

# Multi-Continuum Technology for the Failure of Composites

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NEi Software

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- Multi Continuum Technology (MCT) allows for consideration of micro-mechanical effects in macro-sized FEM models
    - Mechanics of fibers and matrix can be considered individually
    - Properties for the composite are derived from constituent properties
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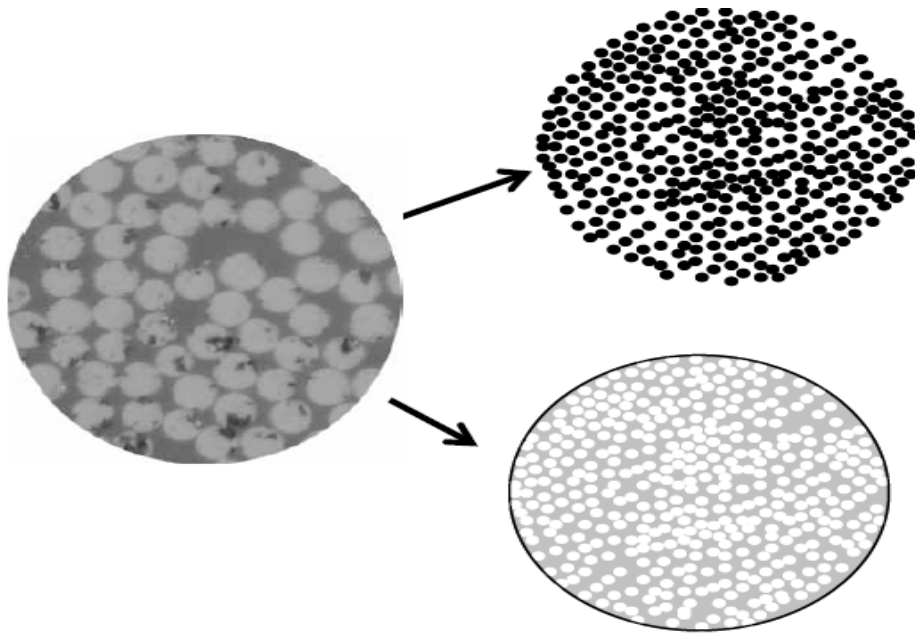
- So what?
    - Much more accurate predictions of composite failure
      - Less need for detail models
    - Better knowledge of material failure point
    - Better and lower safety factors
    - Less material
    - Lower cost and weight
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- MCT Technology developed by Firehole Technology
  - Firehole's Helius product
  - Implemented in NEi Nastran

- Why do we need MCT?
  - Traditional failure theories have been developed based on smeared lamina properties
    - Fibers and matrix are smeared into one
    - Testing and verification needed to develop and tweak models
    - Called the ‘Black Aluminum’ approach
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- So?
  - Smearred properties have limits to what they can tell you
    - Failure theories treat composite as a whole
    - Analysis output is for composite, not individual components
      - Did the fiber fail or just the matrix?
    - Limits to what it can accomplish
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- MCT separates the fibers and matrices
    - Different stiffness
    - Different failure properties
      - Fiber failure theory for fibers
      - Polymer failure theory for matrix
    - Different thermal properties
    - Interaction between the two important
-



**Better Information  
= Better Designs**

FEA Outputs:

$\epsilon_{\text{composite}}, \sigma_{\text{composite}}$

$\epsilon_{\text{fiber}}, \sigma_{\text{fiber}}$

$\epsilon_{\text{matrix}}, \sigma_{\text{matrix}}$

Failure Information:

$FI_{\text{Fiber}}, FI_{\text{Matrix}}$

$R_{\text{Fiber}}, R_{\text{Matrix}}$

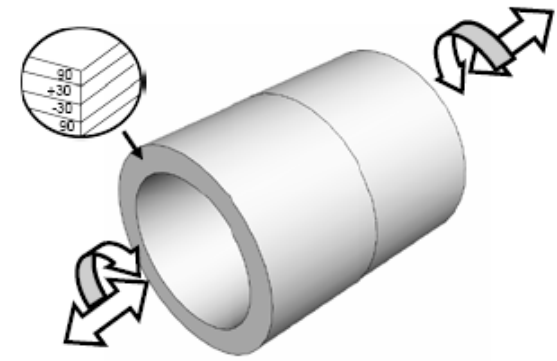
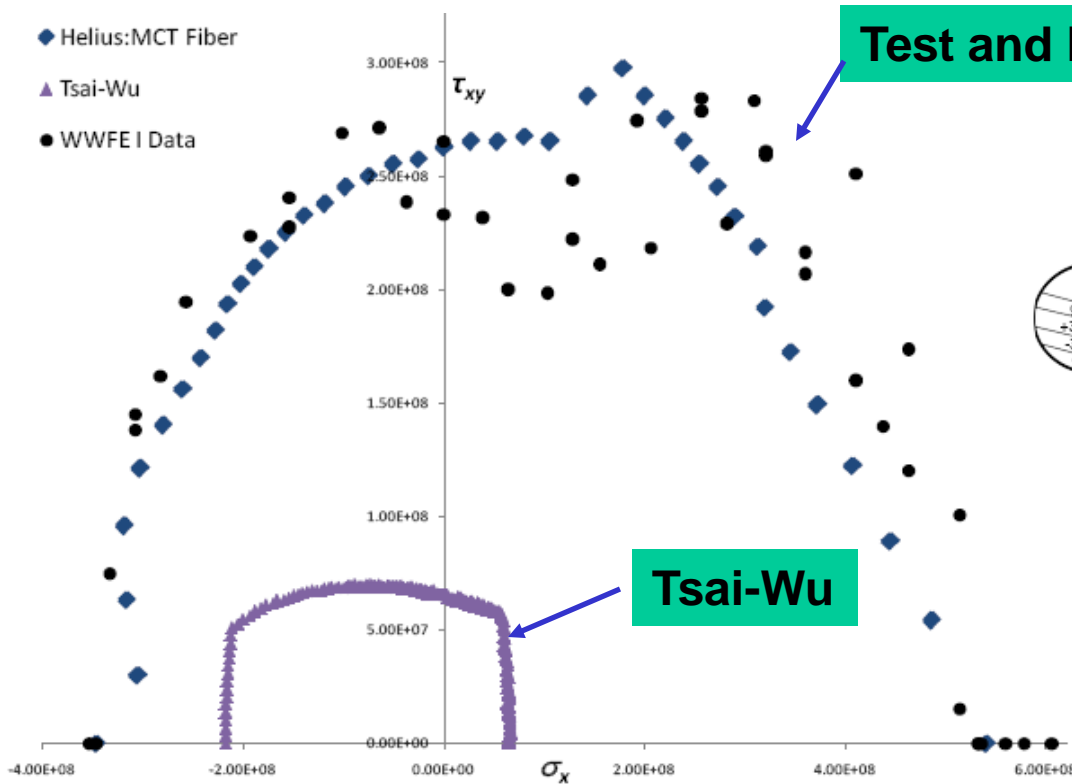
Exact Failure Mode

- Advantages to this approach
    - Proper failure criteria can be applied to the individual constituents
    - 3D failure theory
      - Off-axis stresses are calculated for 2D models
    - Interactions can be handled to a degree
    - Can handle unidirectional **and** woven materials
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- Hasn't this been done before?
- In a way...
  - Micro-mechanics are usually applied to small details
    - Accurate capture of interaction
  - Smearred properties used for large models
    - Less accurate results
  - **MCT captures the accuracy of the detail, but in a large model**

- How do we know this works?
  - The MCT approach has been correlated against many tests and actual failures
  - MCT matches WWFE test results better than most traditional failure theories

