Effect of Microscopic Damage Events on Static and Ballistic Impact Strength of Triaxial Braid Composites

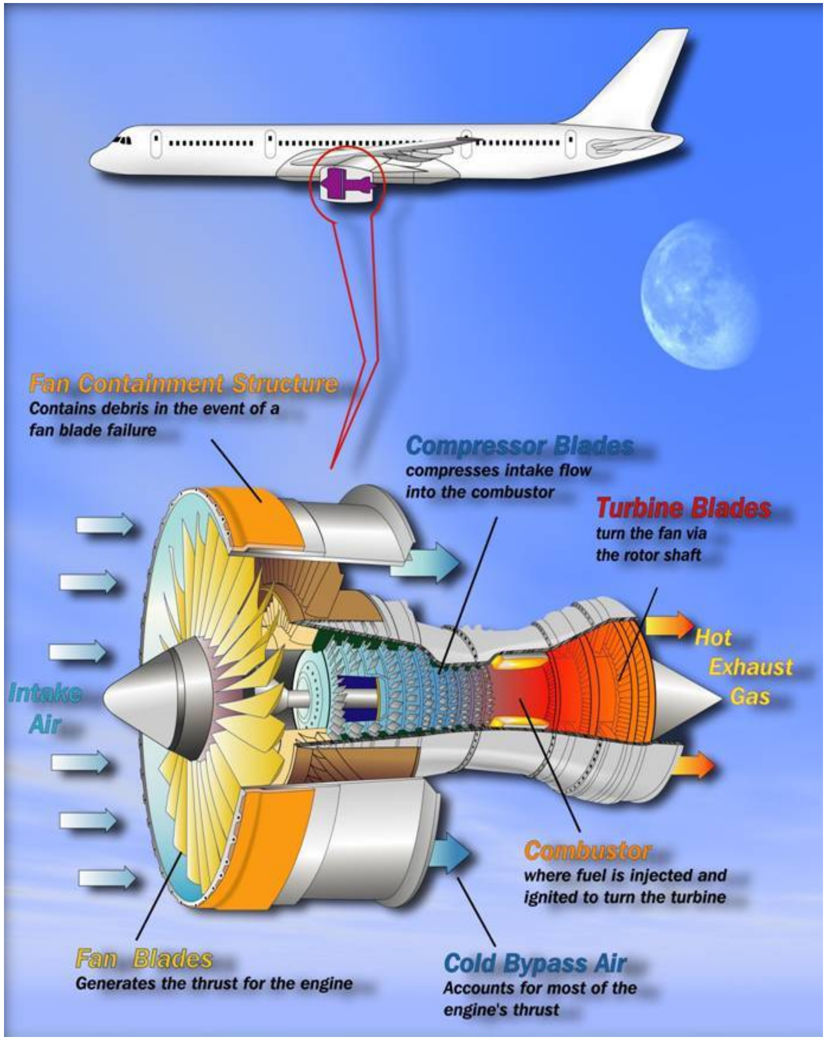
CompTest Conference - Oct. 21 2008
Dayton Ohio

Justin Littell
University of Akron
Akron, Ohio
Justin.D.Littell@nasa.gov

Wieslaw K. Binienda, William A. Arnold – University of Akron, Akron Ohio
Gary D. Roberts, Robert K. Goldberg – NASA Glenn Research Center, Cleveland Ohio

Motivation and Introduction

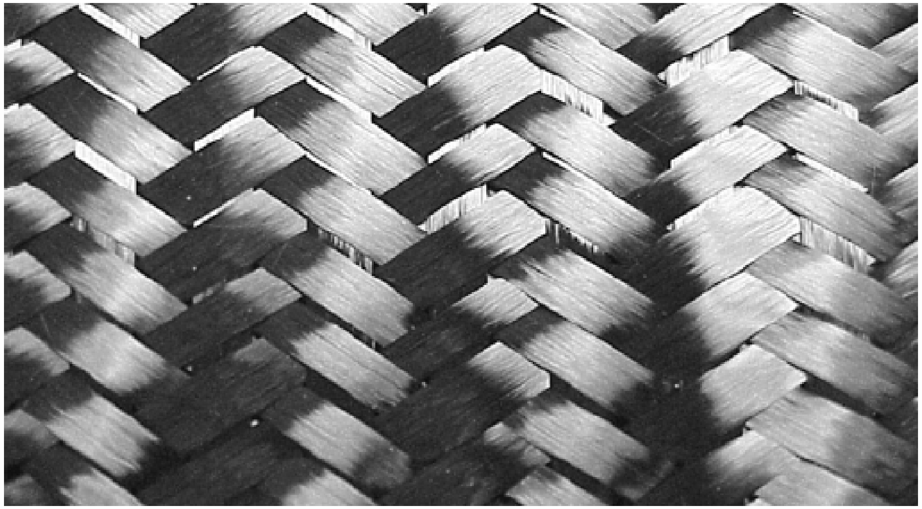
- Triaxial braided carbon fiber composite materials are being used in engines and airframes
  - Static and Dynamic loads
- Computer modeling can complement testing when necessary
  - LS-DYNA – Transient non-linear explicit finite element code
    - impact simulations
- Due to the size of the engine cases, models have to be macromechanical in nature but incorporate micromechanical properties of the materials
  - Incorporate braid architecture/stiffness properties/failure properties
  - Short run times

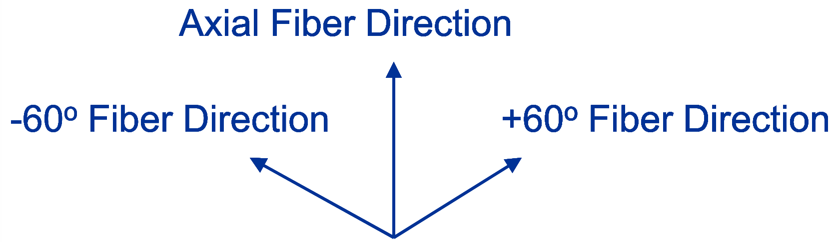


Model Development

- Testing and modeling were done in parallel
  - Test data used optical measurement techniques to obtain full field strain data
    - Quasi-static Testing
  - By examining the test data and using classical composite theory, a new approach was developed to model composites using a novel “Subcell” approach
- Modeling data needs
  - Composite section properties – braid geometry
  - Composite material properties – test data
- Models developed in LS-DYNA
  - Transient, nonlinear, explicit finite element code
  - Primarily impact loading that composites will be subjected

Triaxial Braided Composite Materials

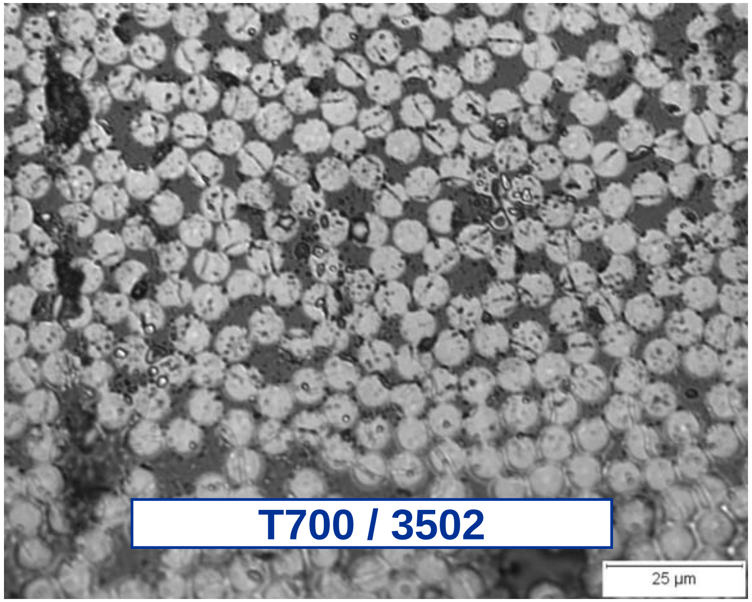


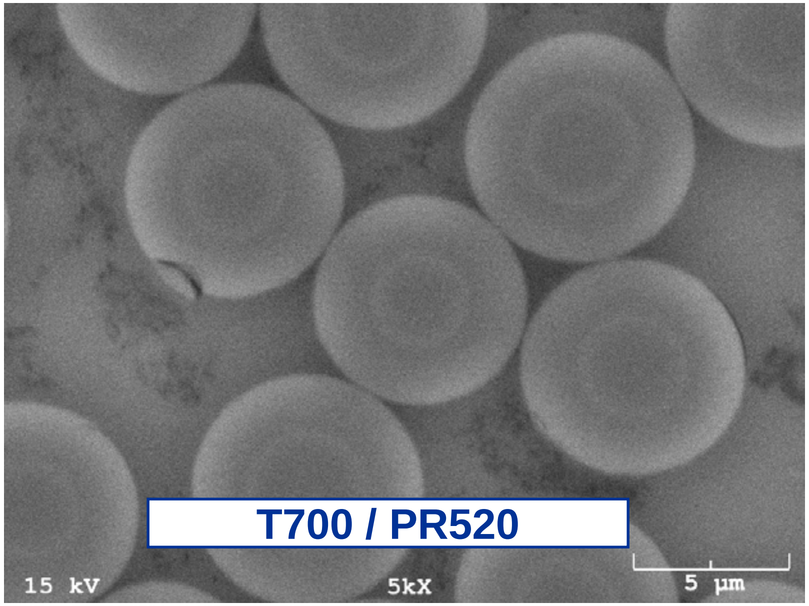


- Two dimensional triaxial braid
- 24k wide axial and 12k wide bias fiber tows
- Layers of +60^{o} and -60^{o} bias fibers braided over a 0^{o} axial fiber
- Quasi-isotropic architecture
- Layup of 6 Layers of braid, total composite thickness 0.125”
- Resin Transfer Molding process (RTM)
- Volume fraction of 56% nominal

