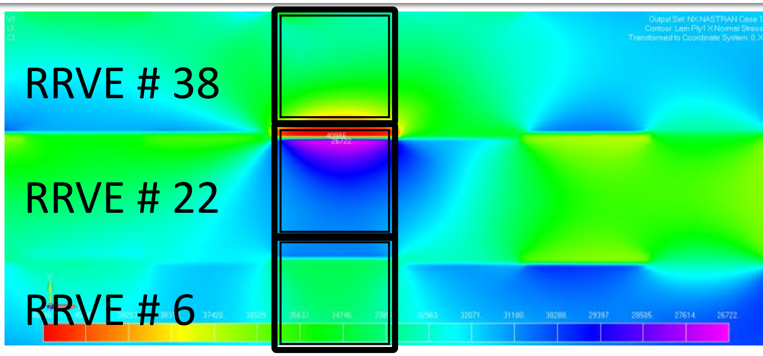
UD $[0]_{8T}$

	E_1	E_2	G_{12}	ν_{12}	F_{1T}	F_{2T}	F_{1c}	F_{2c}	F_{12}
ASTM Standard Tension D 3039	16.5 Msi	1.22 Msi			257.59 Ksi	7.08 Ksi			
Boeing Test Method Compression							139.85 Ksi	38.15 Ksi	
ASTM Standard Shear D 7078			0.6 Msi	0.309					16.6 Ksi

QI $[0/+-45/90]_s$

	E_x	E_y	G_{xy}	ν_{xy}	F_{xt}	F_{yt}	F_{xc}	F_{yc}	F_{xy}
ASTM Standard Tension D 3039					87.7 KSI				