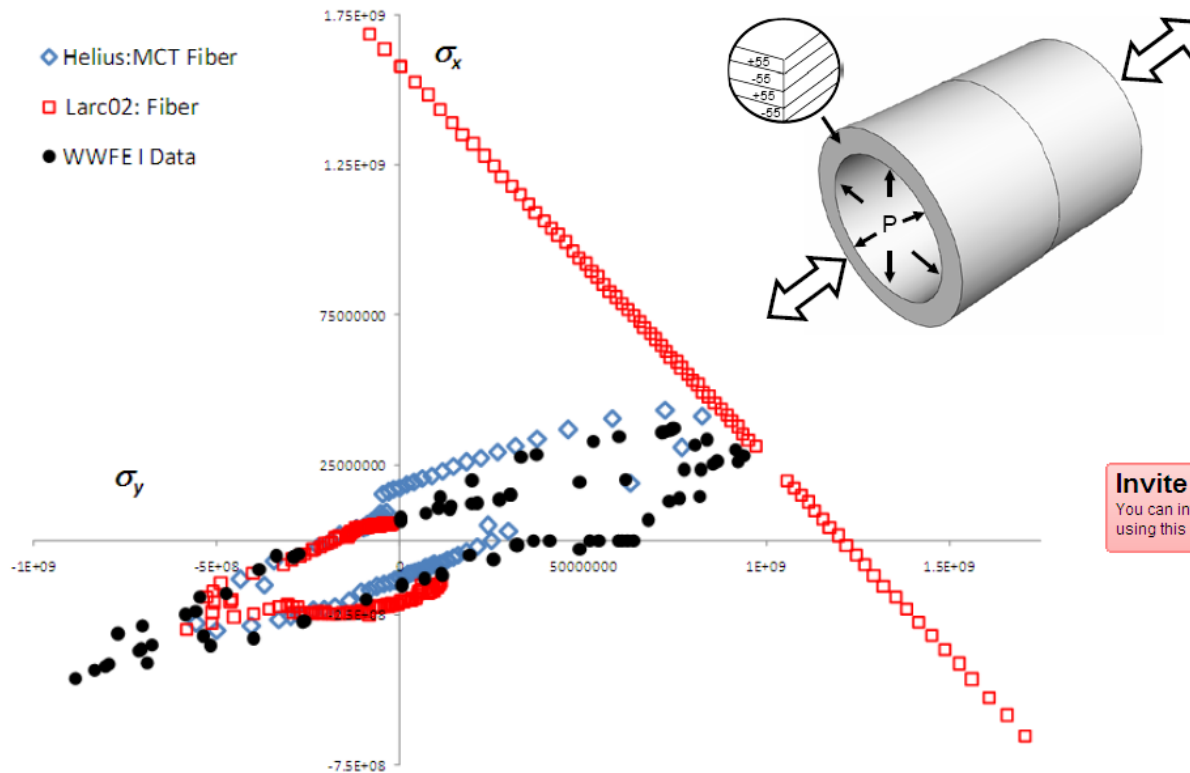
- The World Wide Failure Exercise
    - A challenge to the analysts of the world
    - Rigorous testing performed
    - Several composite materials
    - Several geometric problems
    - Several loading conditions
    - Published results of the tests and material properties
  - How well can you match these?
-



Biaxial  $\sigma_x$ :  $\tau_{xy}$  failure envelope for a  $[90 / 30]_s$  glass/epoxy lamina



Biaxial,  $\sigma_y:\sigma_x$ , failure envelope for a  $[\pm 55^\circ]_s$  laminate made from E-glass/Epoxy



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Firehole and NEi Proprietary



- How does this all work, then?
    - Properties are input for the constituents
      - Fiber properties - Nastran MAT8 entry
      - Matrix Properties – MAT1 or MAT8
      - Combination - MATL8
    - Properties are then calculated/optimized for the composite.
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- FEM model is solved with optimized properties, and element strains and stresses are found
- The composite strains and stresses are then decomposed into fiber stresses and fiber strains based in the individual properties and the micro-mechanical models
- Fibers and matrix results can then be handled separately
  - Failure
  - Strength
  - Stiffness

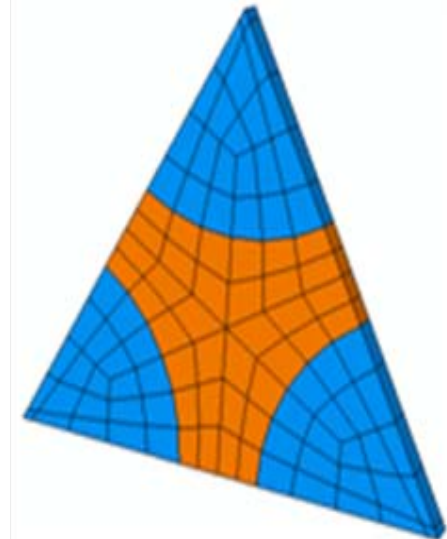
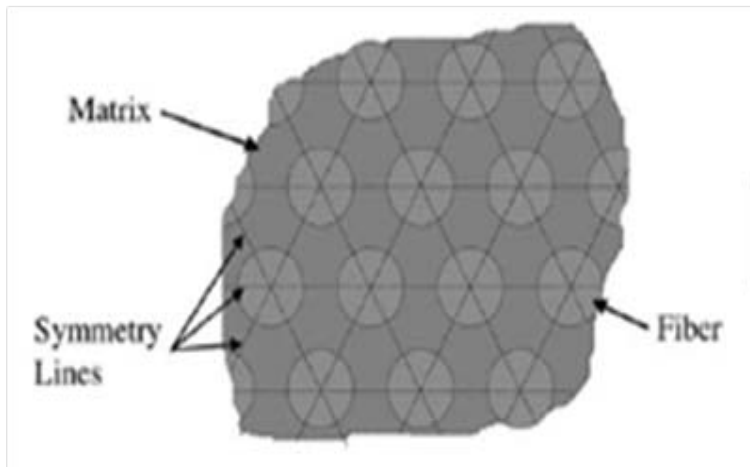
- Ideally, the user inputs material properties for the fibers and matrix
  - Small micromechanical models are constructed and run inside Helius to come up with ‘composite’ properties
    - Can input these composite properties directly
    - Halpin-Tsai method can be used to produce fiber and matrix properties given only the composite property
      - Can use this method even without knowing individual properties
  - These ‘optimized’ composite properties are used for the big FEM model

- Halpin-Tsai is a volume-based approach to combining constituent properties into a composite property.

