Certification of Discontinuous Composite Material Forms for Aircraft Structures

Marco Ciccu and Paolo Feraboli
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The Joint Advanced Materials and Structures Center of Excellence

Certification of Discontinuous Composite Material Forms for Aircraft Structures

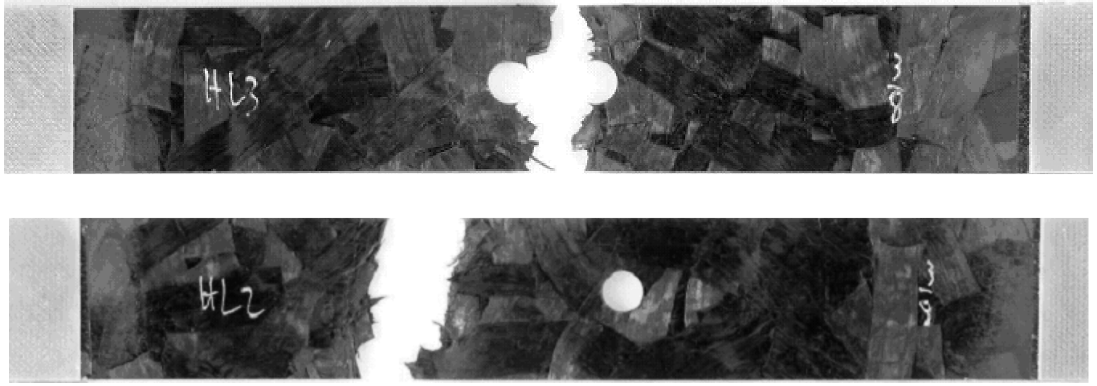
- Funding
  - 2005-2008 provided by Al Miller and Patrick Stickler (Boeing 787 Technology Integration)
  - 2008-onward provided by AMTAS
- Key Issues
  - Traditional analysis methods do not apply because of unique characteristics of this material form (different from traditional tape/ fabric materials)
  - Current analysis method based on isotropic assumption and von Mises failure criterion – only used for prelim sizing but not certification
  - Certification of parts made of these materials currently requires testing large numbers of parts (“point design”)

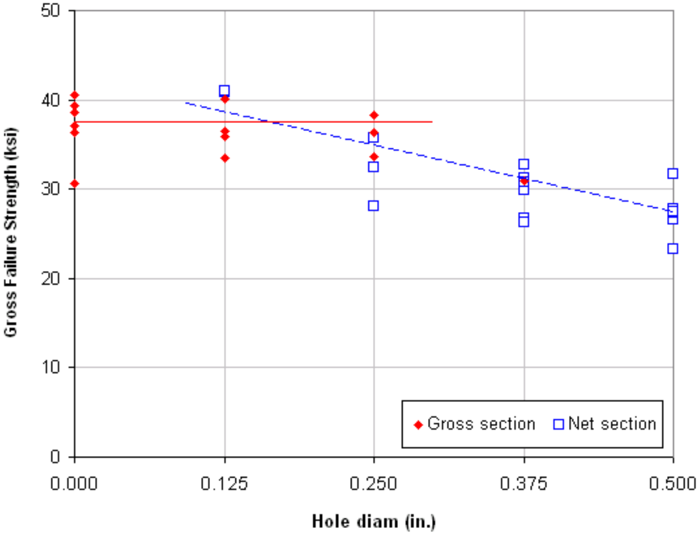
Project Information

- Outline
- Previous results 1: Notch insensitivity
- Previous results 2: Modulus variation
- Previous results 3: Effect of defects
- Previous results 4: Stochastic laminate analogy
- Future work

Previous results - 1

- Notch insensitivity
- Coupons containing small holes do not fail at the tip hole, were classical mechanics predict the highest concentration to occur, but in gross section, away from the hole.