Materials

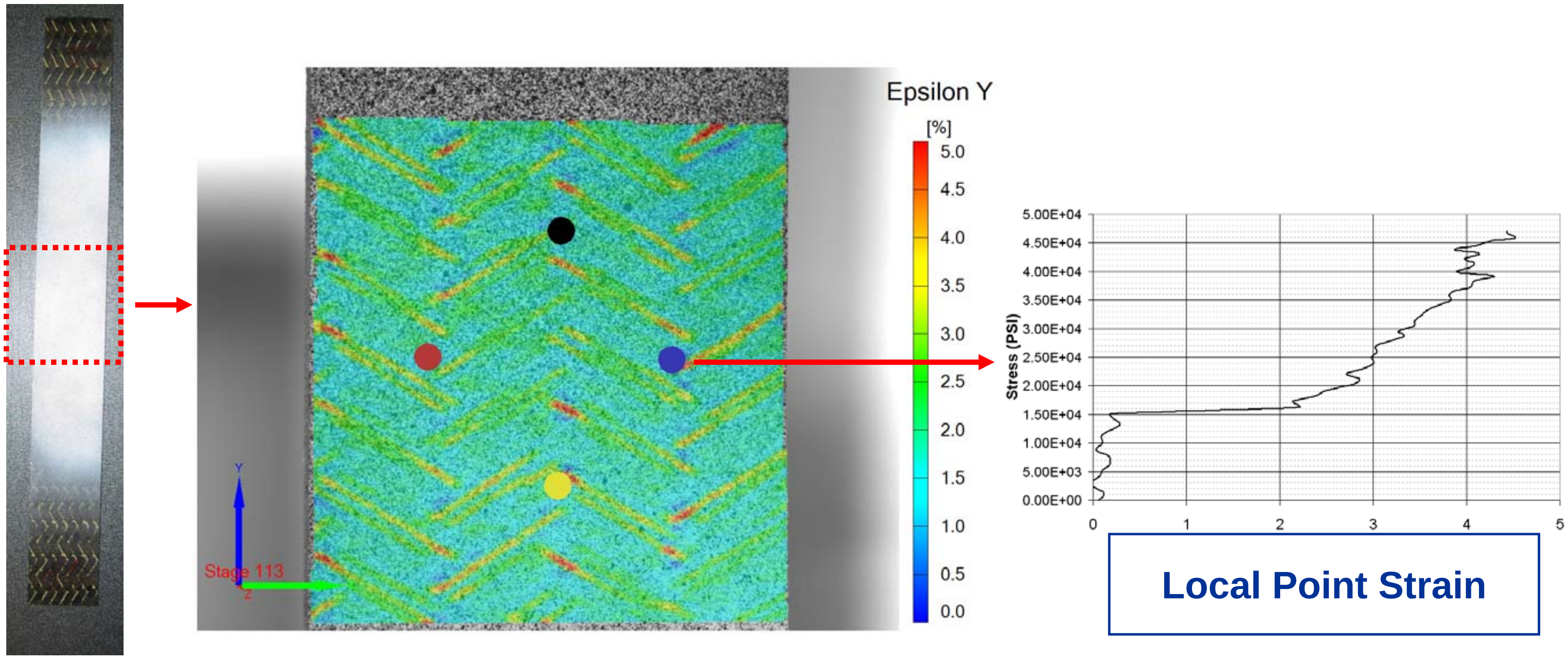
- High Strength, Standard Modulus Fiber – Toray T700
- Two resins
  - Toughened Cytec Cycom ® PR520 – high strength
  - Untoughened Hexcel 3502 – low strength





- Presented as examples to cover range of material response

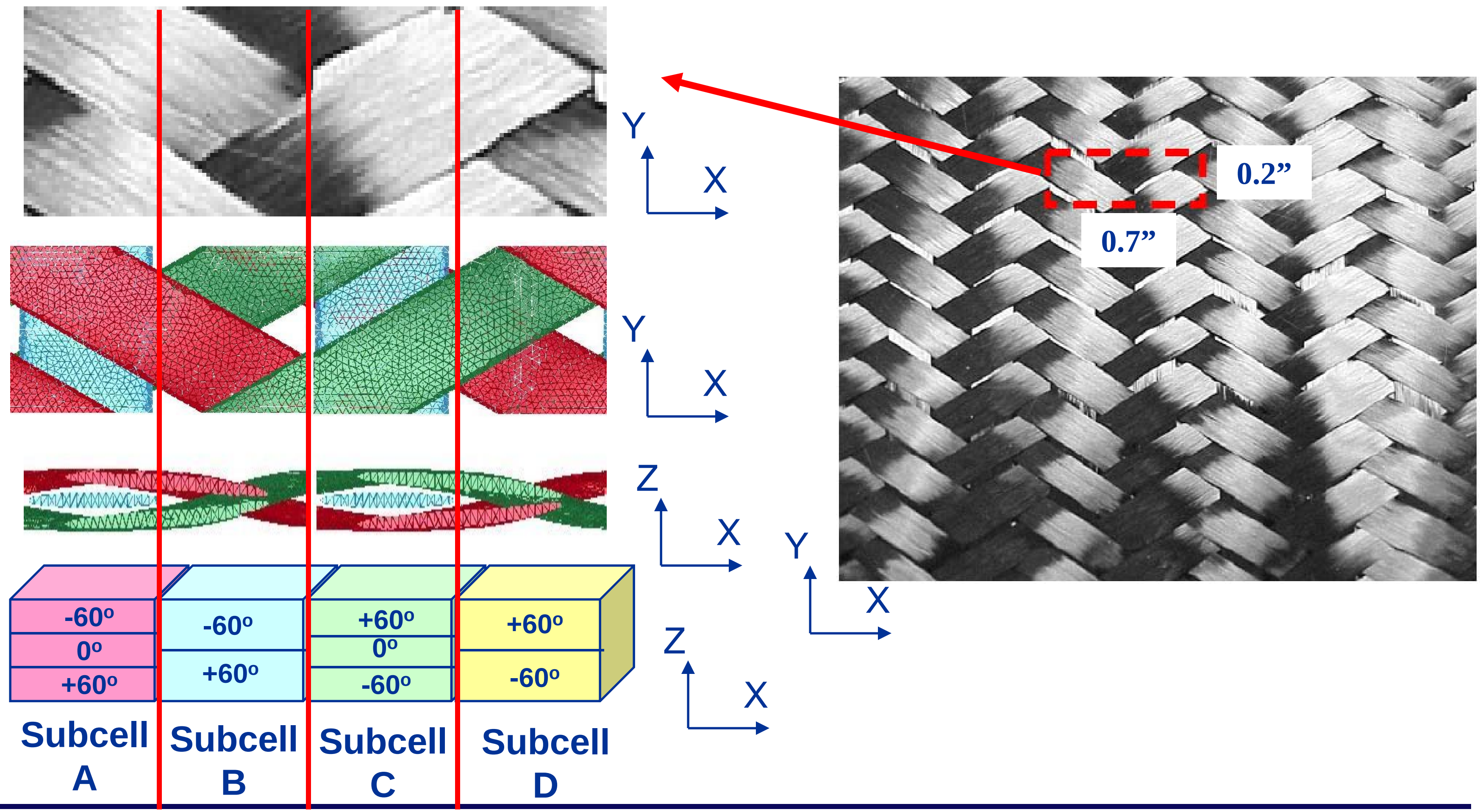
Photogrammetry used for Data Collection



- Global stress vs. strain curves found by creating a “digital strain gage”
- Measures material response in specific areas on specimen
  - Seen by noting lines of high localized strain
- Local failure mechanisms and deformations must be accounted for when developing an analytical method

Triaxial Braided Model Methodology

- Develop a macromechanical finite element model capable of capturing the braid architecture and material properties of triaxially braided composites
  - Layers of unidirectional lamina stacked in a “Subcell” configuration
  - Needs local lamina level modulus and failure properties



A New Methodology Developed for Implementation of Material Properties

Traditional Approach (Bottom - Up)

1. Obtain Fiber, Matrix Properties
2. Micromechanics - Develop effective lamina properties
3. CLPT - Develop effective laminate properties
4. Develop a FEM (One layer, homogenized)

- Items needed
  - Fiber properties - Assumed
  - Matrix properties
- Stackup sequence

New Approach (Top – Down)

1. Obtain Composite stresses, strains From optical measurements
2. CLPT - Back out effective laminate properties
3. Micromechanics - Back out effective lamina properties
4. Develop a FEM (includes layers and subcell props)

- Items needed
  - **COMPOSITE TEST DATA**
- Stackup sequence

Classical Laminated Plate Theory (CLPT) Use in Reverse for Top-Down Approach

- Stresses/Surface Tractions are related to strains by the following

$$\begin{bmatrix}[N]\\ [M]\end{bmatrix}=\begin{bmatrix}[A] & [B]\\ [B] & [D]\end{bmatrix}\begin{bmatrix}[\varepsilon]\\ [\gamma]\end{bmatrix}$$

- Balanced and Symmetric (B and D matrices, also A16, A26 = 0)

$$\begin{bmatrix}Nx\\ Ny\\ 0\end{bmatrix}=\begin{bmatrix}A11 & A12 & 0\\ A12 & A22 & 0\\ 0 & 0 & A66\end{bmatrix}\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ 0\end{bmatrix}$$

Known from optical measurements

Known from micromechanics eqs

- Where

$$A11=\sum \overline{Q}11=\overline{Q}11^{0\deg}*t^{0\deg}+\overline{Q}11^{60\deg}*t^{60\deg}+\overline{Q}11^{-60\deg}*t^{-60\deg}$$

$$\overline{Q}11=m^4Q11+n^4Q22+2m^2n^2Q12+4m^2n^2Q66$$

$$Q11=\frac{E11}{1-v12*v21},Q22=\frac{E22}{1-v12*v21},Q12=\frac{v21*E11}{1-v12*v21},Q66=G12$$

