

APPROACHES FOR TENSILE TESTING OF BRAIDED COMPOSITES

For angleply composites, lamina tension and compression strengths are commonly determined by applying classical lamination theory to test data obtained from testing of angleply composite specimens. For textile composites such as 2D triaxial braids, analysis is more complex and standard test methods do not always yield reliable strength measurements. This paper describes recent research focused on development of more reliable tensile test methods for braided composites and presents preliminary data for various approaches.

The materials investigated in this work have $0^\circ/\pm 60^\circ$ 2D triaxial braid architecture with nearly equal fiber volume fraction in each of the three fiber directions. Flat composite panels are fabricated by resin transfer molding (RTM) using six layers of the braided preform aligned along the 0° fiber direction. Various epoxy resins are used as matrix materials. Single layer panels are also fabricated in order to examine local variations in deformation related to the braid architecture. Specimens are cut from these panels in the shape of standard straight-sided coupons, an alternative “bowtie” geometry, and an alternative “notched” geometry. Axial tensile properties are measured using specimens loaded along the 0° fiber direction. Transverse tensile properties are measured using specimens loaded perpendicular to the 0° fibers. Composite tubes are also fabricated by RTM. These tubes are tested by internal pressurization using a soft rubbery material sealed between the inside diameter of the tube and the load fixtures. The ends of the tube are unconstrained, so the primary load is in the hoop direction. Tubes are fabricated with the 0° fibers aligned along the tube axis by overbraiding the preform on a mandrel. Since the loading is in the hoop direction, testing of the overbraided tube provides a measure of transverse tensile strength.

Previous work has indicated that straight-sided coupons yield a transverse tensile strength that is much lower than the expected material strength because of premature edge-initiated failure. Full-field strain measured during transverse tensile tests clearly showed accumulation of edge damage prior to failure. In the current work, high speed video and testing of single layer specimens are used to investigate potential failure mechanisms in more detail. High speed video clearly shows the edge initiation in six layer transverse tensile test coupons. Specimens with the bowtie geometry and the notched geometry minimize this edge effect and yield significantly higher transverse tensile strength values compared to the straight-sided coupons. However, bowtie and notched specimens geometries are not ideal because of the non-uniform stress and strain fields in the region of failure. Testing of tubes using internal pressurization eliminates edge-initiated failure and provides a more uniform state of stress and strain. Preliminary results indicate that bowtie, notched, and tube specimens yield comparable values for transverse tensile strength and that these values are much higher than the strength measured using a straight-sided coupon.



Approaches for Tensile Testing of Braided Composites

Gary D. Roberts and Jonathan A. Salem
NASA Glenn Research Center, Cleveland, Ohio

Justin L. Bail
Ohio Aerospace Institute, Cleveland, Ohio

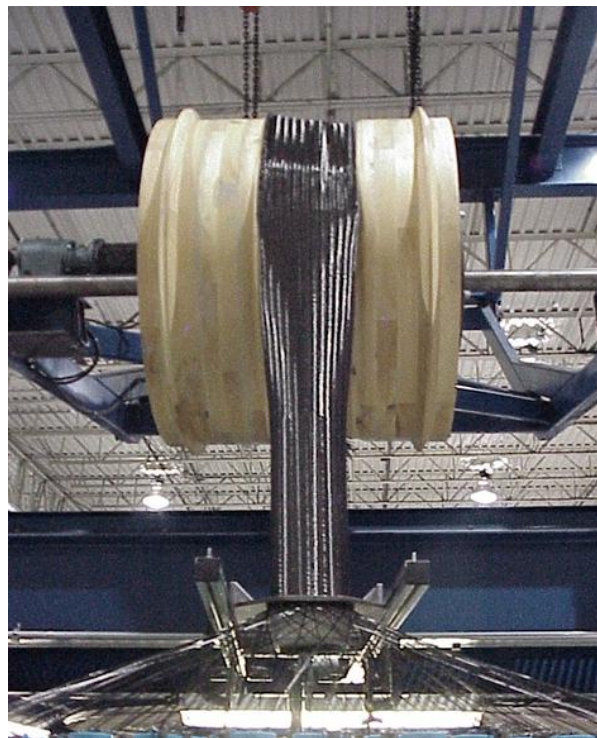
Lee W. Kohlman and Wieslaw K. Binienda
The University of Akron, Akron, Ohio