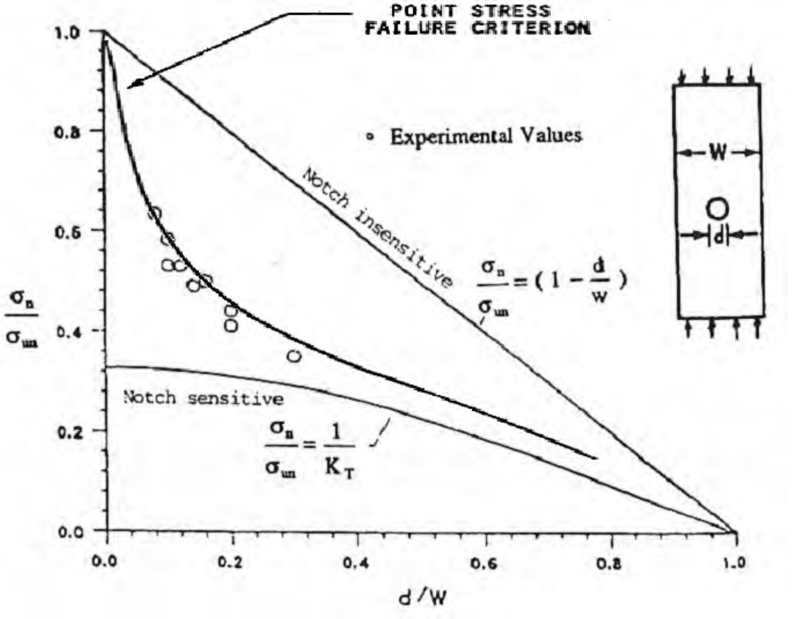


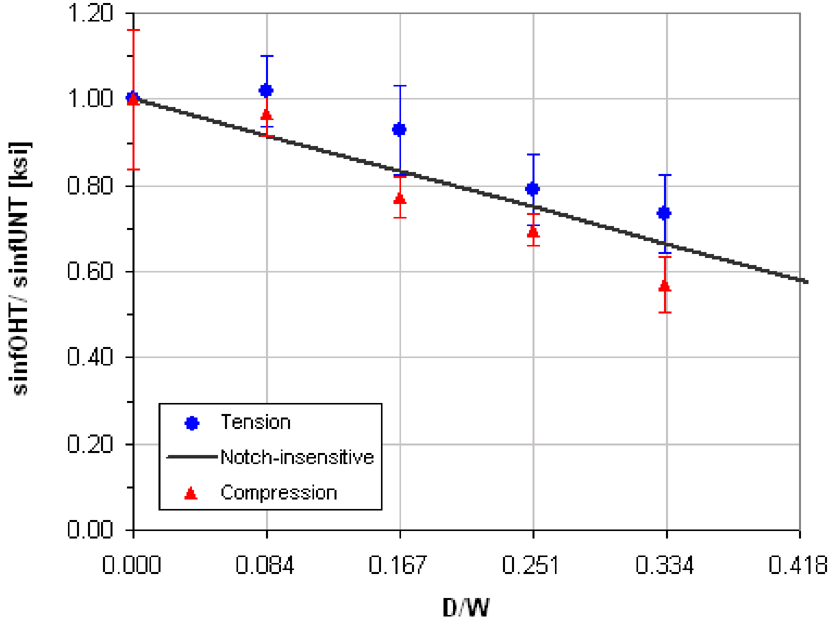


“Notched behavior of prepreg-based discontinuous carbon fiber/ epoxy systems”, P. Feraboli, E. Peitso, T. Cleveland, P. Stickler, J. Halpin – <u>Composites (Part A)</u>, 40/3, 2009, pp. 289-299

Previous results - 1

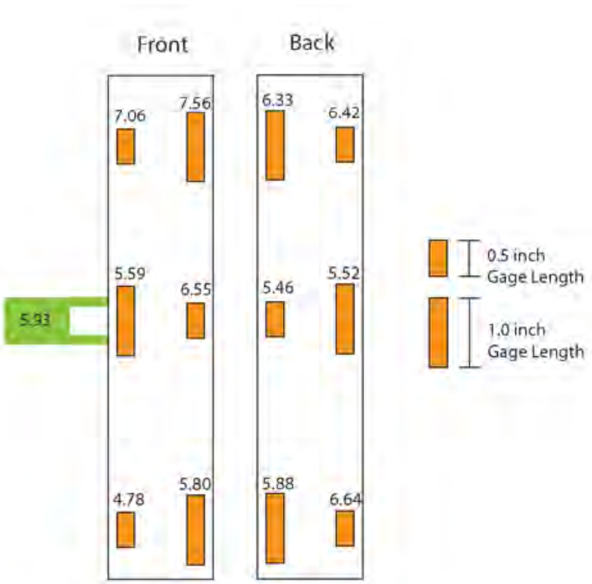
- Notch insensitivity
- This atypical behavior is due to the non-homogeneous structure of the material which features discontinuities in stress distributions at the chip intersections, with stress concentrations at the chip ends

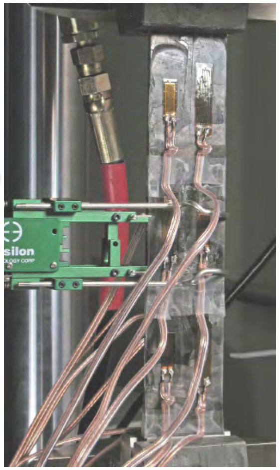


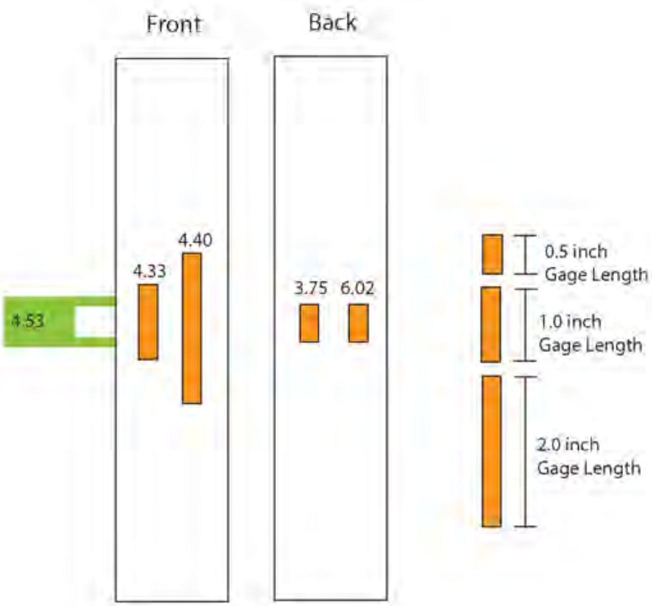


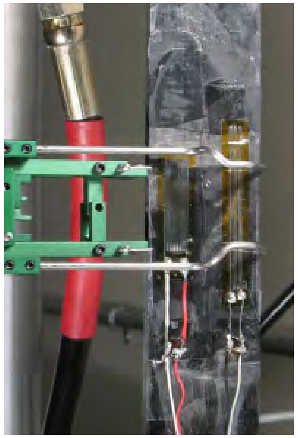
Previous results -2

- Modulus variation
- Extensometer or strain gage measurements showed up to 19% modulus variation within batches
- Multi-gage measurements show variation within specimen across width, along length and on each side