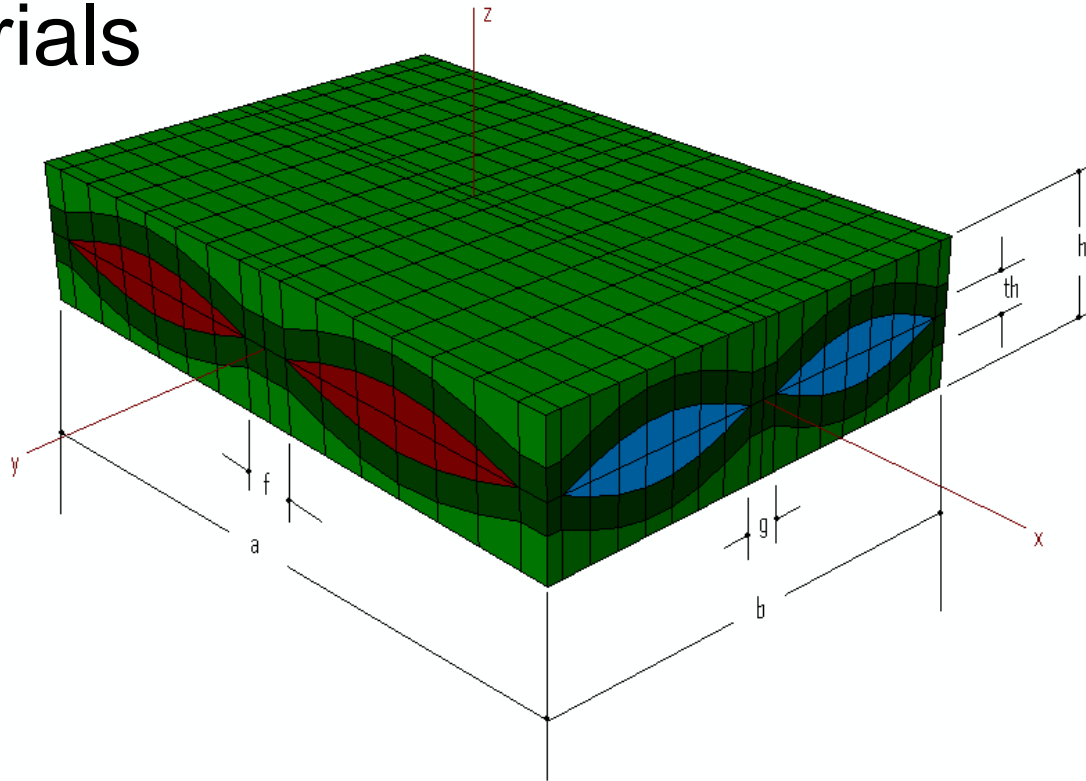
$$E_{11} = E_f V_f + E_m (1 - V_f)$$

- $V_f$  is the volume fraction of the fibers
  - Other properties calculated similarly
  - Can be modified to account for geometry of the material or known interactions between the materials
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- Micro-mechanics model for Unidirectional materials



- Micro-mechanics model for woven materials



- The small models are called RVEs “representative volume elements”
- Loads from the model elements are applied to the RVEs
- A detailed 3D picture of the stress state in the individual components can be developed this way
- Reported as fiber and matrix values

- NEi has implemented a subset of the HELIUS product into Nastran
  - Layered Composite Shells (PCOMP, MAT8)
- Coming in the next release:
  - Solid Layered Composites (PCOMP, MAT12)

- User inputs:
    - Fiber properties and matrix properties
      - MAT8, MAT1
    - Composite failure limits
      - And composite properties if known
      - MAT8
    - Tie together with MATL8
      - Which fibers and matrices go together?
      - Composite type, volume fraction for Halpin-Tsai
-

```

$ ... Material for MCT
MATL8  4      401      402      403      .620      1      2      1
$ ... Matrix for MCT
MAT8   401      3.5424E9 3.8504E9 .3870  1.5845E9 1.5845E9 1.2834E9      0.+
+
+
+
+      3.8504E9 .5000      .3870
$ ... Fibers for MCT
MAT8   402      83.825E9 82.743E9 .2149  34.677E9 34.677E9 33.185E9      0.+
+
+
+
+      82.743E9 .2467      .2149
$ ... Composite properties
MAT8           403 53.101E9 17.456E9 .2769  5.7206E9 95.7206E9 95.5410E9  2006.+MT      5
+MT      5      0.      0.      0.1140.E6 35.E6  570.E6  113.E6  72.E6      +MA      5
+MA      5
+MB      5
+MC      517.456E9 .5751      .2769  0.1000  0.1000  0.1000  0.1000  0.1000      +MB      5
+MC      5
$