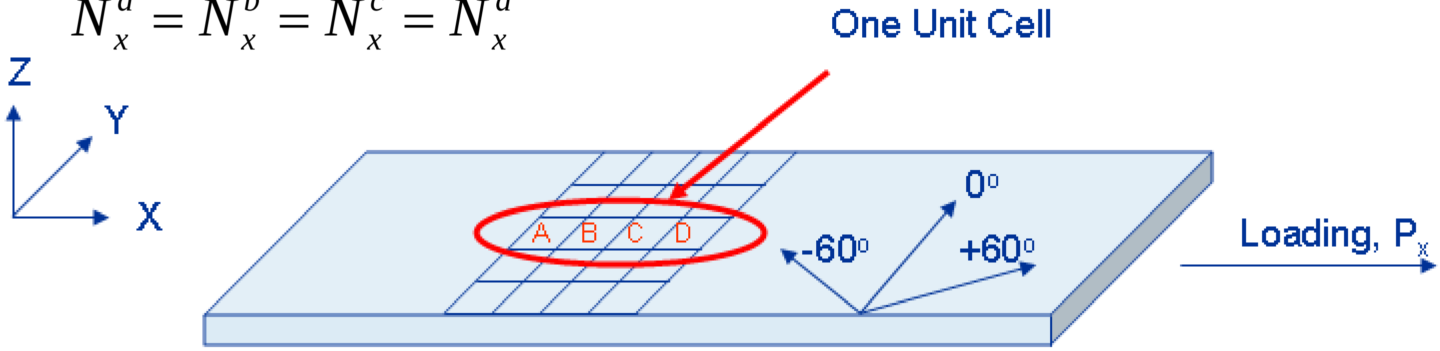
- E11, E22, v12, v21, G12 are parameters needed in LS-DYNA

Equation Development

Micromechanics of Composite Materials for Surface Tractions

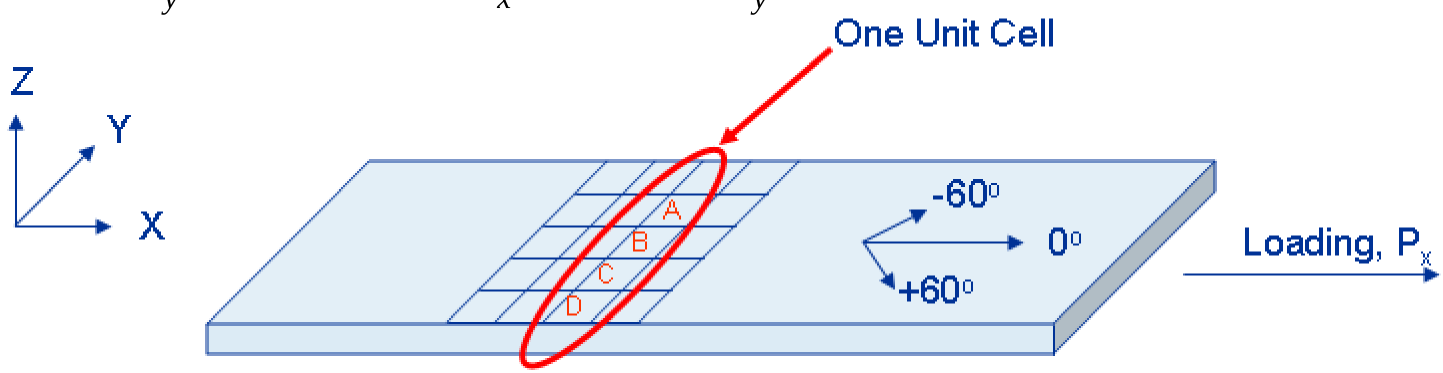
- Transverse ASTM 3039 specimen
  - $V_f^a * N_y^a = V_f^b * N_y^b$

    $N_x^a = N_x^b = N_x^c = N_x^d$

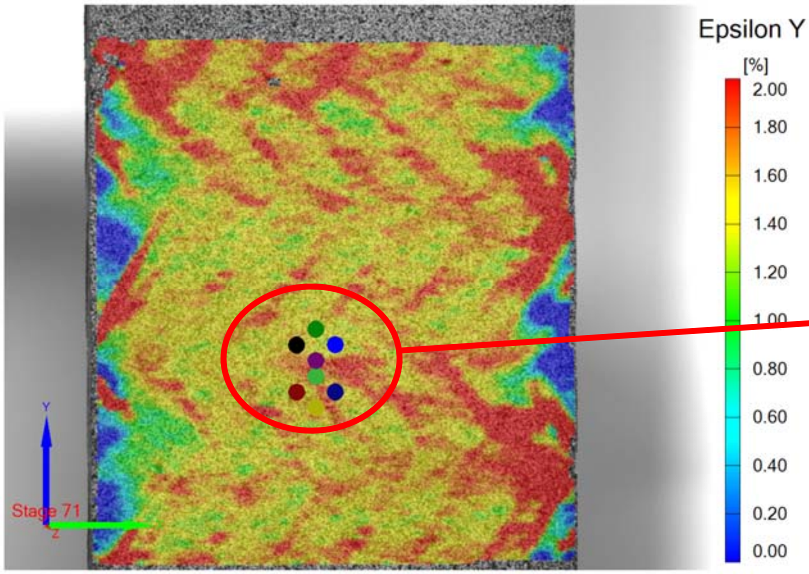


- Axial ASTM 3039 specimen
  - $N_y^a = N_y^b = N_y^c = N_y^d = 0$

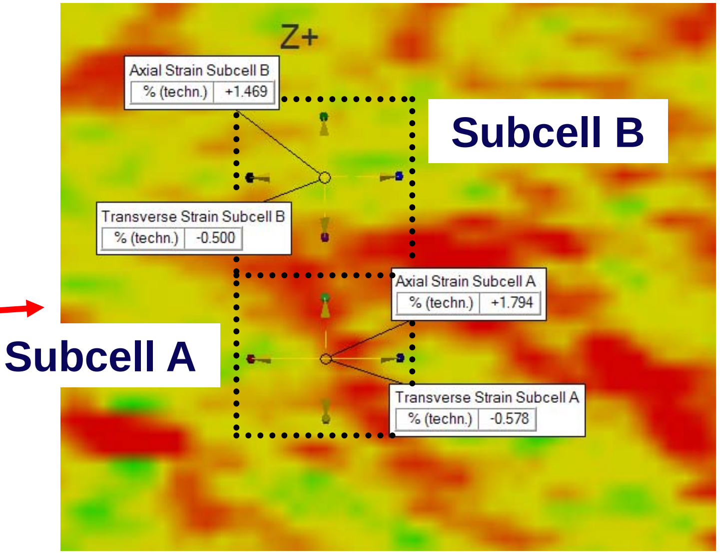
    $N_y^a = 0 = A12^a * \varepsilon_x^a + A22^a * \varepsilon_y^a$



Developed Equations (using Subcell Strains)



Transverse Tensile Test Global Axial Strain



Local Subcell Strains

- Strains are found using the optical measurement system
- In the end, there are 6 variables (Q11,Q12,Q22,Q66,Ny^a,Ny^b) and 6 equations
  - 2 from TT Subcells A and C (CLPT)
  - 2 from TT Subcells B and D (CLPT)
  - 1 from volume fraction averages (Micromechanics)
  - 1 from AT Subcells A and C (CLPT)
- Solve simultaneously

Material Card
MAT_RATE_SENSITIVE_COMPOSITE_FABRIC

```
$$$$ USING AS TESTED T700s/PR520 Material Properties and mat 158
*MAT_RATE_SENSITIVE_COMPOSITE_FABRIC
$       MID        RO        EA        EB      (EC)      PRBA      TAU1    GAMMA1
         11 6680E-04   7.45E+6   3.63E+6                 .071
$       GAB       GAC       GCA    SLIMT1    SLIMC1    SLIMT2    SLIMC2     SLIMS
  2.75E6                                                    1
$      AOPT     TSIZE     ERODS      SOFT        FS
        2.0                   1                  -1
$                                      A1        A2        A3
                                      0.0       1.0       0.0
$                                      D1        D2        D3
                                      1.0       0.0       0.0
$      E11C      E11T      E22C      E22T       GMS
      0.018    0.0216     0.011    0.0168     0.012
$        XC        XT        YC        YT        SC
   5.469E+4  1.515E+5   5.00E+4   5.25E+4  4.457E+4
$         K
   6.762E+6
```

Controls elastic/plastic behavior of failure

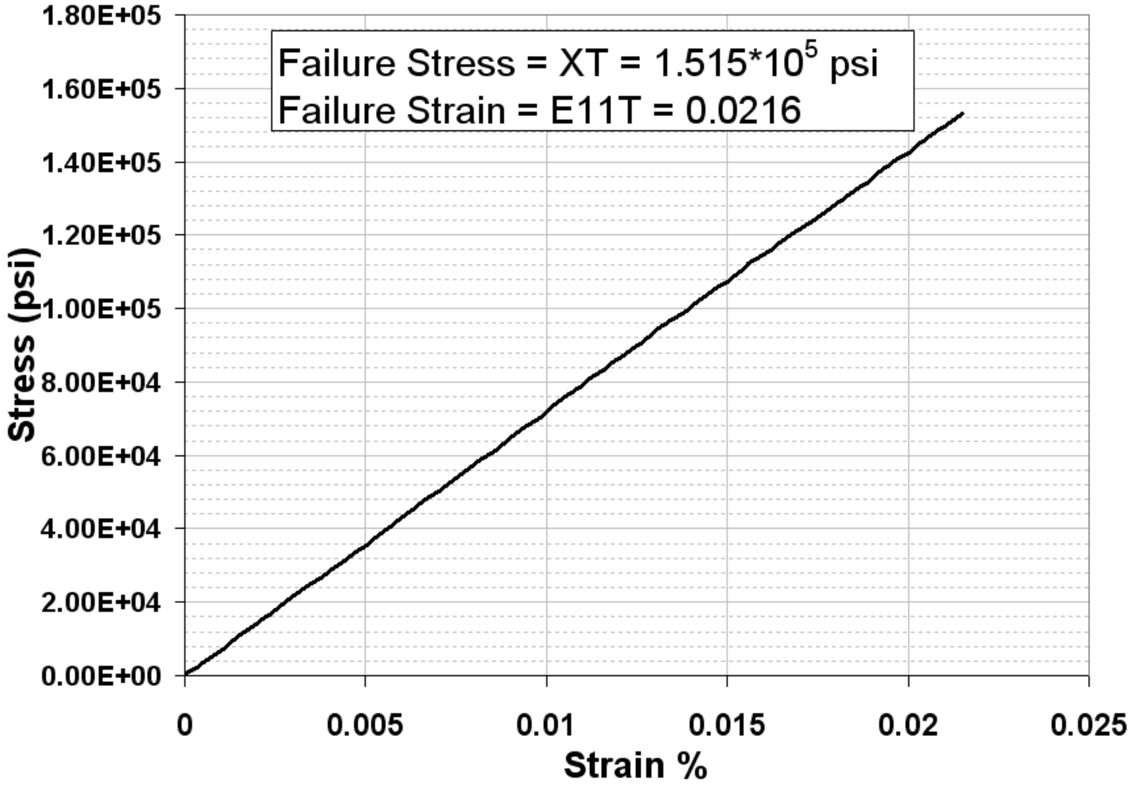
Material Coordinate Definition

Material Response Properties	
Property	Value
EA	Axial Modulus
EB	Trans. Modulus
PRBA	In Plane Poisson
GAB	In Plane Shear Mod.