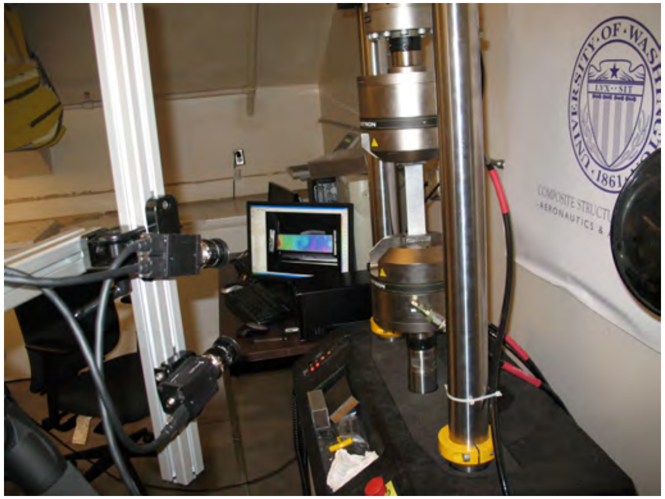


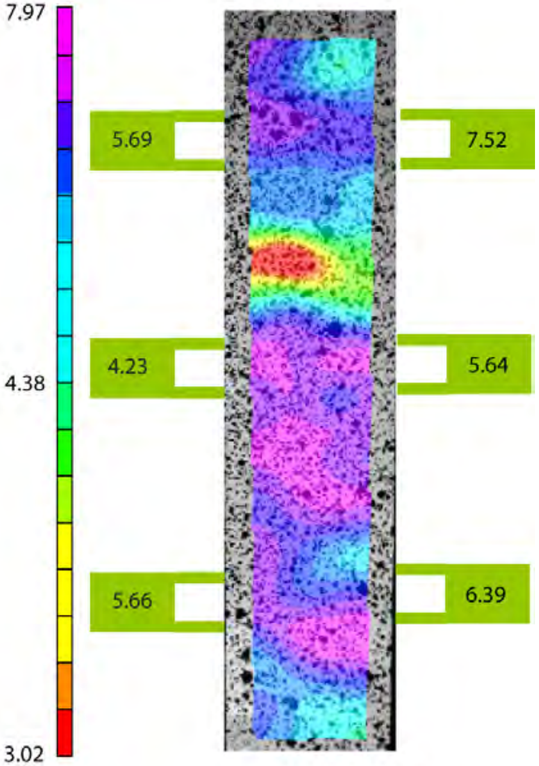




Previous results -2

- Modulus variation
- Digital Image correlation shows presence of large strain gradients on surface of specimen
- Averaged measurement is however very consistent (5% variation within batch)



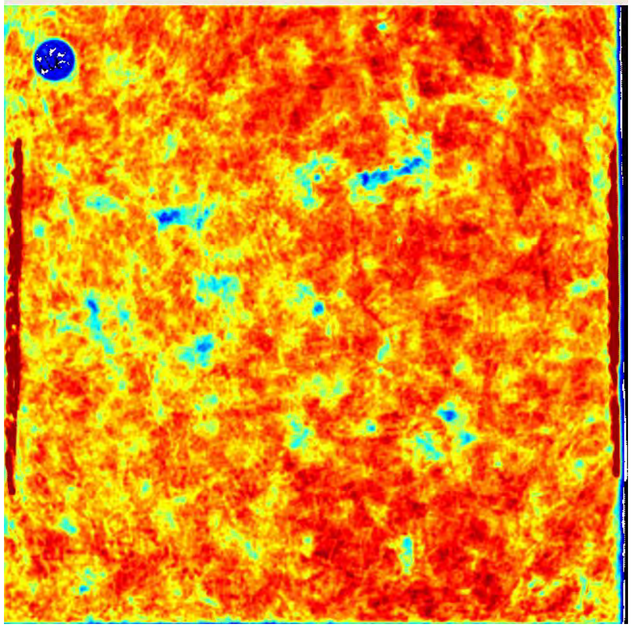


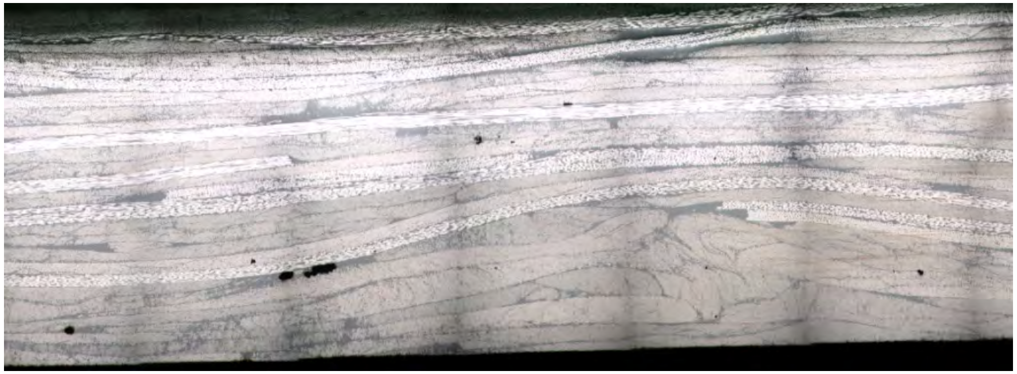
"Modulus measurement of prepreg-based discontinuous carbon fiber/ epoxy systems", P. Feraboli, E. Peitso, T. Cleveland, P. Stickler – Journal of Composite Materials, 43/19, 2009, pp. 1947-1965