Richard E. Martin
Cleveland State University, Cleveland, Ohio

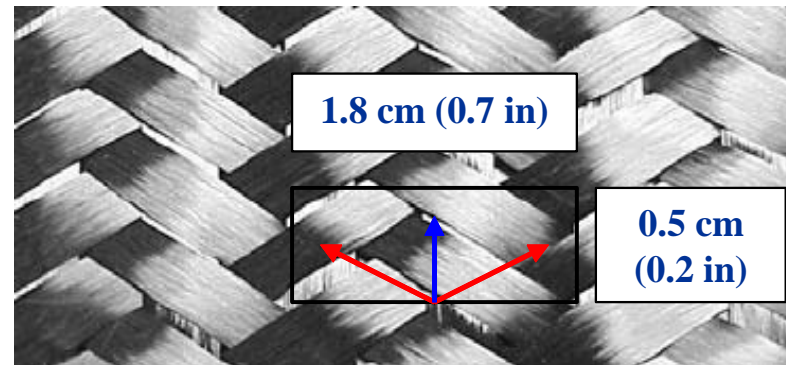
Braiding approach for composite fan cases

Preform fabrication

(A&P Technology, Cincinnati, Ohio)



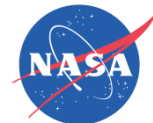
0/+60/-60 braid architecture



Braid architecture effects

- Minimizes interlaminar stresses
 - Reduces delamination
- Increases intralaminar stresses
 - Causes local damage within the unit cell
 - Causes excessive edge damage in straight-sided test coupons

- Need to know what fiber/matrix combinations give the best balance of static strength and impact strength
- Improved test methods are needed to measure static strength

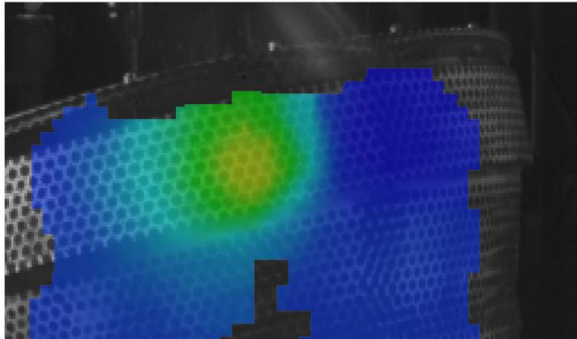


Materials

- High strength, standard modulus carbon fiber
 - Torayca® T700S fiber (Toray)
 - Strength: 4,900 MPa (711 ksi)
 - Modulus: 230 GPa (33.4 Msi)
 - Elongation: 2.1 %
- 350°F cure epoxy matrix resins
 - CYCOM® PR520 RTM (Cytec)
 - EPIKOTE™ 862 /EPI-Cure Curing Agent W (Resolution Performance Products)
 - CYCOM® 5208 (Cytec)
 - 3502 (Hexcel)
- Composite (fabricated by resin transfer molding)
 - 0/+60/-60 2D triaxial braid preform, 536 g/m², 6 layers
 - 0.125 in thick, 0.028 in/ply (3.18 mm thick. 0.53 mm/ply)
 - 56% fiber volume fraction

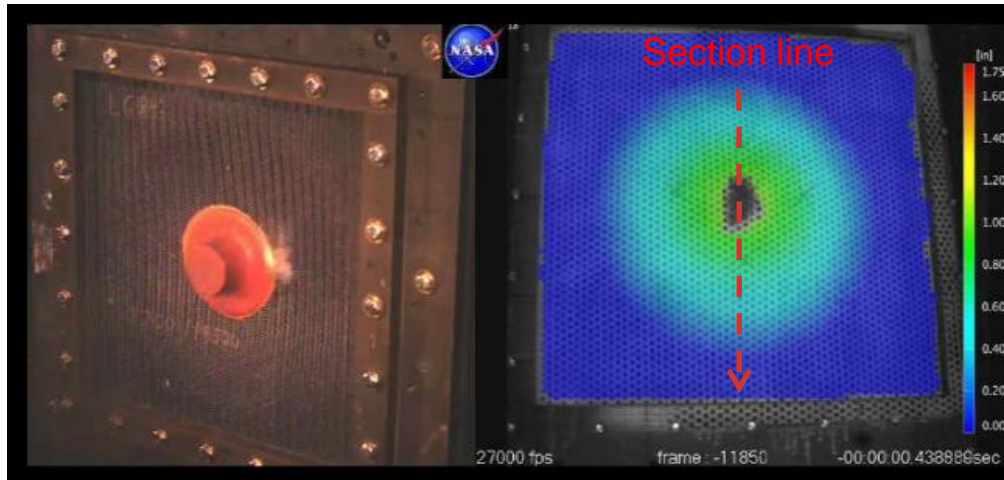
Failure initiation during impact

Composite case test (Out of plane deformation)