Failure Properties			
Property	Name	Property	Value
E11C	Comp. strain (Ax.)	XC	Comp. strength (Ax.)
E11T	Tens. Strain (Ax.)	XT	Tens. Strength (Ax.)
E22C	Comp. strain (Trans.)	YC	Comp. Strength (Trans.)
E22T	Tens. strain (Trans.)	YT	Tens. Strength (Trans.)
GMS	Shear strain	SC	Shear Strength

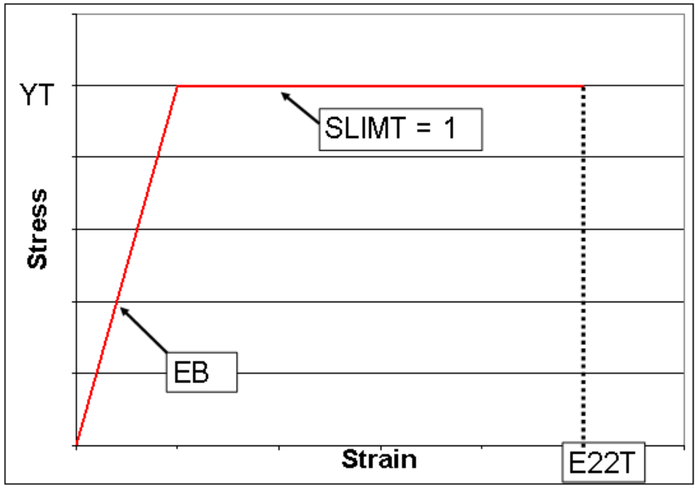
Axial Tensile (AT) Strength

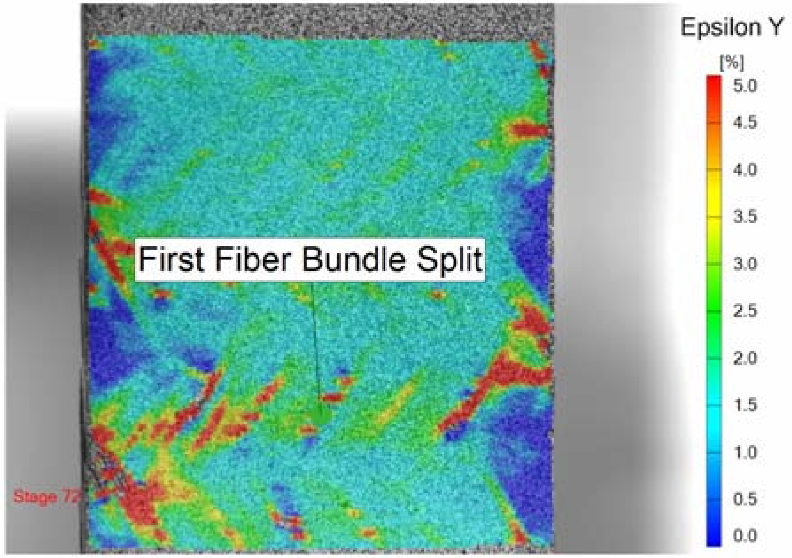
- Assume that in AT tests, the AT fiber carries most of the load
- E11T comes from ultimate strain at AT failure

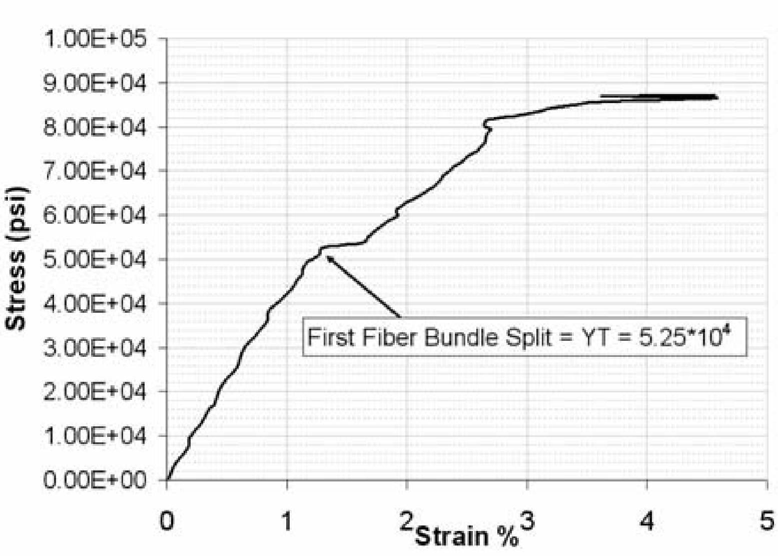


Transverse Tensile (TT) Strength

- Look at fiber splitting on TT specimen
- Load at first split will be YT
- SLIMT will be set to 1
- E22T will be set to failure strain of test

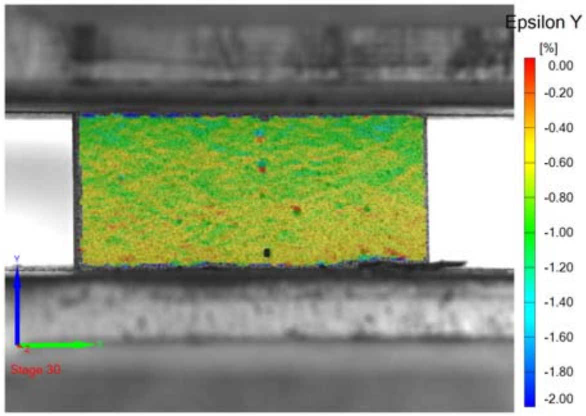


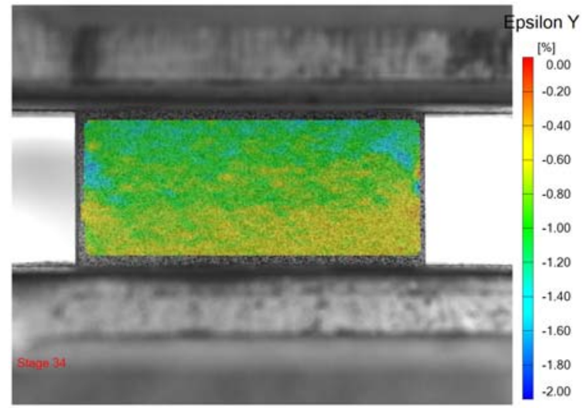


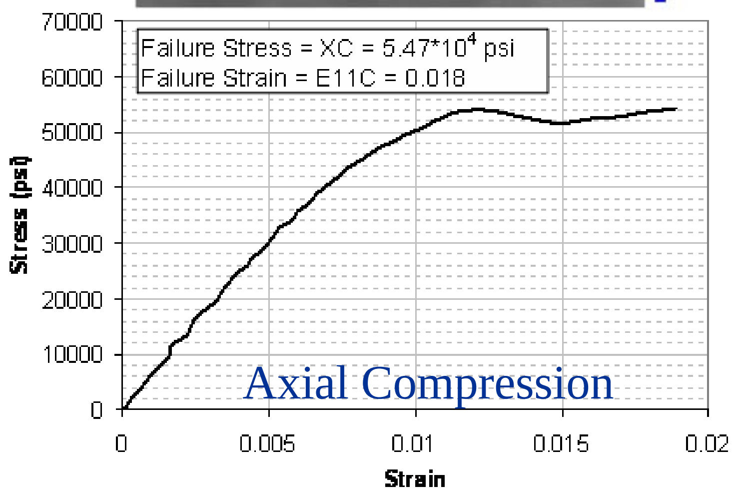


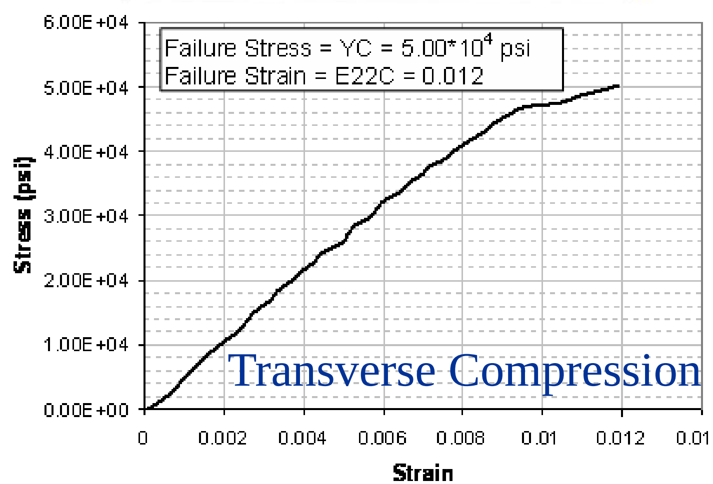
Compressive Strain/Strength

- Material behaves as a homogenous
  - Use strength at failure for both Axial and Transverse tests
  - Use strain at strength for both Axial and Transverse tests