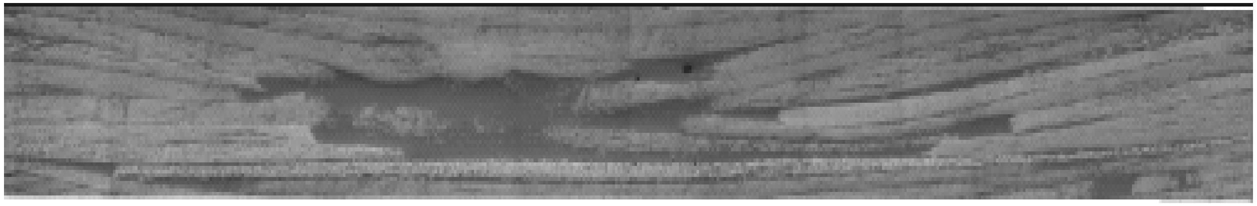
Previous results -3

- Effect of defects
- Ultrasonic inspection difficult because material is very noisy
- Some areas of large attenuation called "hot spots"
- These are defects that can be macrovoids (entrapped air), swirls or resin rich areas

"Defect and damage analysis of advanced discontinuous carbon/ epoxy composite materials", Paolo Feraboli, Tyler Cleveland, Marco Ciccu, Patrick Stickler, Composites (Part A), accepted and to be published May 2010.