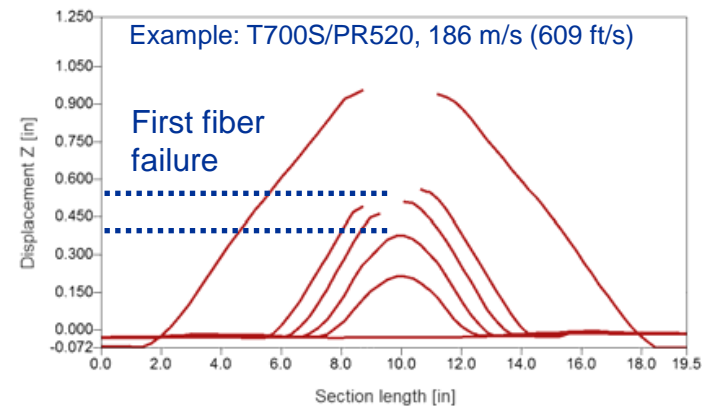


- Panel tests simulate deformation and failure in case tests
 - Reference: Roberts et al., 19th ISABE Conference (ISABE 2009) sponsored by the International Society for Air Breathing Engines, Montreal, Canada, September 7-11, 2009. (Also NASA/TM-2009-215811)
- Deformation is measured by digital image correlation (DIC)
- Calculated strain is limited by
 - Camera resolution and frame rate
 - Software settings used for DIC (e.g. facet size and filtering)
- First fiber failure during impact seems to occur at a higher strain than expected based on static test data

Composite panel test [2 ft X 2 ft (0.61 m X 0.61 m) panels]



Out of plane displacement along a section line at 37 μ s time steps





Impact strength vs static tensile strength

(Straight-sided coupons used for tensile data)

Material	Axial tensile loading			Transverse tensile loading			Impact penetration threshold		
	Strength (MPa)	Modulus (GPa)	Failure Strain (%)	Strength (MPa)	Modulus (GPa)	Failure Strain (%)	Measured (m/s)	Scaled by transverse strength	Scaled by axial strength
T700S/PR520	1046	47.6	2.16	599	42.0	1.69	186 - 194	186 - 194	186 - 194
T700S/E-862	800	46.9	1.78	462	41.6	1.44	Incomplete data	143 - 150	142 - 148
T700S/5208	693	47.5	1.51	310	41.3	0.85	172 - 179	96 - 100	123 - 129
T700S/3502	608	47.2	1.51	336	40.6	1.00	> 216	104 - 109	108 - 113



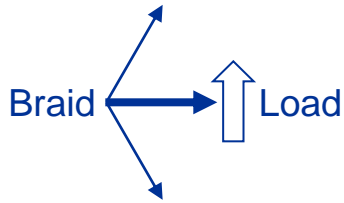
Scaling based on static strength underestimates measured impact strength



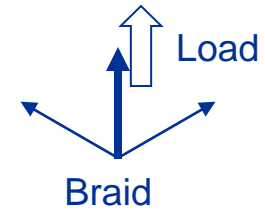
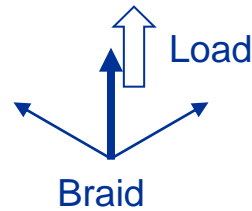
Limitations of straight-sided coupons for measuring strength

Tensile loading of straight-sided coupons (Local damage)