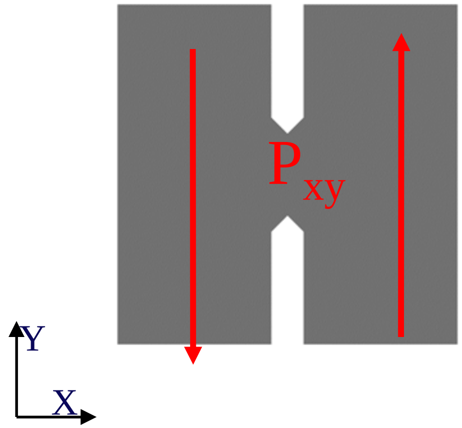


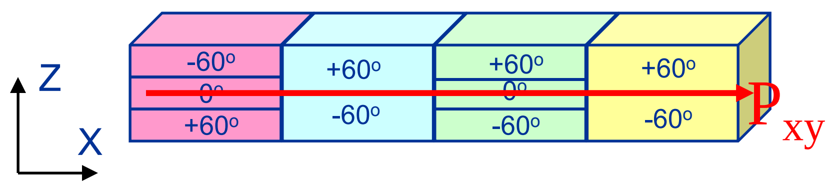


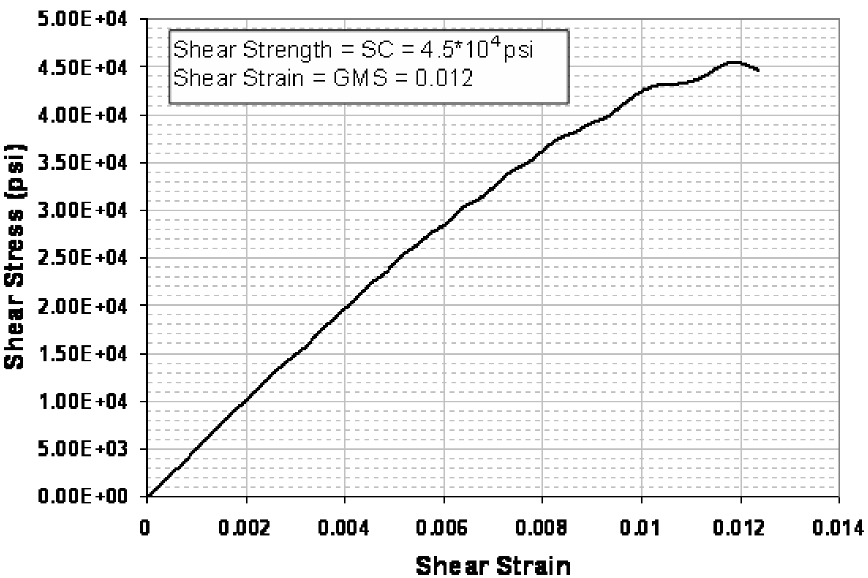


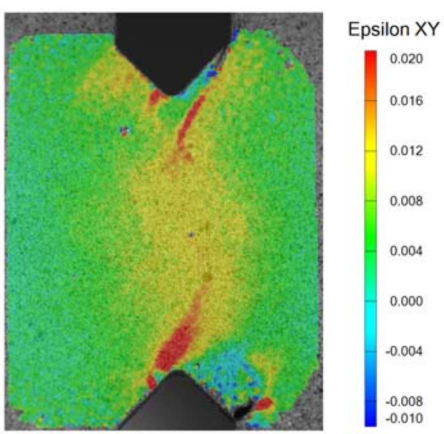
Shear Strength

- Using Modified Shear Specimen Design based on Kohlman
  - **ASTM 5379**
- P_{xy}, N_{xy} is for each of the integration layers
  - Can be directly implemented for shear strength
- LS-DYNA needs ε_{xy} for GMS

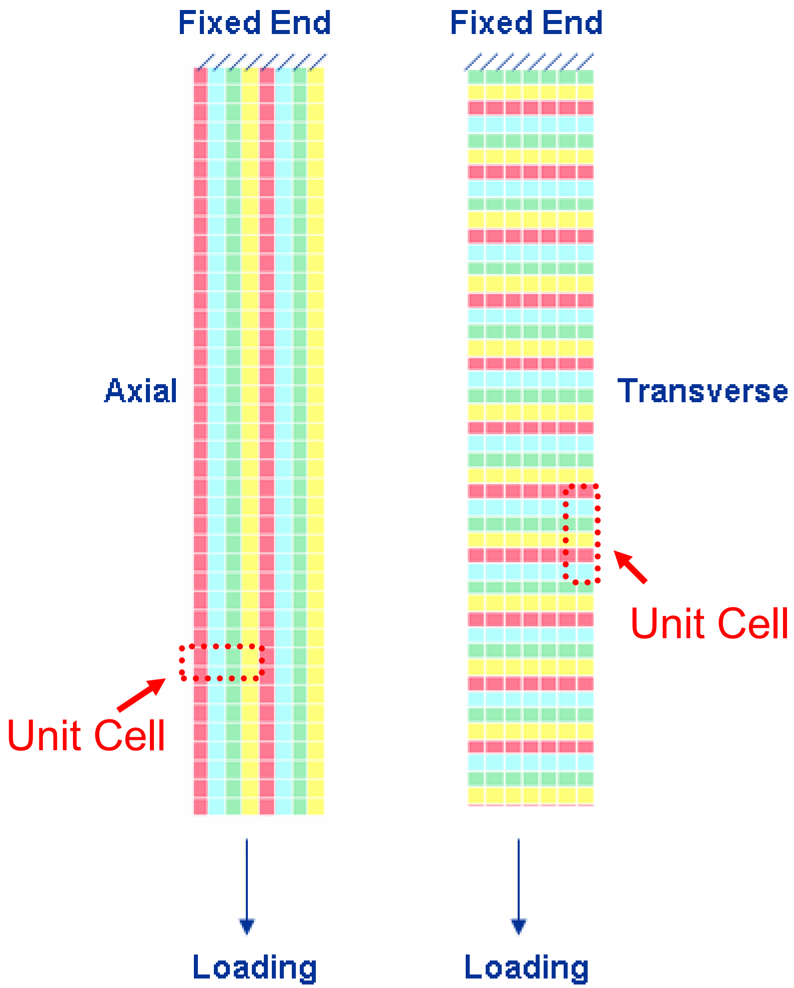








Finite Element Models



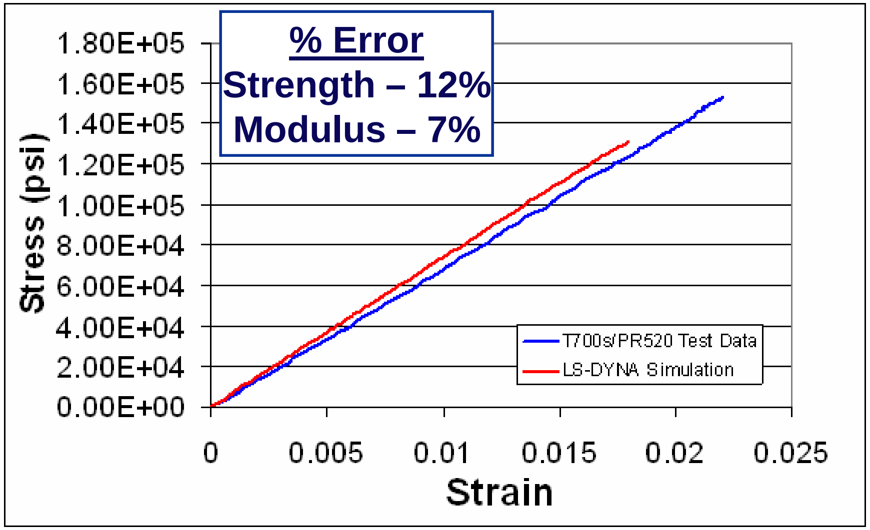
- Both Axial and Transverse Specimens were developed using ASTM D3039 specimen geometries
- Fixed end boundary conditions were used to simulate the fixed grip
- Loading was applied at the opposite end using enforced displacement