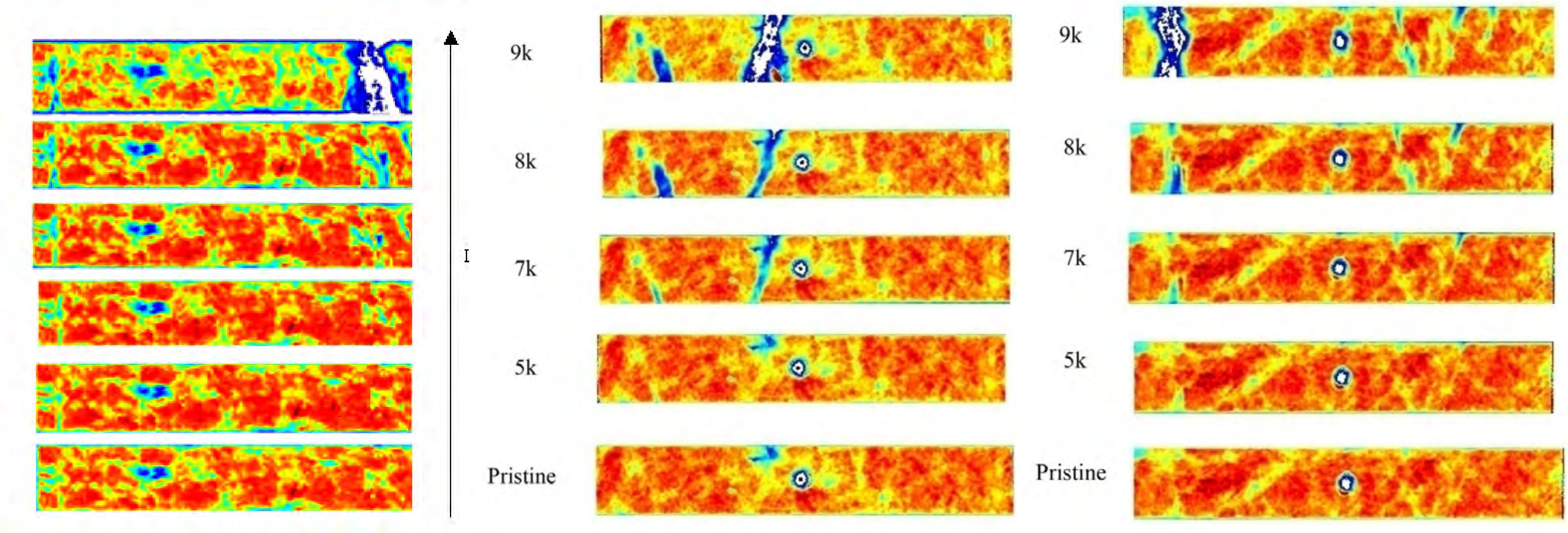






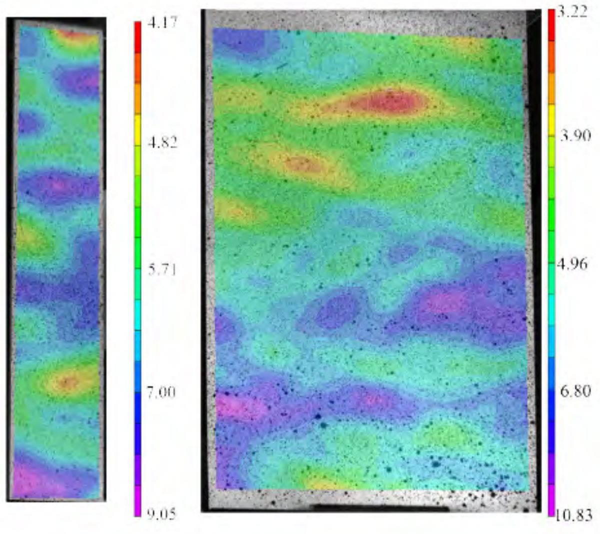
Previous results -3

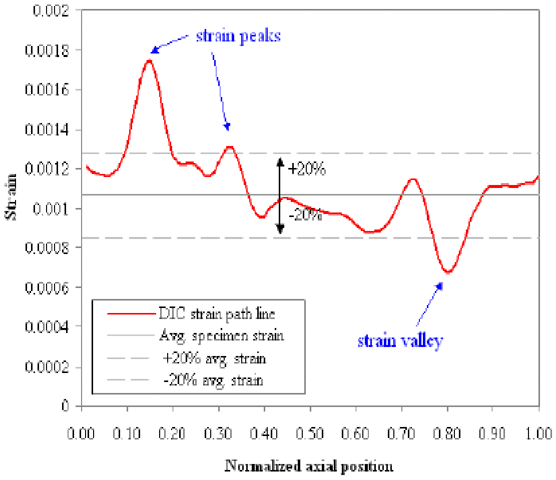
- Effect of defects
- Progressive loading, unloading, inspection and reloading
- Unnotched and open-hole specimens
- Hot spots grow
- Failure occurs 50% of time away from hot spots, and away from hole

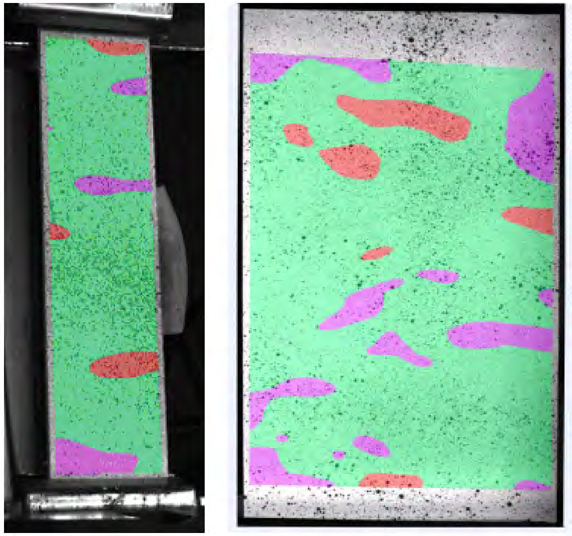


Previous results -4

- Narrow and wide specimens tested to capture full size of modulus distribution
- Regions of high or low strain/ modulus exist
- These are RRVE = random representative volume elements
- Apply filter to isolate the regions and remove “noise”







Previous results -4

- Average dimension of these RRVE patterns is 0.25 in2
- Actual shapes is somewhat elliptical
- Approximated as 0.5 in x 0.5 in squares
- Burn-off and de-plying shows multitude of shapes and sizes of chip fragments/ fractions within that volume

Number of regions	Small tensile specimen	Large tensile specimen
1	0.151 (97.4)	0.902 (581.9)
2	0.119 (76.8)	0.142 (91.6)
3	0.237 (152.9)	0.436 (281.3)
4	0.058 (37.4)	0.074 (47.7)
5	0.29 (187.1)	0.462 (298.1)
6	0.416 (268.4)	0.117 (75.5)
7	-	0.276 (178.1)
8	-	0.019 (12.3)
9	-	0.024 (15.5)
10	-	0.142 (91.6)
11	-	0.593 (382.6)
12	-	1.077 (694.8)
13	-	0.272 (175.5)
14	-	0.055 (35.5)
15	-	0.467 (301.3)
16	-	0.449 (289.7)
17	-	0.247 (159.4)
18	-	0.221 (142.6)
Average	**0.212 (136.8)**	**0.317 (204.5)**

“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

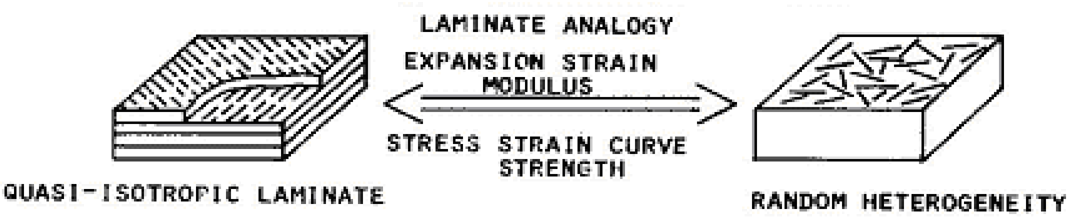
Previous results -4

- Several analysis approaches can be pursued

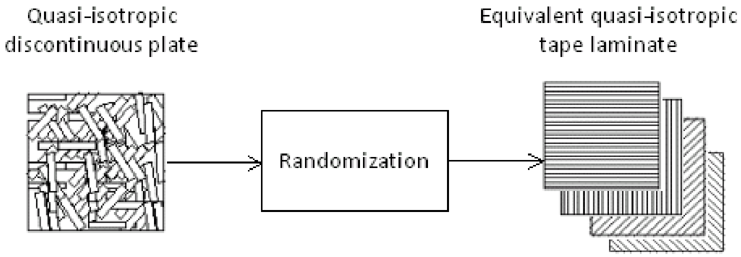
- Micro-scopic level (constituent):
  - Micromechanics approach is not appealing for commercial aircraft applications
- Macro-scopic level (laminate):
  - Laminate Allowables approach may be viable
- Meso-scopic level (lamina):
  - Lamination theory

Previous results -4

- Halpin and Pagano in the 1960s proposed the laminate analogy to predict the modulus of chopped fiber composites based on CLPT. This assumes repeatable behavior (low CoV among specimens and within specimen).
- Randomization process that generates statistical distributions of fractions and orientations of chips in order to capture the random fiber microstructure of HexMC
- Through the laminate analogy, it applies CLPT to an equivalent quasi-isotropic tape laminate to calculate its average elastic properties.