Transverse loading



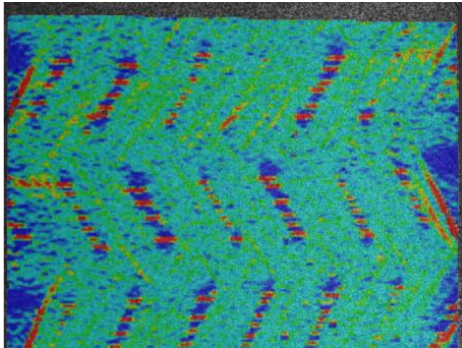
Axial loading



Strain in load direction

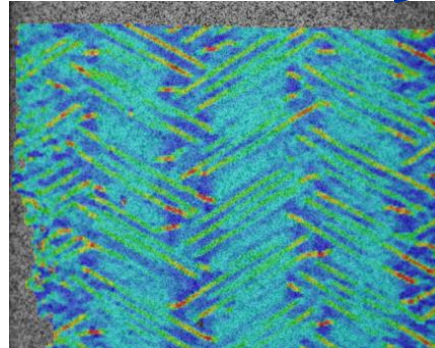
Out-of-plane deformation

Edge damage
(blue regions on edges)

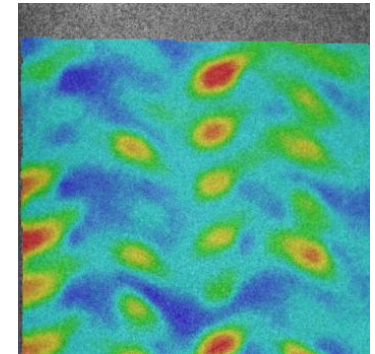


Axial tow splits

Possible
edge damage



Bias tow splits



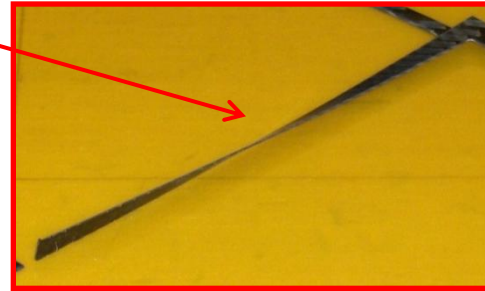
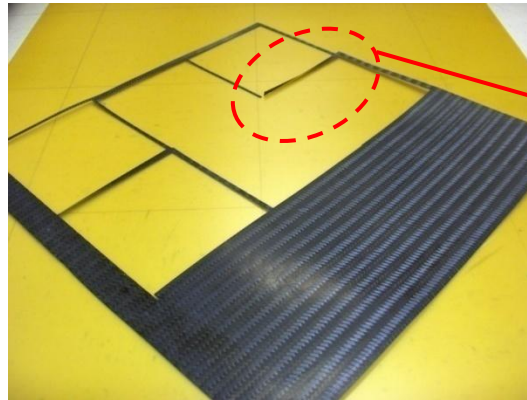
Delamination
between tows

- Interior damage is a characteristic of the bulk material
- Edge damage is a result of stresses and unconstrained fiber tows at specimen edges

Deformation of a single layer laminate

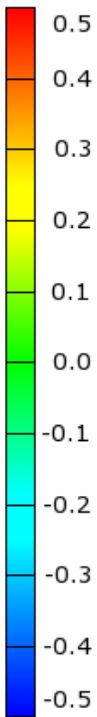
Effect of laminate unbalance at the unit cell level

Flat 2 ft X 2 ft
(0.61m X 0.61m)
panel



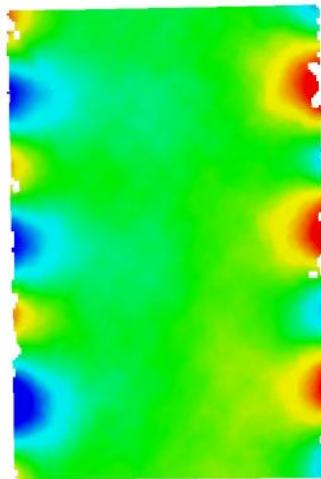
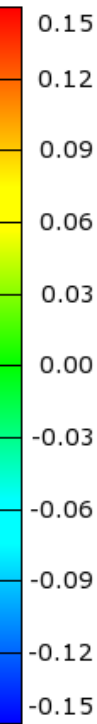
Twisted (+60/0/-60)
strip containing one
axial tow

[mm]



Out of plane displacement induced by in-plane tensile loading (A custom script is used to measure deviations from the best fit plane)

[mm]