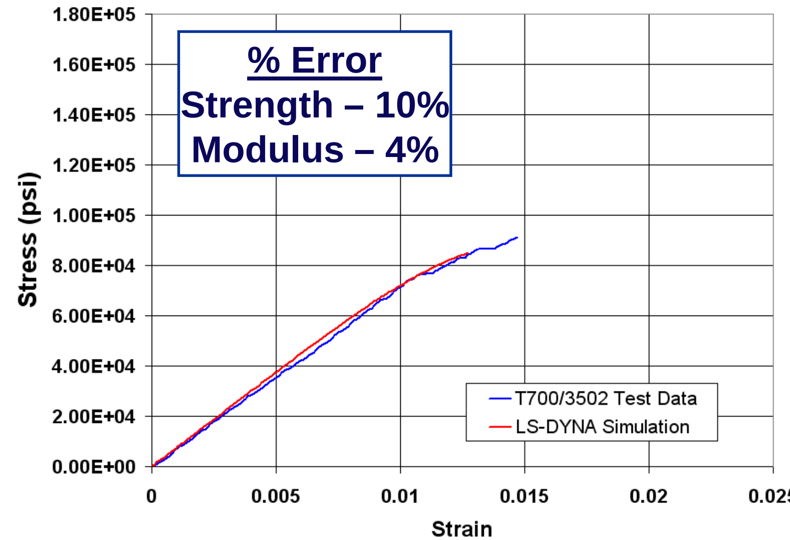
Static Results

T700 / PR520

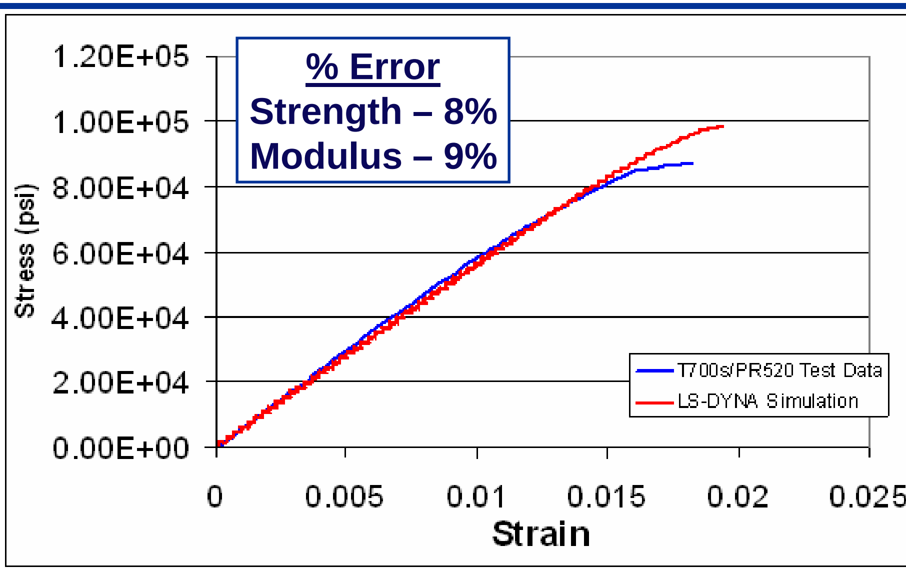
T700 / 3502

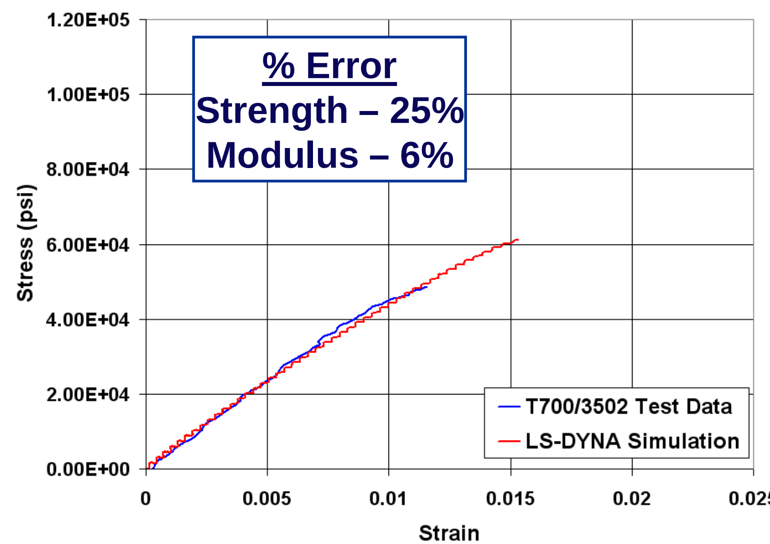
Axial Tension



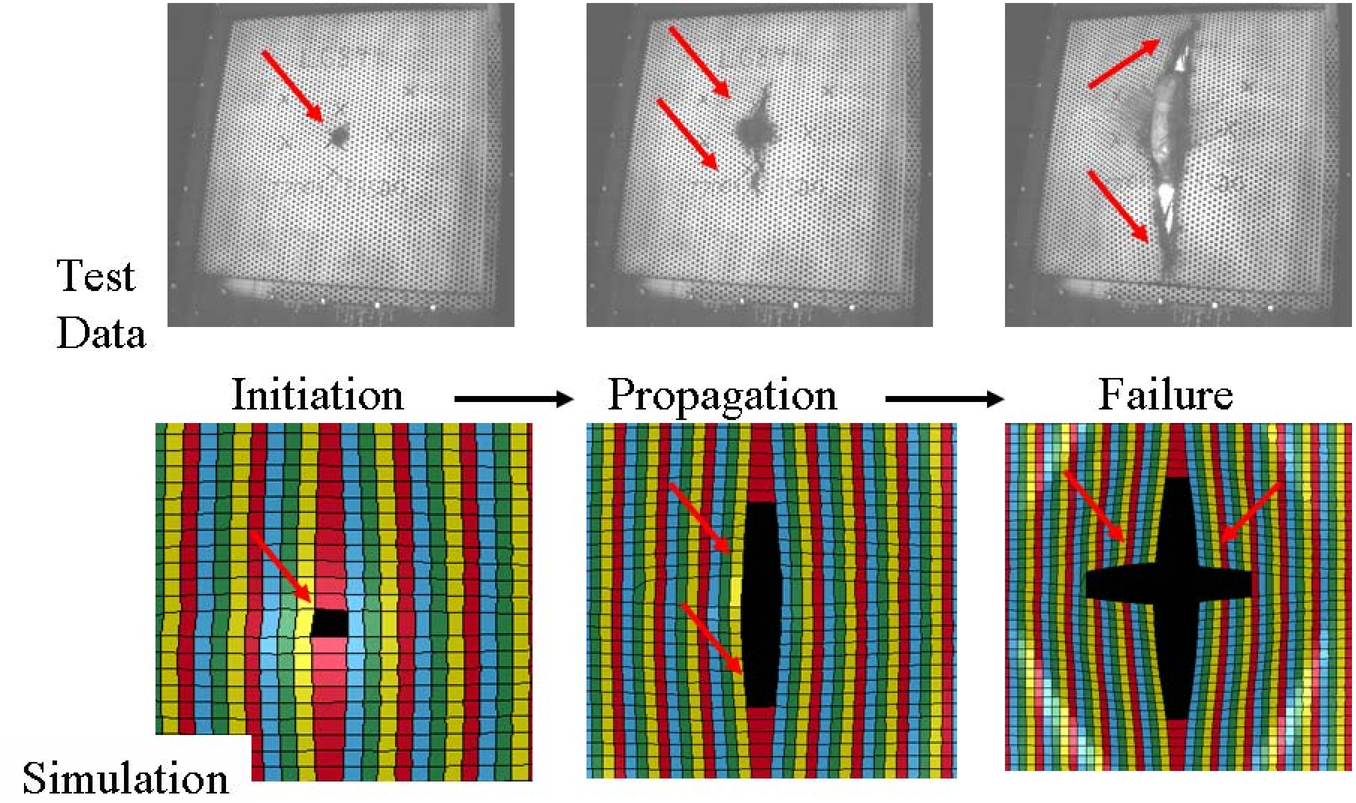


Transverse Tension



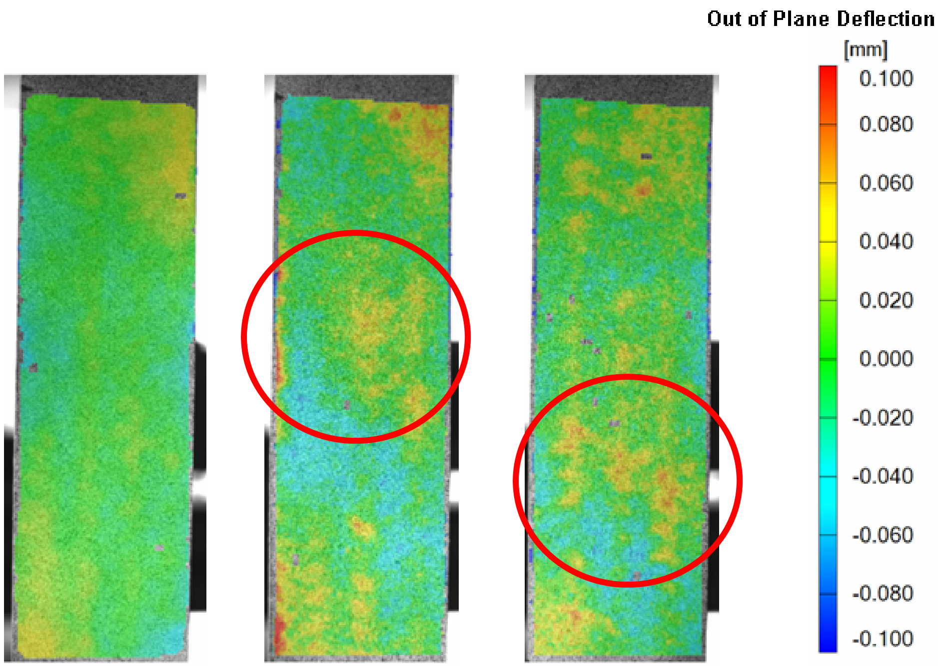


Determination of T700 fiber / PR520 Resin Impact Characteristics



- Simulations were completed Spring 2008
  - Showed penetration threshold at 630 ft / sec
- Used as a starting point for impact tests
- Impact tests conducted Summer 2008
  - Penetration threshold was between 609 and 637 ft / sec

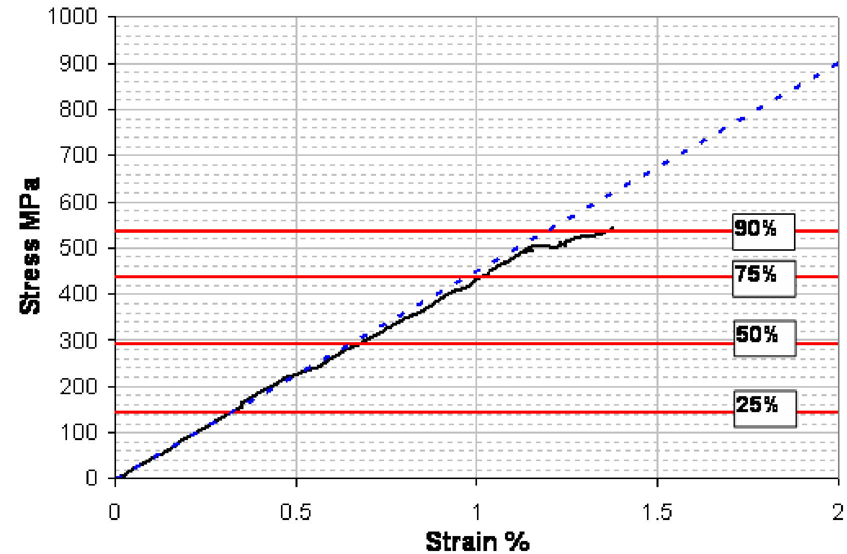
Limitations: Delaminations for T700 fiber / 3502 resin