```

## Volume Fraction

## Composite Limits

**3D properties**

- User Inputs
  - Specify 'MCT' for the failure theory in place of HILL or other on PCOMP

PCOMP	1		0.		MCT255.3722			+
+	2	2.54-4	0.	YES	1	2.54-4	0.	YES+
+	1	2.54-4	90.	YES	1	2.54-4	90.	YES+
+	1	2.54-4	0.	YES	2	2.54-4	0.	YES

- Extras...
  - Want to run something quick w/ reasonable defaults?
    - PARAM,TSAI2MCT
      - Provides default values and material recognition for certain classes of glass, kevlar and carbon composites

- New output vectors...

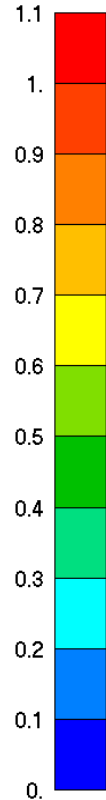
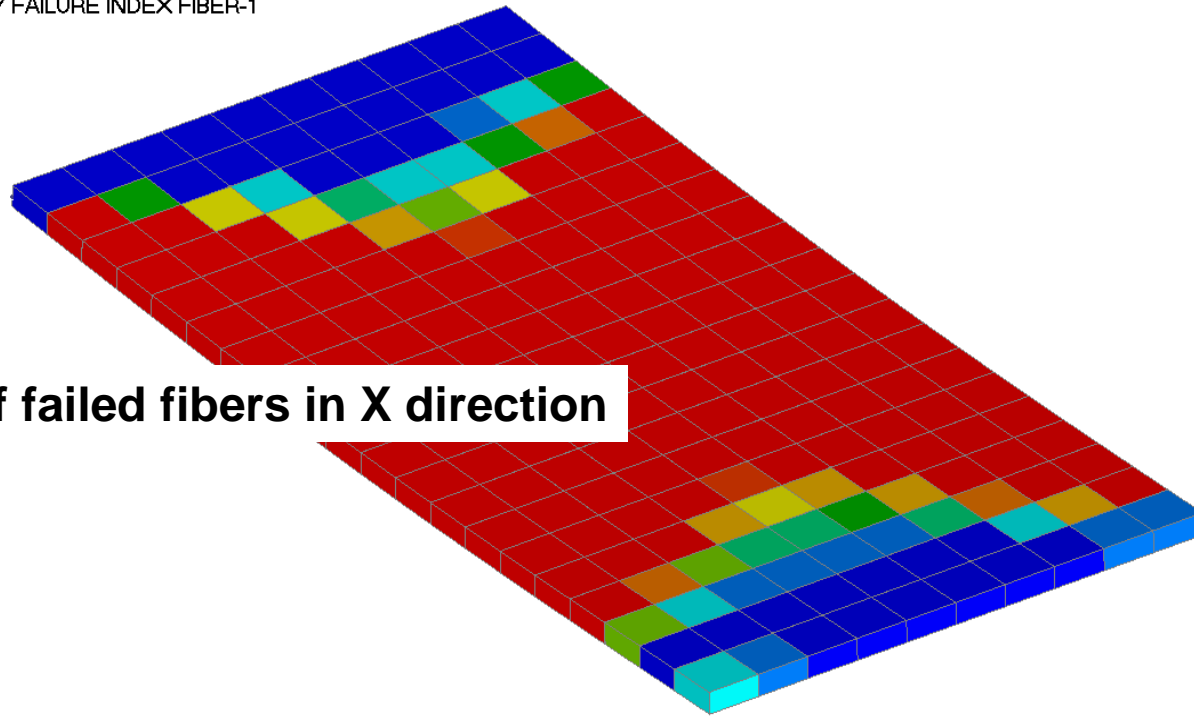
**Individual FIs for Matrix and Fiber**

- In two directions!