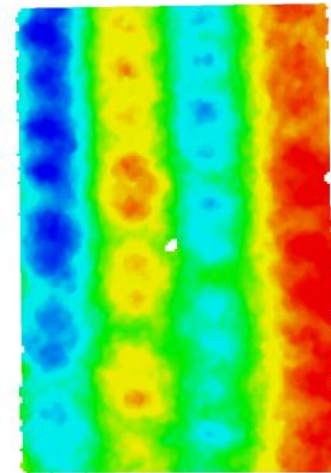


Localized
edge
displacement
and damage

Transverse load

Horizontal
undulations

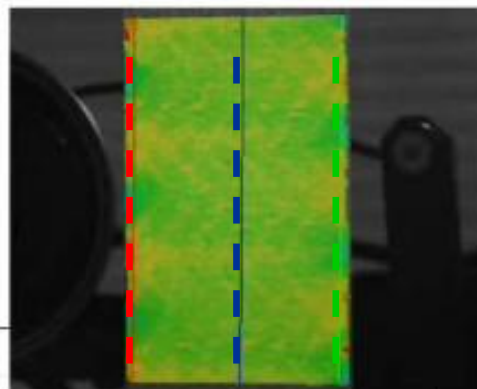
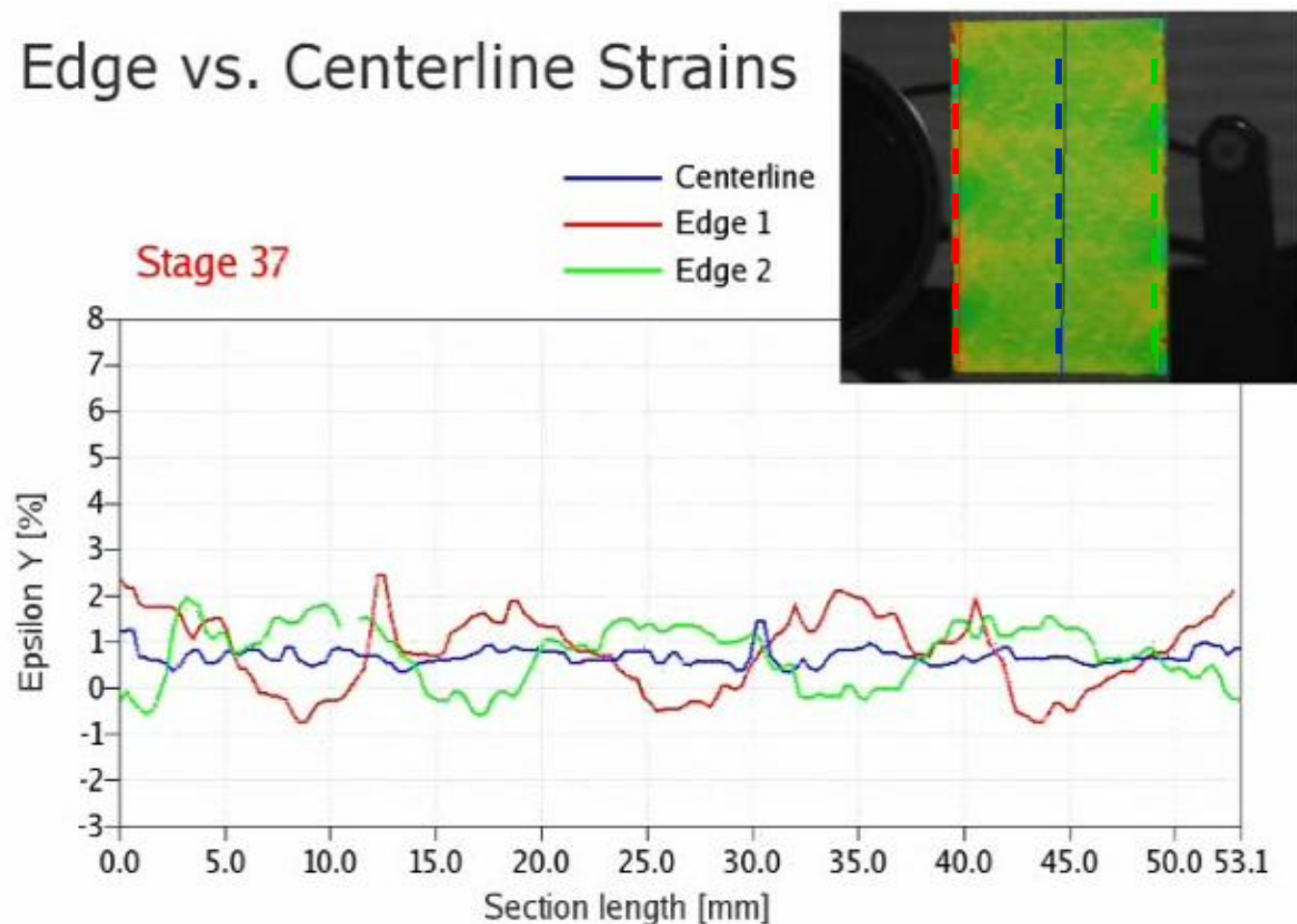
Axial load