Laminate analogy



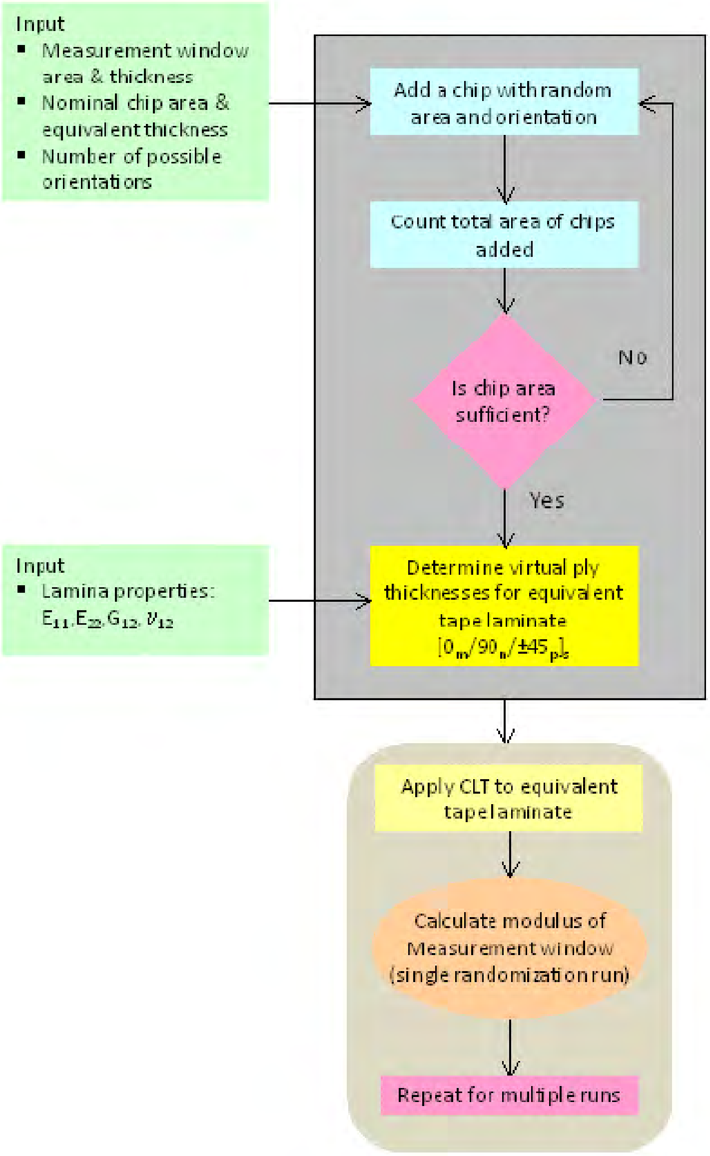
Previous results -4

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

$$t^{mw} \cdot A^{mw} = t^{c} \cdot \left[A(\theta_1) + \ldots + A(\theta_i) + \ldots + A(\theta_n)\right]$$

$$A(\theta_i) = A^{c} \cdot \sum \left(k_j\right)_{(\theta_i)}$$

$$t_c \cdot \sum A(\theta_i) = 2 \cdot t_{\theta i} \cdot A^{mw}$$



Previous results -4

Example input (US customary units of in., lb, Msi):

$A^{mw} = 12.0$ in.^{2}, $t^{mw} = 0.165$ in. #measurement window Area and thickness#

$A^c = 0.66$ in.^{2}, $t^c = 0.00495$ in. #single chip area and thickness#

n = 4 #number of possible chip orientations# : $\theta_1 = 0$, $\theta_2 = +45$, $\theta_3 = -45$, $\theta_4 = 90$

runs = 5,000 #number of algorithm cycles to be repeated#

$E_{11} = 16.5$ Msi, $E_{22} = 1.22$ Msi, $G_{12} = 0.6$ Msi, $\nu_{12} = 0.309$ #tape lamina elastic properties#

While loop begins – adds random fractions of chips k_j at each random orientation θ_i:

0	±45	90
0.321	0.023	0.001
0.622	0.112	0.646
…	…	…

The quantities below are generated:

$$\begin{Bmatrix} A(0) = A_c \cdot \sum\left[k_j(0)\right] = 0.66 \cdot \left[0.321 + 0.622 + \ldots\right] = 247.3\,in.^2 \\ A(\pm 45) = A_c \cdot \sum\left[k_j(\pm 45)\right] = 0.66 \cdot \left[0.023 + 0.112 + \ \ldots\right] = 83.4\,in.^2 \\ A(90) = A_c \cdot \sum\left[k_j(90)\right] = 0.66 \cdot \left[0.001 + 0.646 + \ldots\right] = 69.3\,in.^2 \end{Bmatrix}$$

The while loop ends when the condition below is satisfied:

$$\frac{t^{mw} \cdot A^{mw}}{t^c} = 400\,in.^2 = \left[A(0) + A(\pm 45) + A(90)\right]$$

With ply percentages are:

$$\begin{Bmatrix} \%0 = \dfrac{247.3}{400} = 0.618 = 61.8\% \\ \%\pm 45 = \dfrac{83.4}{400} = 0.208 = 20.8\% \\ \%90 = \dfrac{69.3}{400} = 0.173 = 17.3\% \end{Bmatrix}$$

Example output:

$$\begin{Bmatrix} t_0 = \dfrac{1}{2} \cdot 0.618 \cdot 0.165 = 0.0510\,in. \\ t_{+45} = \dfrac{1}{4} \cdot 0.208 \cdot 0.165 = 0.0085\,in. \\ t_{-45} = \dfrac{1}{4} \cdot 0.208 \cdot 0.165 = 0.0085\,in. \\ t_{90} = \dfrac{1}{2} \cdot 0.173 \cdot 0.165 = 0.0143\,in. \end{Bmatrix}$$

These are the ply thicknesses for the equivalent laminate, an 8-ply quasi-isotropic $[0/+45/-45/90]_s$.