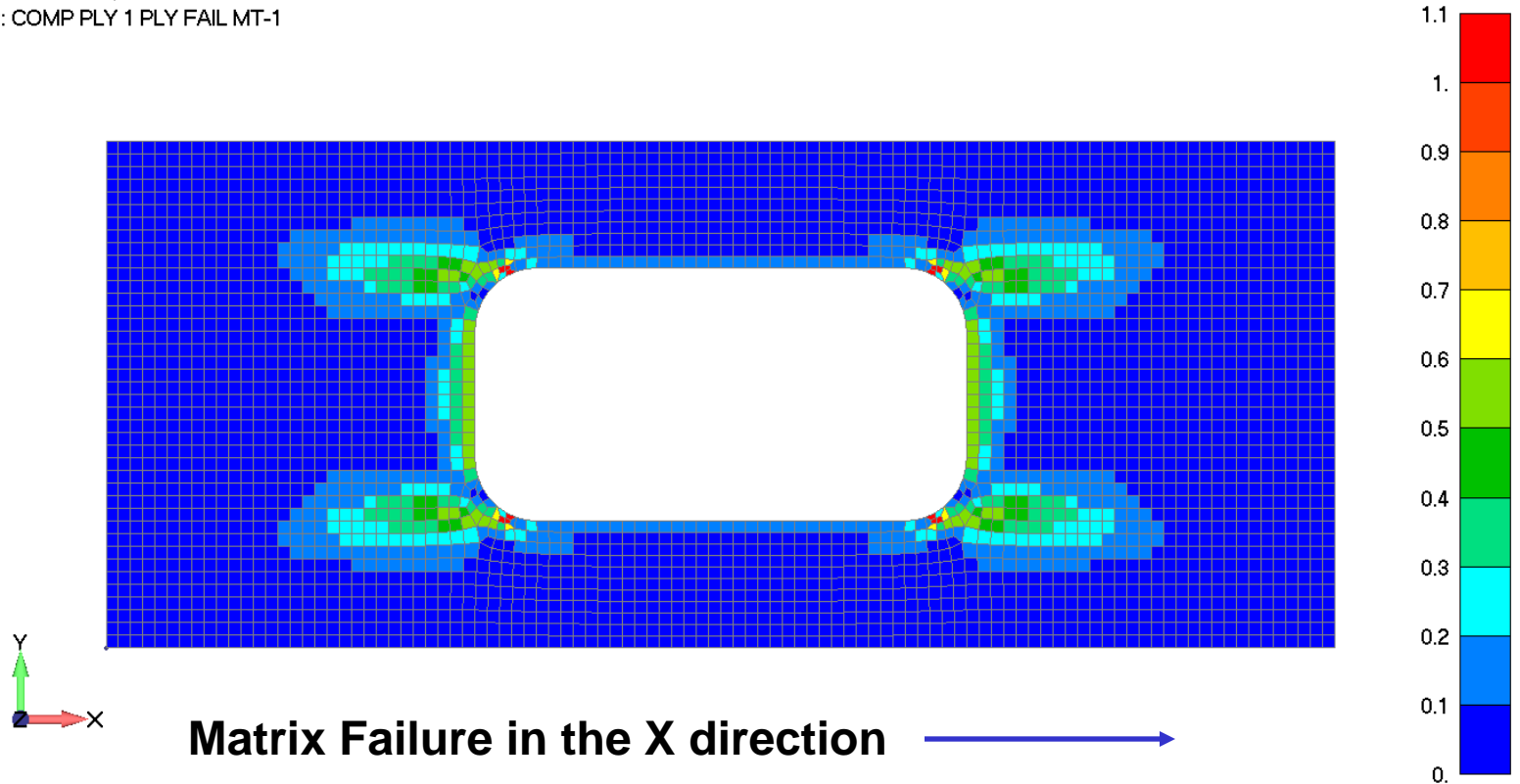
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6117..COMP STATUS
1000020..COMP PLY 1 NORMAL-1
1000021..COMP PLY 1 NORMAL-2
1000023..COMP PLY 1 SHEAR-12
1000024..COMP PLY 1 SHEAR-XZ
1000025..COMP PLY 1 SHEAR-YZ
1000026..COMP PLY 1 MAX PRINCIPAL
1000027..COMP PLY 1 MIN PRINCIPAL
1000031..COMP PLY 1 MAX SHEAR
1000032..COMP PLY 1 EQUIVALENT STRESS
1000033..COMP PLY 1 VON MISES
1000090..COMP PLY 1 PLY FAILURE INDEX
1000091..COMP PLY 1 BOND FAILURE INDEX
1000101..COMP PLY 1 PLY FAILURE INDEX MATRIX-1
1000102..COMP PLY 1 PLY FAILURE INDEX MATRIX-2
1000103..COMP PLY 1 PLY FAILURE INDEX FIBER-1
1000104..COMP PLY 1 PLY FAILURE INDEX FIBER-2
1000105..COMP PLY 1 FAILURE THEORY
1000107..COMP PLY 1 STRENGTH RATIO ERROR
1000108..COMP PLY 1 STATUS
1000109..COMP PLY 1 EFFECTIVE STRAIN
1000220..COMP PLY 2 NORMAL-1
1000221..COMP PLY 2 NORMAL-2
1000223..COMP PLY 2 SHEAR-12
1000224..COMP PLY 2 SHEAR-XZ
1000225..COMP PLY 2 SHEAR-YZ
1000226..COMP PLY 2 MAX PRINCIPAL
1000227..COMP PLY 2 MIN PRINCIPAL
1000231..COMP PLY 2 MAX SHEAR
1000232..COMP PLY 2 EQUIVALENT STRESS
```

Output Set: INCR 1, LOAD=0.0125  
Deformed(0.0102): TOTAL TRANSLATION  
Contour: COMP PLY 1 PLY FAILURE INDEX FIBER-1