Details



Stress

RRVE # 38: $E1 = 72\ Msi$

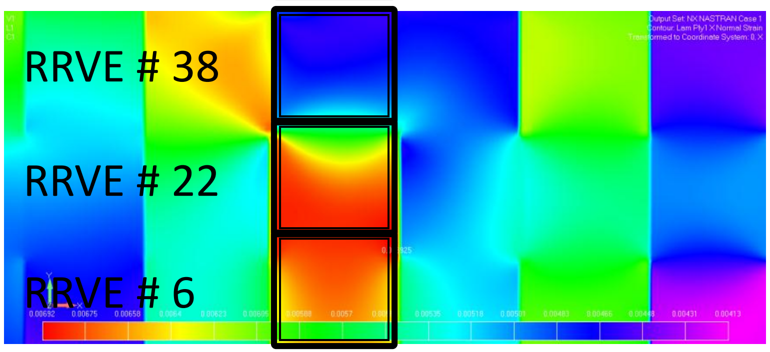
$E2 = 66\ Msi$

RRVE # 22: $E1 = 46\ Msi$

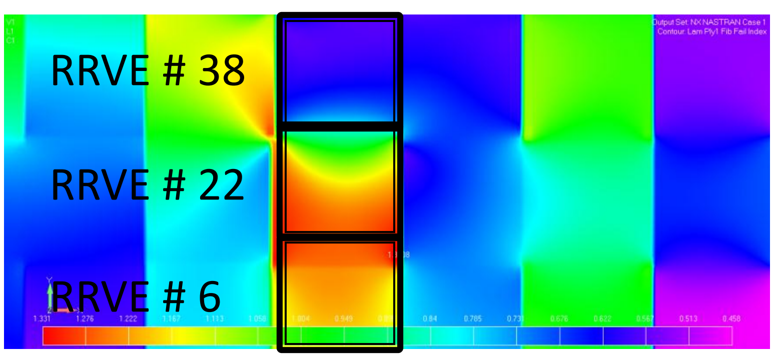
$E2 = 81\ Msi$

RRVE # 6: $E1 = 51\ Msi$

$E2 = 63\ Msi$



Strain



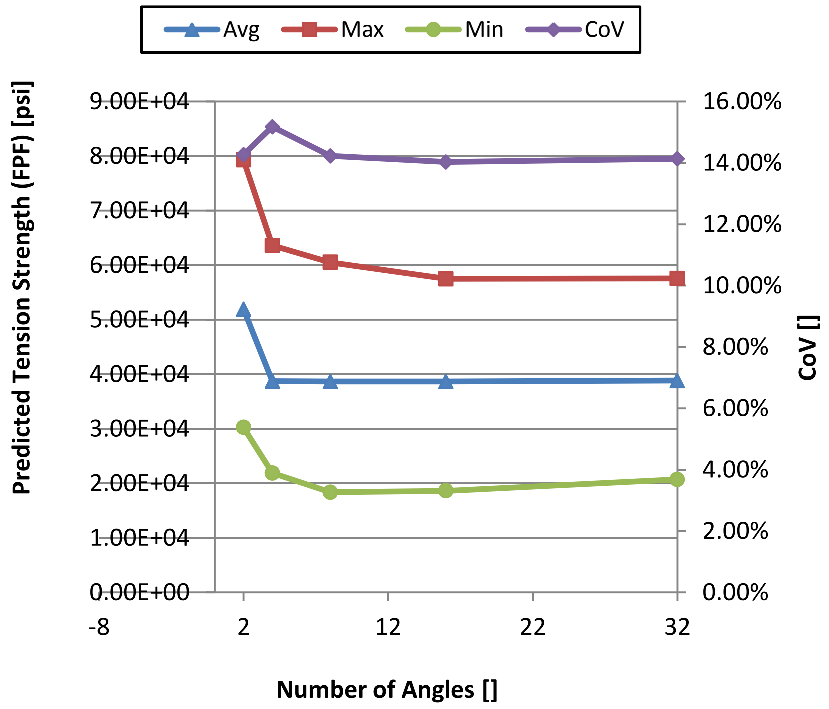
Failure Index

>1 fails

<1 doesn't fail

Number of Orientations

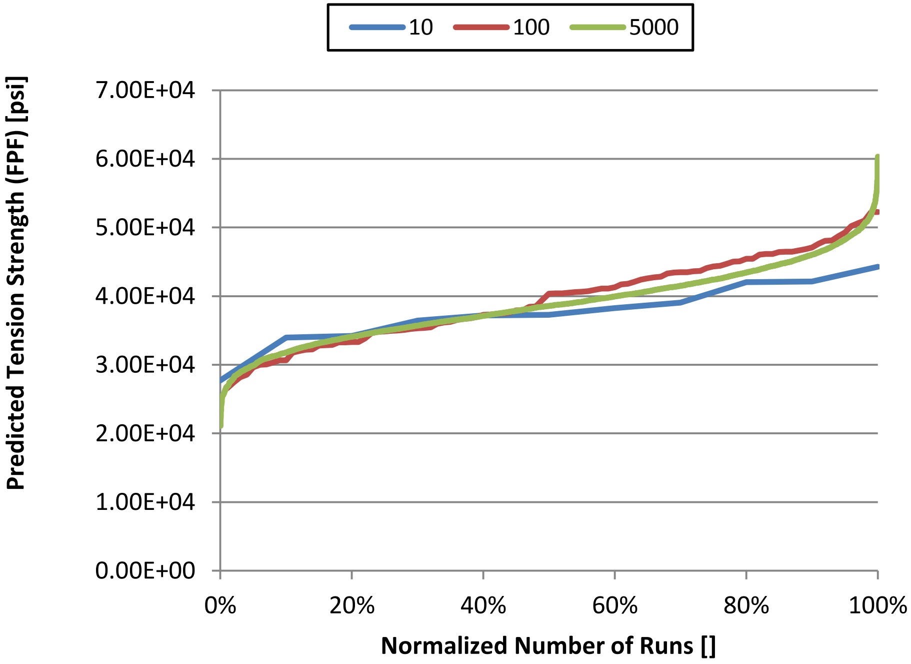
- 5000 Number of Runs
- Variable Orientations
- Measurement window: 0.25 inch^2 (RRVE)



- The trend related to the mean strength values do not vary over the number of cycles considering a laminate with at least four principal orientations

Normalized Number of Runs

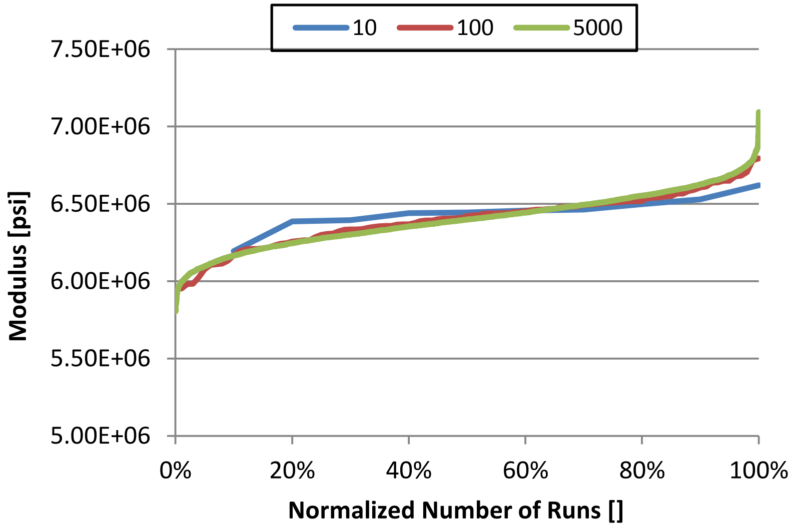
- Variable Number of Runs
- 8 Orientations
- Measurement window: 0.25 $inch^2$ (RRVE)



- Each run represents a “specimen” with the size equal to measurement window dimensions

Variables Analyzed for Modulus

- Configurations Tried:
  - Runs [unitless]: (10/100/500/1000/5000/10000/15000/20000)
  - Measurement Window Size (inch^2): (0.0625/0.25/0.3/12/40)
  - Number of Angles: (2/4/8/16/32)



- **Baseline Configuration:**
  - **5000 run**
  - **12 inch^2 measurement window size**
  - **8 number of angles**