50%
292 MPa

75%
439 MPa

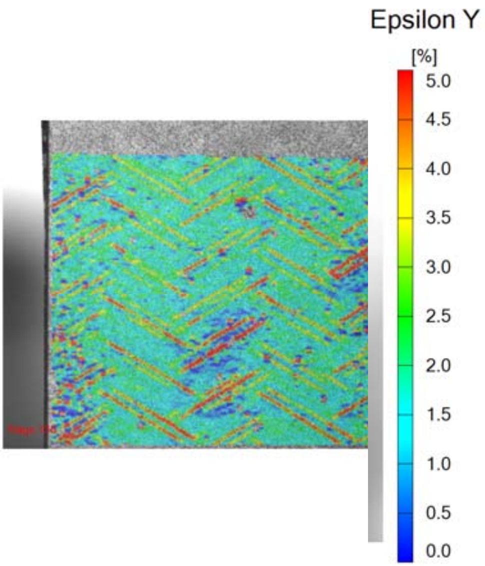
90%
535 MPa

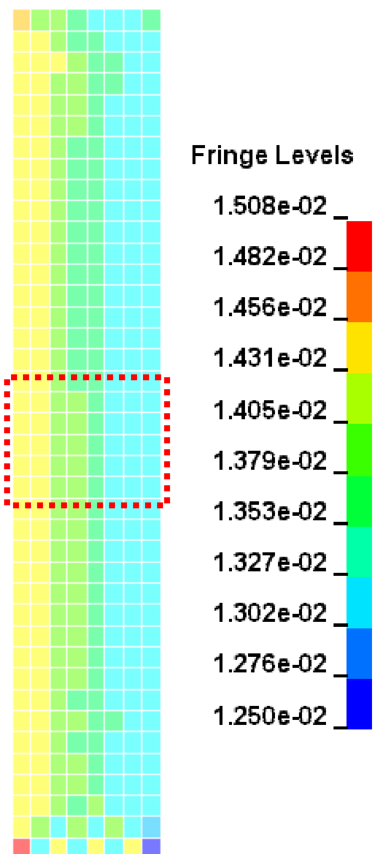


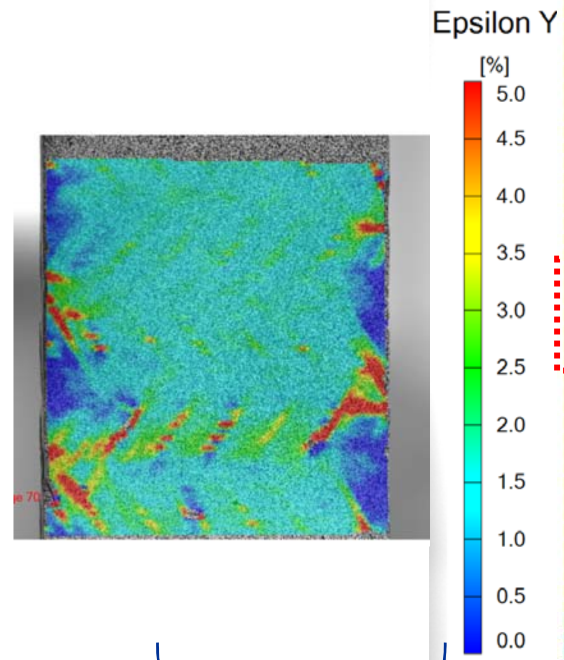
- OOP displacements verified by NDE
- Global Material response curves become non-linear after delaminations occurred
- Due to the nature of integration point formulation, cannot simulate ultimate failure values between layers

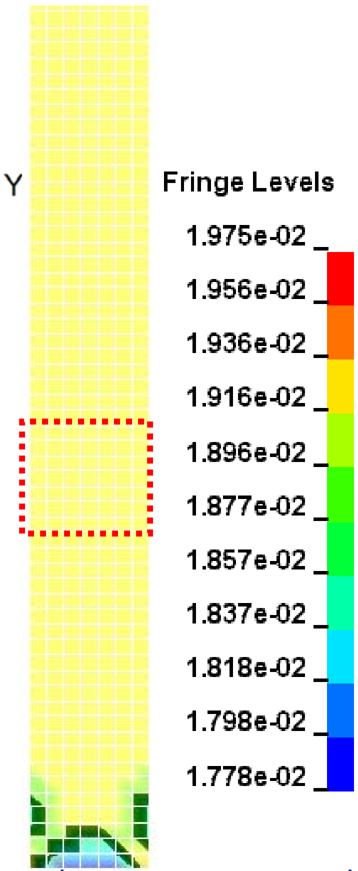
Limitations: FEM cannot simulate fiber bundle splitting

- Axial Tension (axial strain)
- Transverse Tension (axial strain)









Optical Measurements | LS-DYNA | Optical Measurements | LS-DYNA

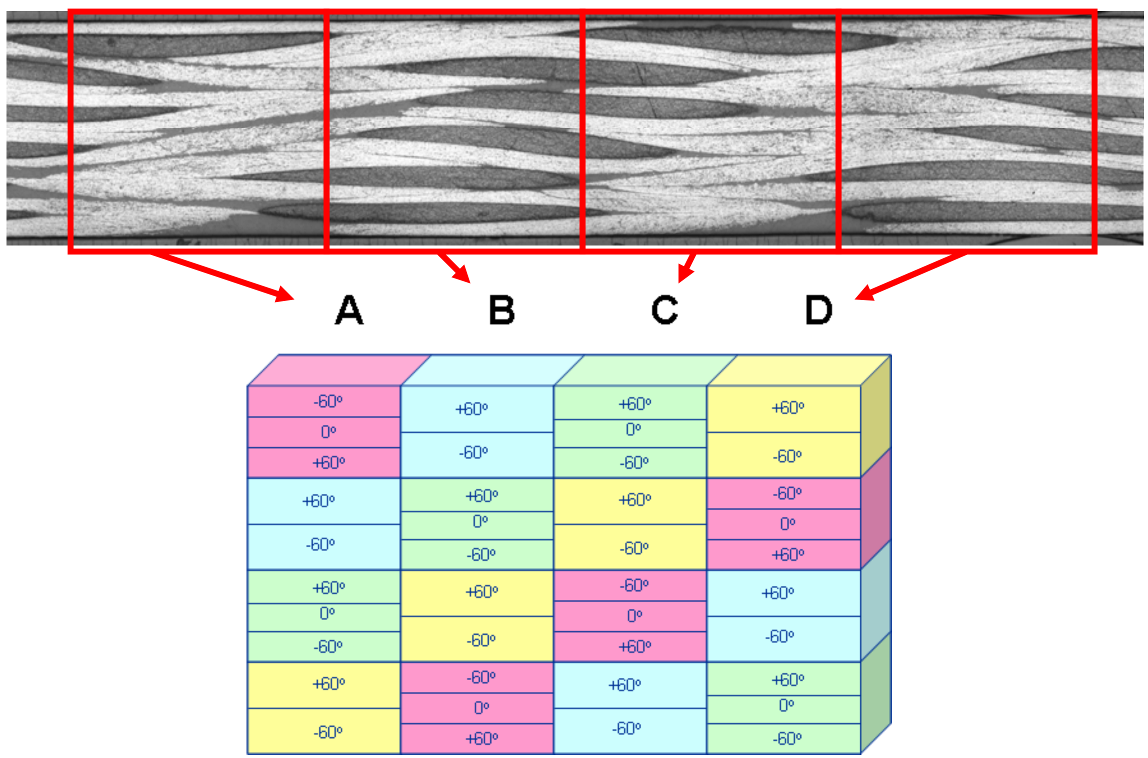
Conclusion

- Standardized test methods in conjunction with an optical measurement system have been used to collect material property data for triaxial braided composite materials
  - Global material response curves
  - Local transverse fiber bundle splitting
  - Local subsurface delaminations
- A hybrid micro-macromechanical computer model has been developed
  - Incorporates braid architecture
  - Incorporates tested material property data
- Comparisons between test and simulation show good agreement
  - 10% in static simulations
  - Penetration threshold in impact simulations
- Factors seen in the test data cannot be simulated as of now
  - Ongoing work

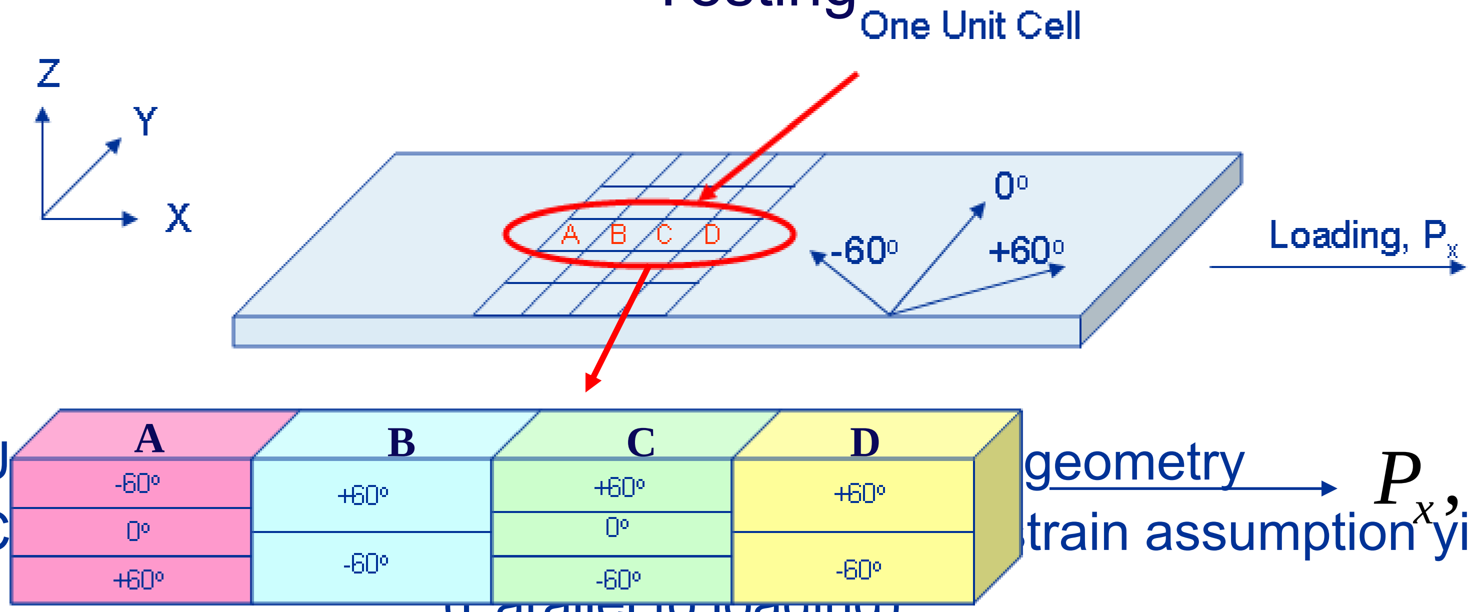
Backup

Defining the Braid Geometry (Section)

- Each part has unique section properties
  - Each section contains information about number of layers (15) and braid angle (Θ) at each layer
- Braid was modeled as layers of unidirectional lamina
  - Shifted (Idealized)



Equation Development – Transverse Tensile Testing



- U… geometry → P_x, N_x
- C… train assumption yields
- (Parallel to loading)
- (Perpendicular to loading)

$$N_x^a = N_x^b = N_x^c = N_x^d$$

$$V_f^a * N_y^a = V_f^b * N_y^b$$

Rewriting the equations for each Subcell (Transverse Tensile Testing)