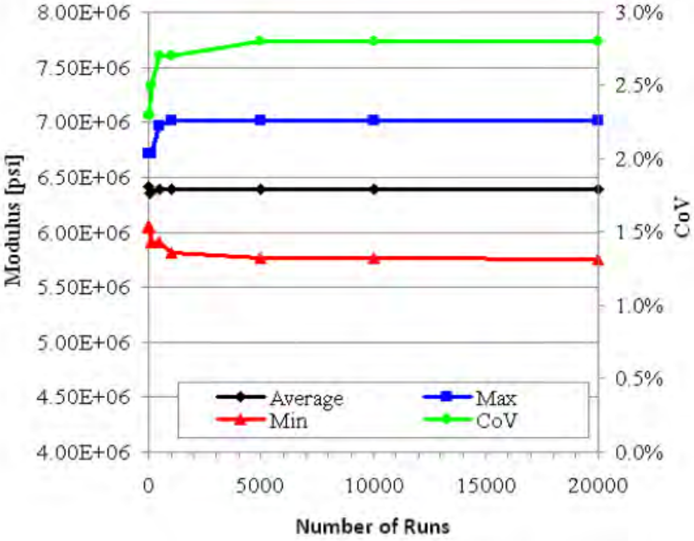
$$\boxed{[A]_{x,y}, [B]_{x,y}, [D]_{x,y}}$$

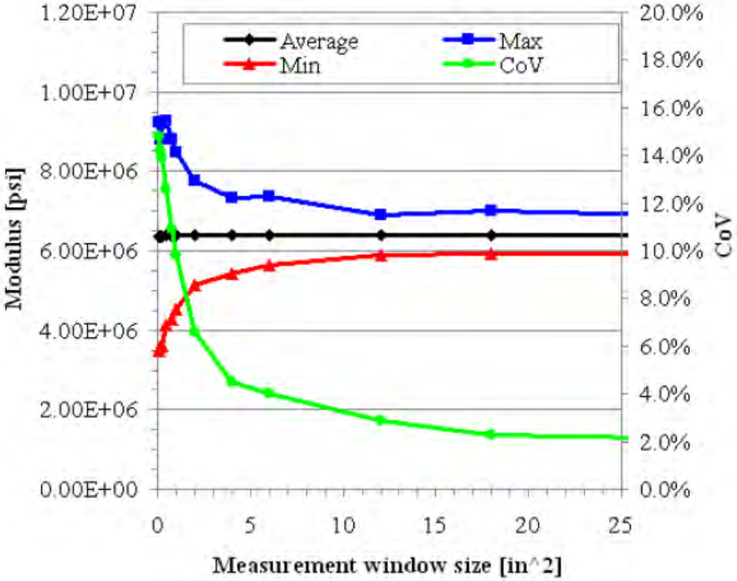
$$E_x = \frac{1}{t}\left(A_{xx} - \frac{A_{xy}^2}{A_{yy}}\right)$$

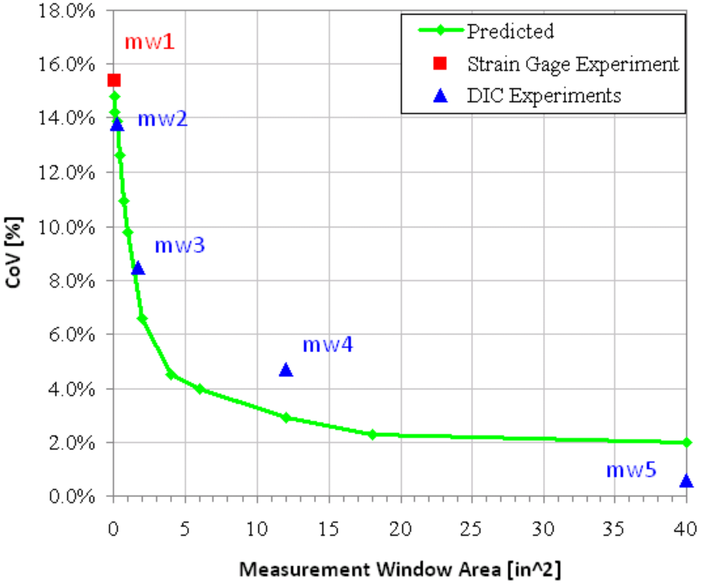
$E_x = 11.3$ Msi (77.9 GPa).

Previous results -4

- Model converges quickly
- The larger the specimen (window size), the smaller the variation observed
- Max, min, avg and CoV values line up well with experiments