Deformation and failure of a single layer laminate (T700S/E-862 material)

Damage evolution during transverse tensile loading

Edge vs. Centerline Strains



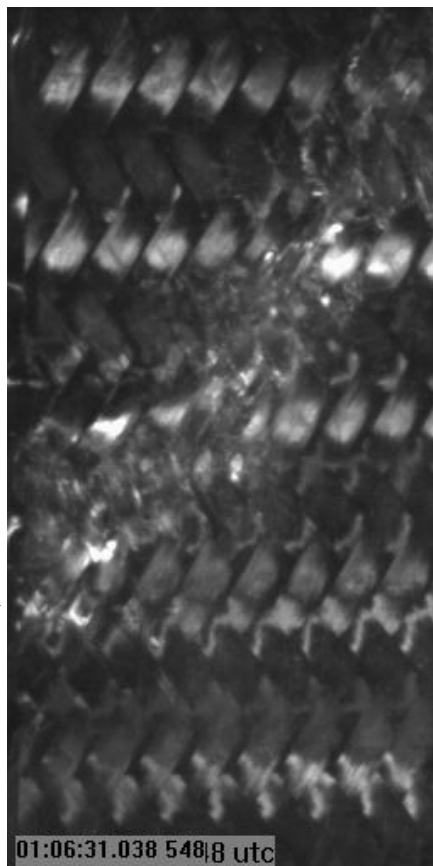
Edge-initiated
shear failure



Deformation and failure of 6 ply laminates (T700S/E-862 material)

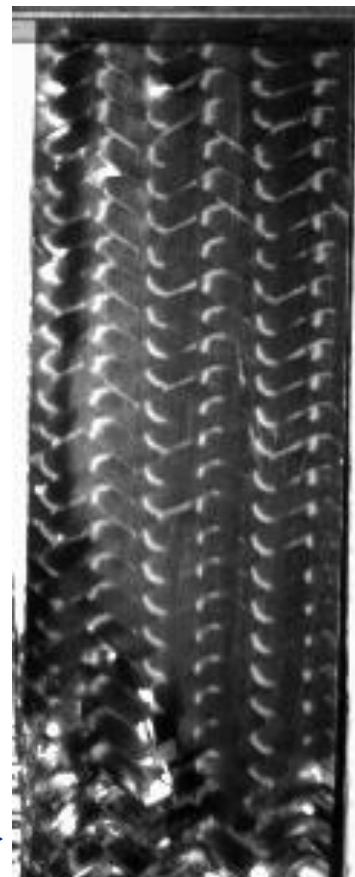
High speed video frames just after failure initiation

Failure
initiation



Transverse loading
(Edge-initiated shear failure)

Failure
initiation



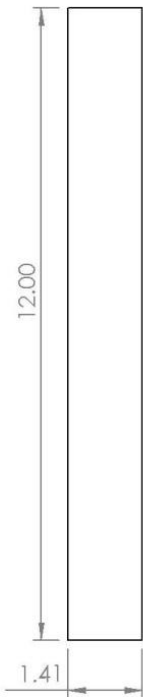
Axial loading
(Edge-initiated tensile failure)



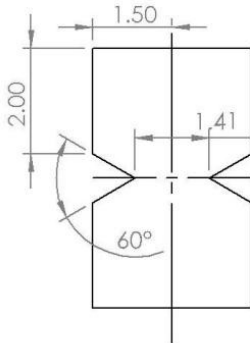
Alternative approaches for measuring tensile strength