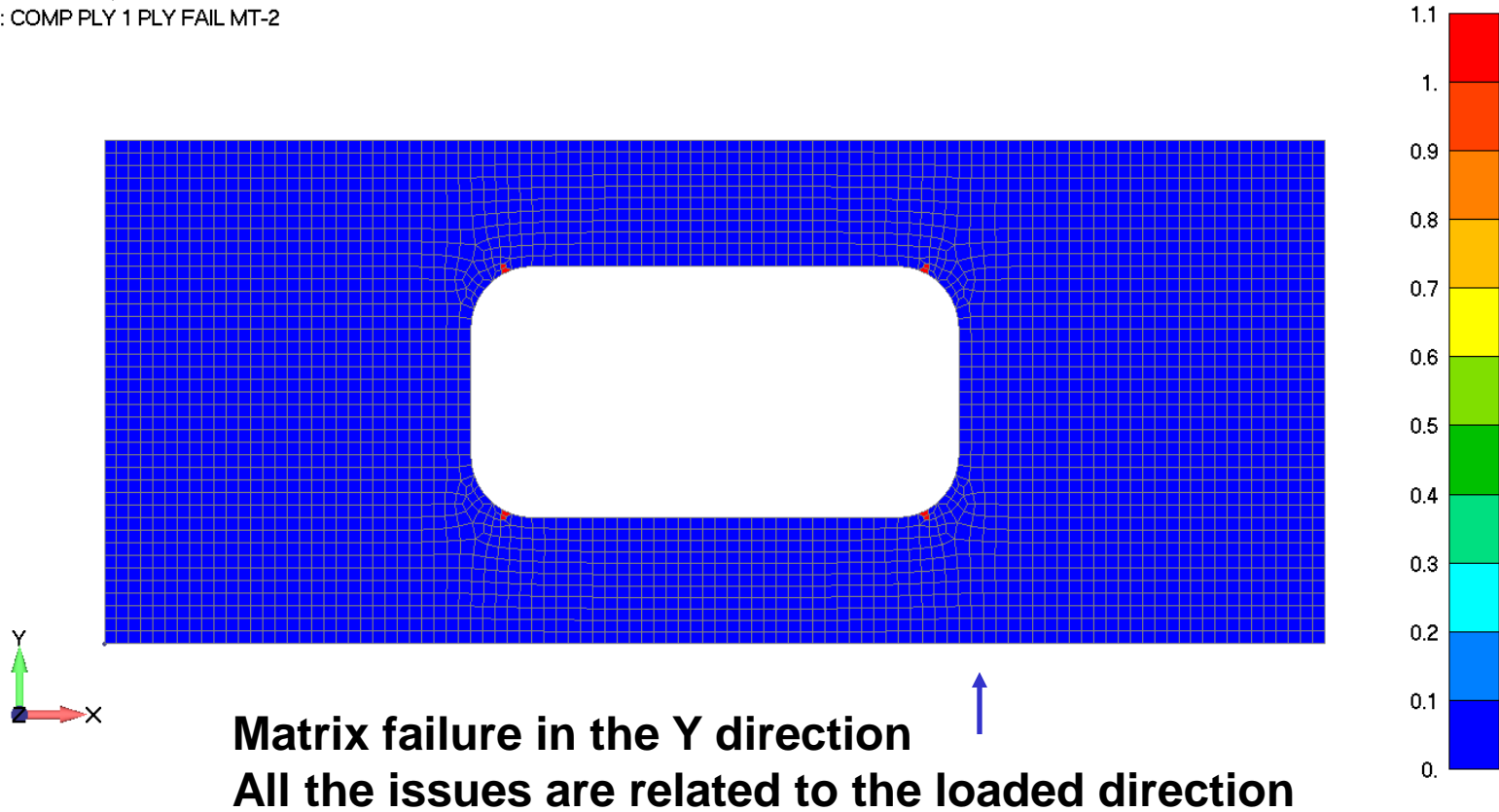
Area of failed fibers in X direction



Output Set: INCR 13, LOAD=0.26  
Contour: COMP PLY 1 PLY FAIL MT-1



Output Set: INCR 13, LOAD=0.26  
Contour: COMP PLY 1 PLY FAIL MT-2



- So what does this buy me?
- A simple thermal example...
  - Consider a block of material subject to a change in temperature

- Without any constraints, this is a zero stress event for an isotropic material
  - But composites are not isotropic!
    - Fibers and matrix have different CTEs
    - Potentially significant stresses in opposite directions in the fiber and matrix
    - Also out of plane!
    - A traditional failure theory would report the composite stress as zero
      - Because it is treated as a smeared material
-

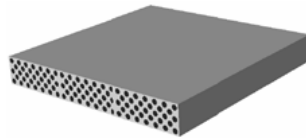
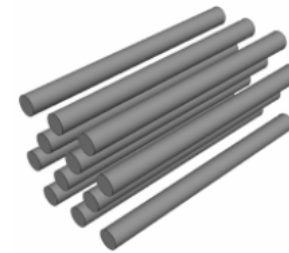
## Composite Under Thermal Loading

Composite Stress:

$$\begin{aligned}\sigma_{11} &= 0 \\ \sigma_{22} &= 0 \\ \sigma_{33} &= 0\end{aligned}$$

Fiber Stress:

$$\begin{aligned}\sigma_{11f} &= -44.5 \text{ (MPa)} \\ \sigma_{22f} &= -17.25 \text{ (MPa)} \\ \sigma_{33f} &= -17.25 \text{ (MPa)}\end{aligned}$$

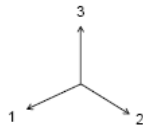
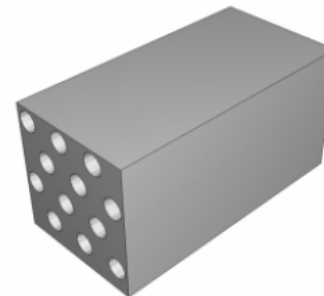


$\Delta T = -216 \text{ }^\circ\text{C}$