- Subcell A
  - N_x is applied load and all strains are found from optical measurement system

$$N_x^a = A11^a * \varepsilon_x^a + A12^a * \varepsilon_y^a$$

$$N_y^a = A12^a * \varepsilon_x^a + A22^a * \varepsilon_y^a$$

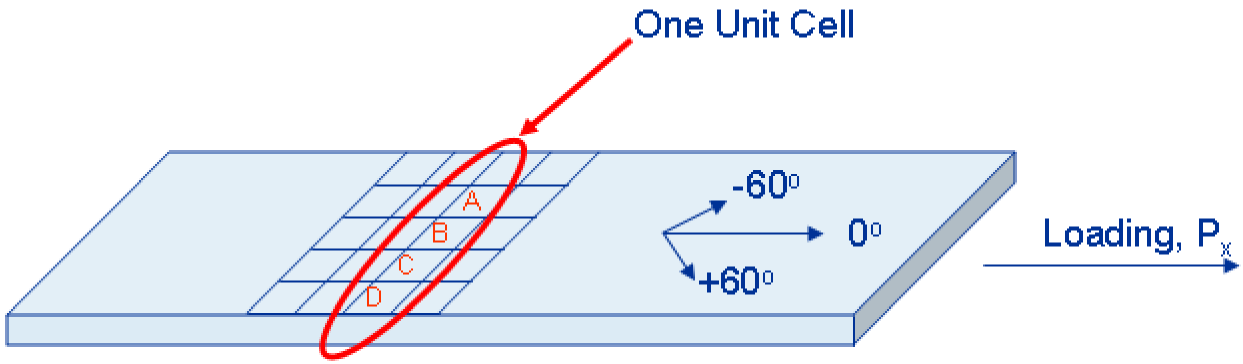
- Subcell B
  - N_x is applied load and all strains are found from optical measurement system

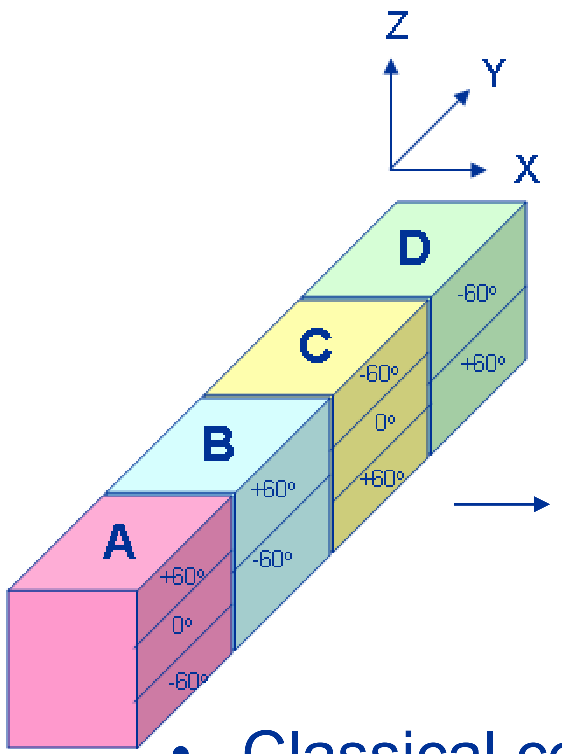
$$N_x^b = A11^b * \varepsilon_x^b + A12^b * \varepsilon_y^b$$

$$N_y^b = A12^b * \varepsilon_x^b + A22^b * \varepsilon_y^b$$

- Four Equations

Equation Development – Axial Tensile Testing





$$P_x, N_x$$

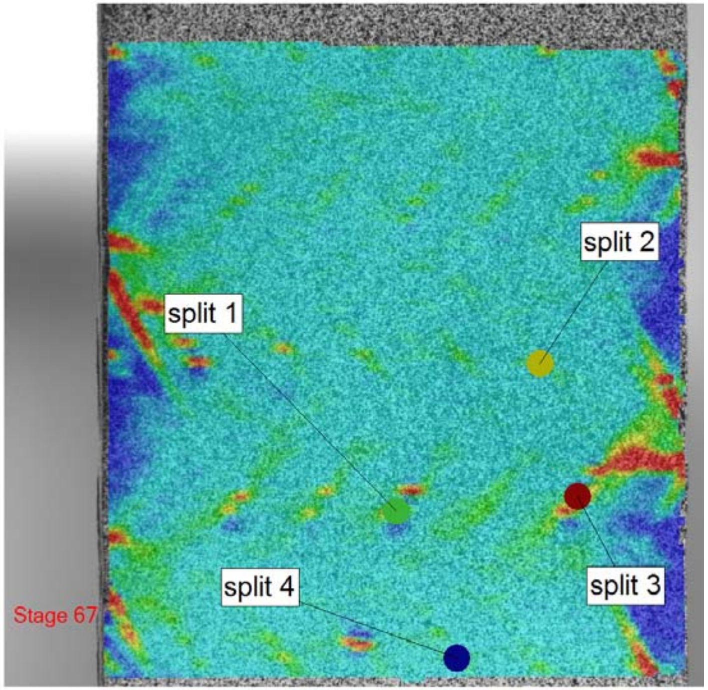
- Classical composite laminate micromechanics assumptions yield

$$N_y^a = N_y^b = N_y^c = N_y^d = 0$$

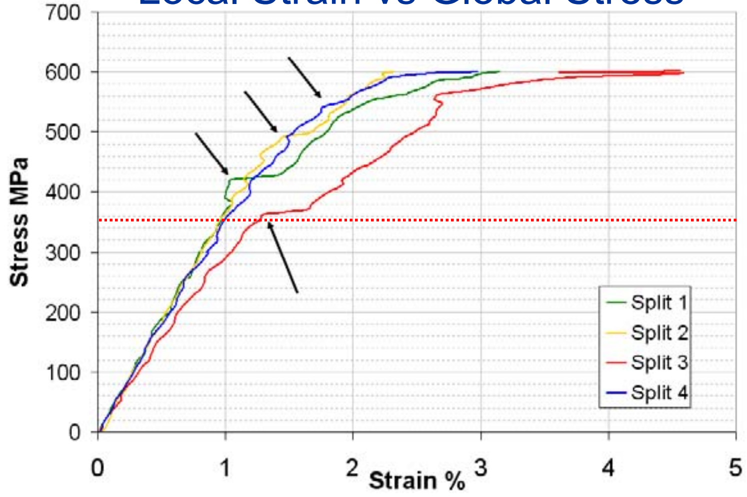
$$N_y^a = 0 = A12^a * \varepsilon_x^a + A22^a * \varepsilon_y^a$$

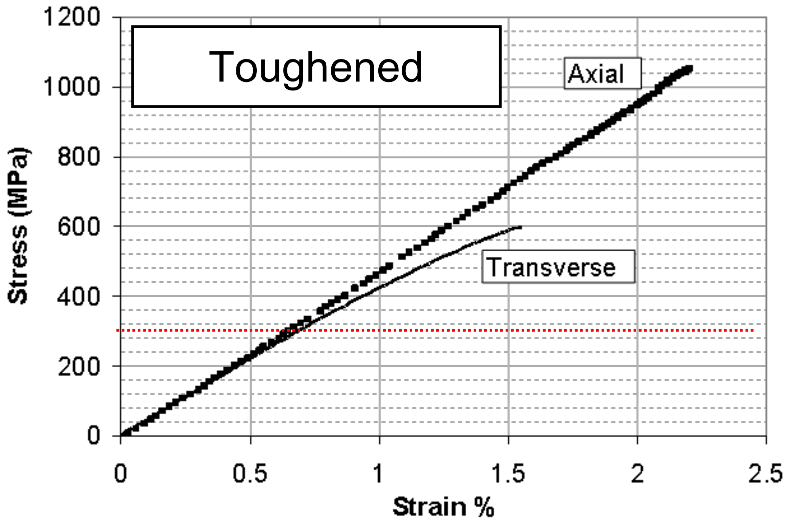
Advanced Data Analysis

Toughened Fiber Bundle Splitting – Transverse Testing



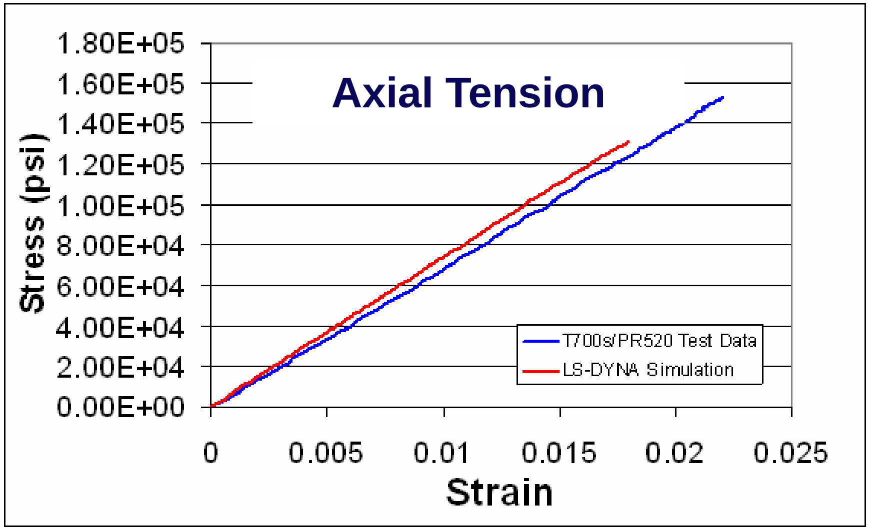
Local Strain vs Global Stress





- Identify local failure strain
- Local failure initiation correlations to global non-linearities

T700 Fiber / PR520 Resin Static Results



	Axial Tension Modulus (psi)	*Axial Tension Strength (psi)*
Test	6.8E6±1.6E5	1.52E5±4.9E3
LS-DYNA	7.4E6	1.31E5
% Error	7%	12%

	Transverse Tension Modulus (psi)	*Transverse Tension Strength (psi)*
Test	6.2E6±2.3E5	8.69E4±4.3E2
LS-DYNA	5.6E6	9.38E4
% Error	9%	8%