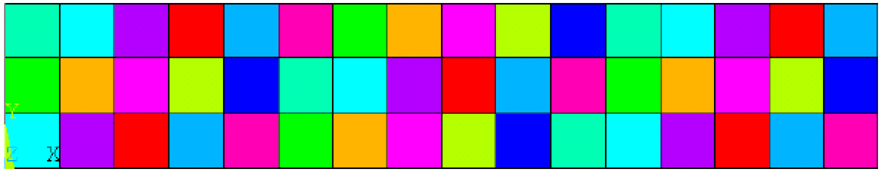


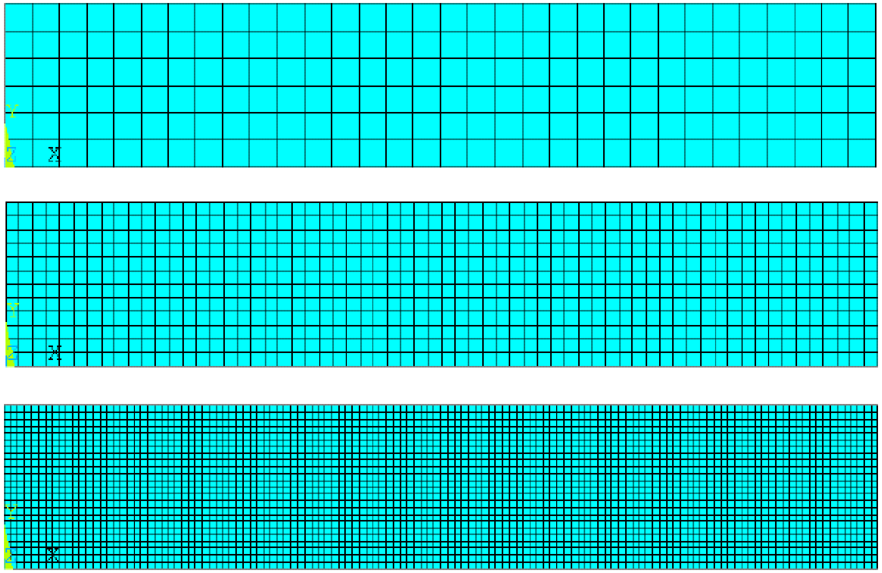




Previous results -4

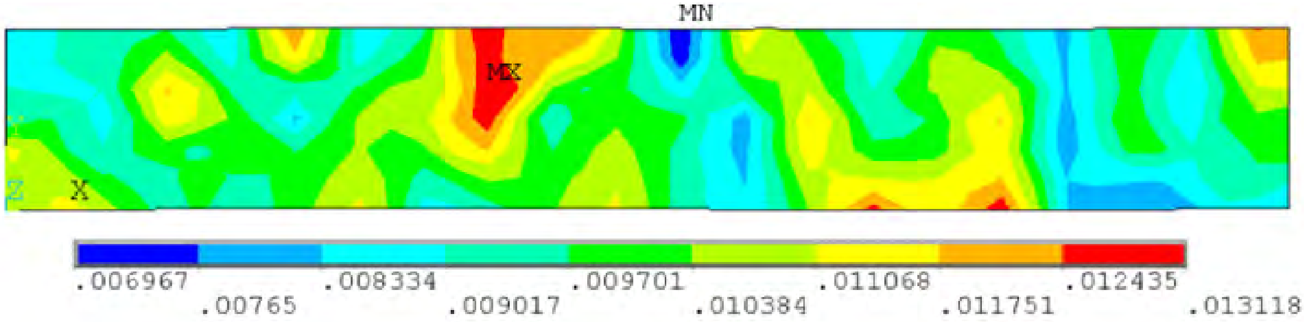
- Application to ANSYS FEA
- Discretize the geometry in RRVE
- Each RRVE is assigned different elastic properties
    - Directly generated by subroutine using the stochastic laminate code in Matlab
- Mesh size is independent from RRVE size
- Shell element model only

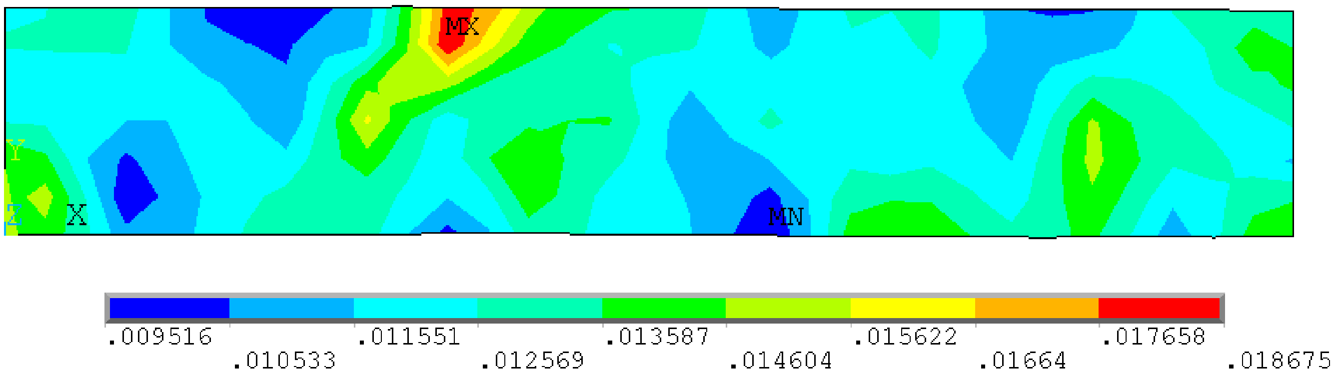




Previous results -4

The proposed method captures Modulus variability





Next stage of research

Future work:

- Convert from ANSYS to NASTRAN
- Applying stochastic laminate analogy approach to strength (first ply failure)
- Capture stress concentration insensitivity
- Predict response of more complex geometries
- Validate against experiment of intercostal from certification

Onset of failure

- Ultimate strength of HexMC is noticeably lower than the quasi-isotropic AS4/ 8552 tape
- HexMC failure is a matrix dominated event.
- Prediction based on CLPT and progressive ply degradation following first ply failure of tape
- Appears that Ultimate strength of HexMC = First ply failure of quasi tape