Matrix Stress:

$$\begin{aligned}\sigma_{11m} &= 66.75 \text{ (MPa)} \\ \sigma_{22m} &= 25.87 \text{ (Pa)} \\ \sigma_{33m} &= 25.87 \text{ (Pa)}\end{aligned}$$



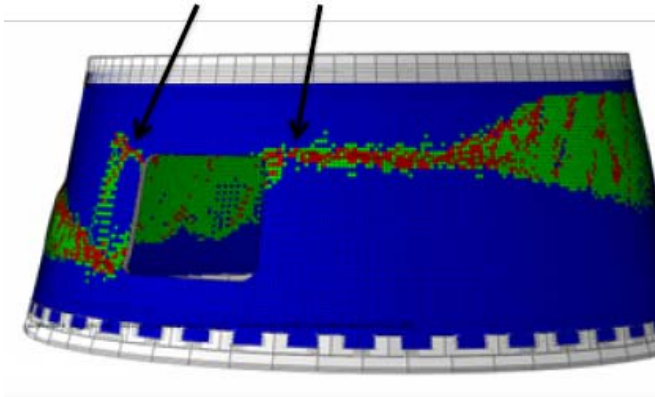
- Structural loading scenarios have similarly unexpected results
    - In-plane loads can generate significant out-of-plane stresses in composites
      - The MCT 3D approach finds these values
    - Delamination may be caused by these loads
      - MCT predicts this better
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### Results

Helius:MCT Predicted Failure

Red = Fiber Failure

Green = Matrix Failure



✓ **Location**

✓ **2.5%**

- Can we do even better?
  - Some ideas for even better prediction
    - Fiber buckling (once matrix failed)
    - Incomplete fiber/matrix bonds
    - Better post-failure approximations

- MCT is a much better way to predict the actual limits of composites.
    - Especially in larger shell models
  - Simple to use – relatively few additional properties needed.
    - Don't have to resort to local models as much
  - Better prediction = better design
  - Better design = lower material cost, lower weight
  - Use MCT today!
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