Test method comparison for tensile strength

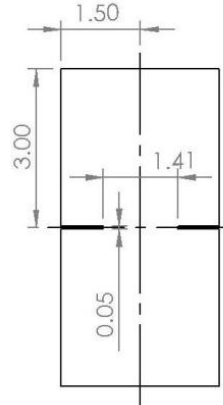
Axial Tension ASTM D 3039



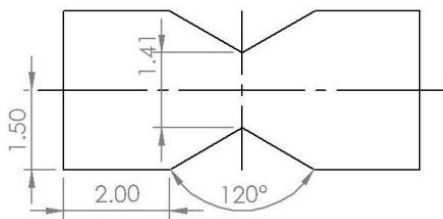
Axial Tension Bowtie



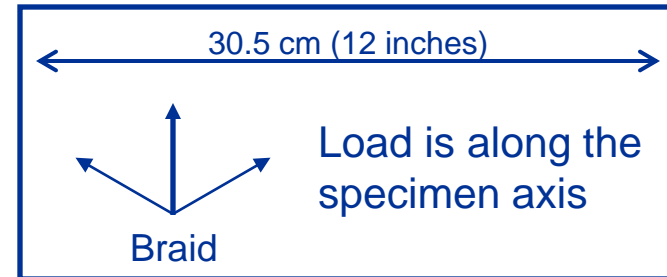
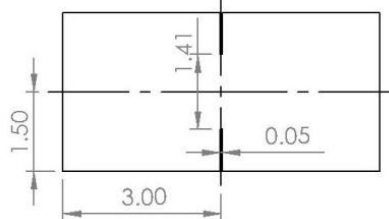
Axial Tension Notch



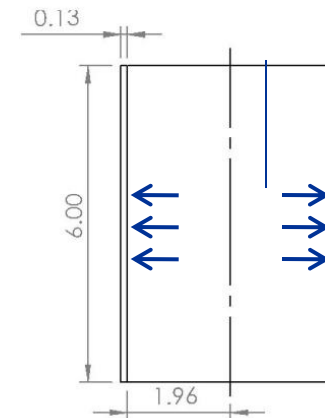
Transverse Tension Bowtie



Transverse Tension Notch



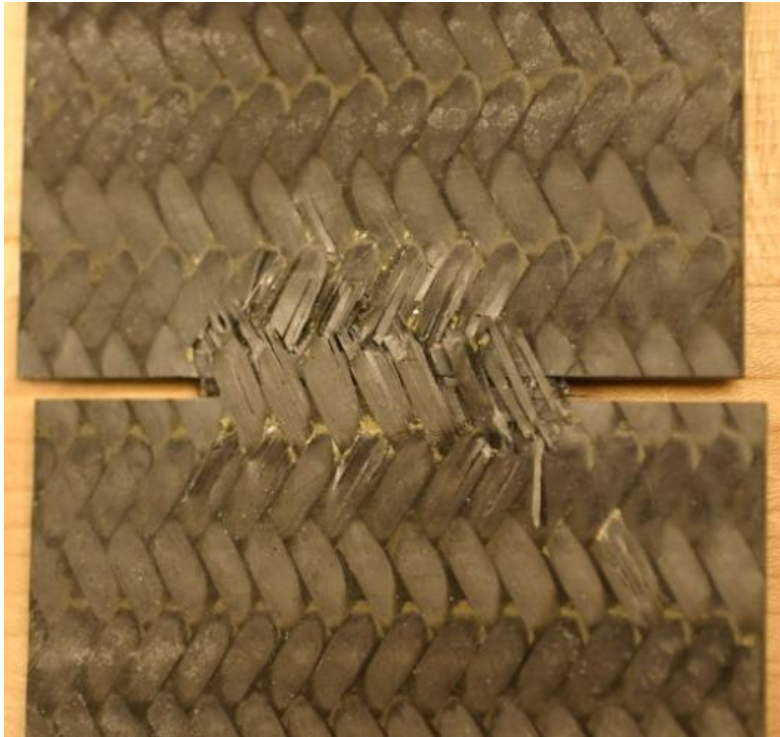
Internal Pressurization Tube



Tensile strength of T700S/E-862 (MPa)				
	Straight-sided	Bowtie	Notched	Tube ¹
Axial	800 (5)	744 (2)	765 (2)	
Transverse	462 (5)	868 (1)	813 (2)	785 (1)
1 Tube has defects along an axial mold line () = # of tests				

Tensile strength of T700S/E-862 (ksi)				
	Straight-sided	Bowtie	Notched	Tube ¹
Axial	116 (5)	108 (2)	111 (2)	
Transverse	67 (5)	126 (1)	118 (2)	114 (1)
1 Tube has defects along an axial mold line () = # of tests				

Notched transverse tensile specimen (T700S/E-862 material)



- Tensile failure mode
- No edge damage

Failure stress:

- 462 MPa - straight-sided
- 813 MPa - notched

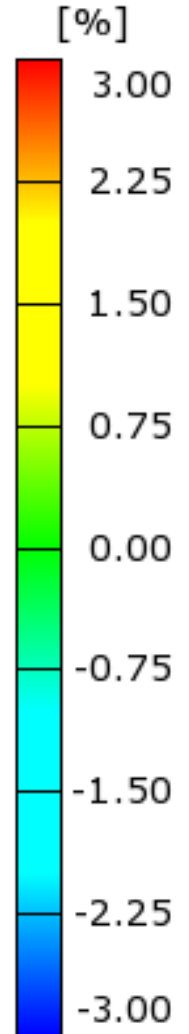
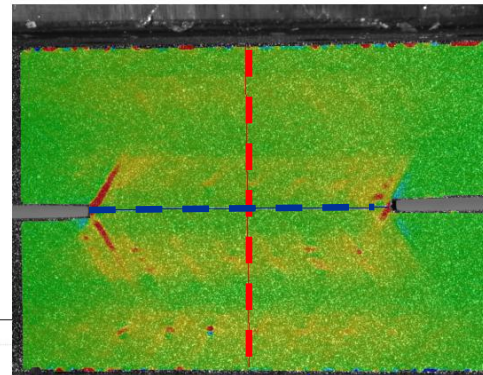
Back of specimen
(DIC measurements are made on front of specimen)

Notched transverse tensile specimen (Vertical strain)

Failure stress:

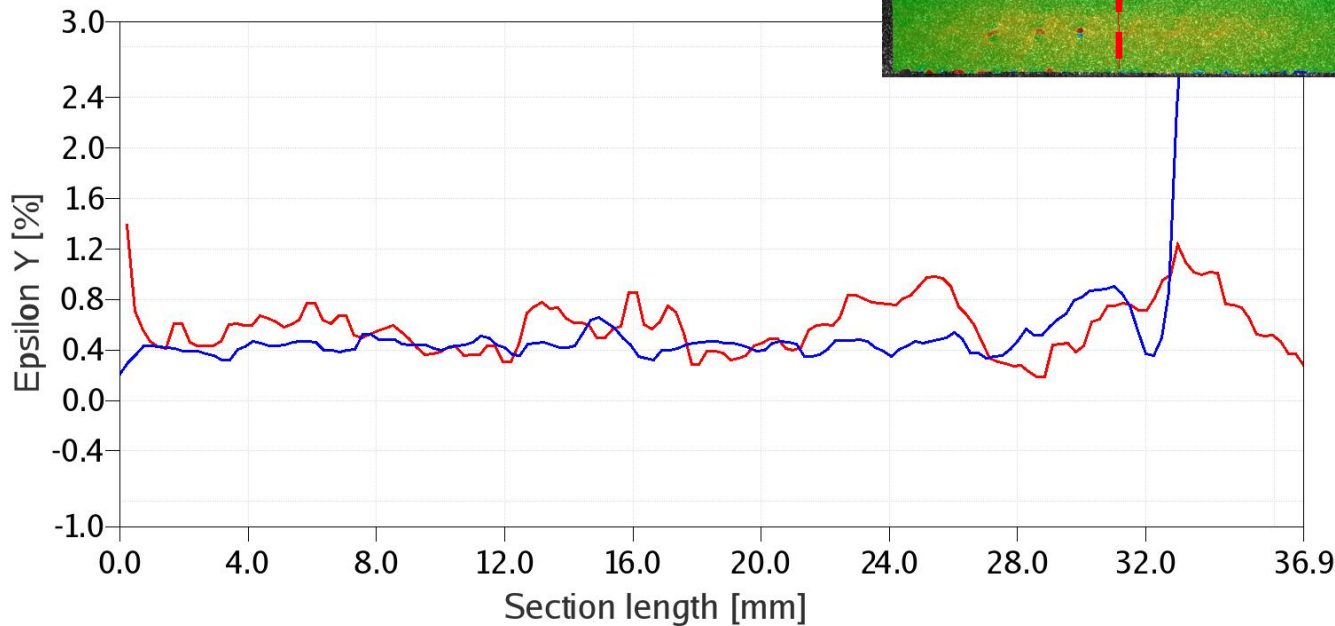
- 462 MPa - straight-sided
- 813 MPa - notched

Vertical strain
(Front of specimen)



351 MPa
Stage 64

Section lines
— Horizontal (blue)
— Vertical (red)



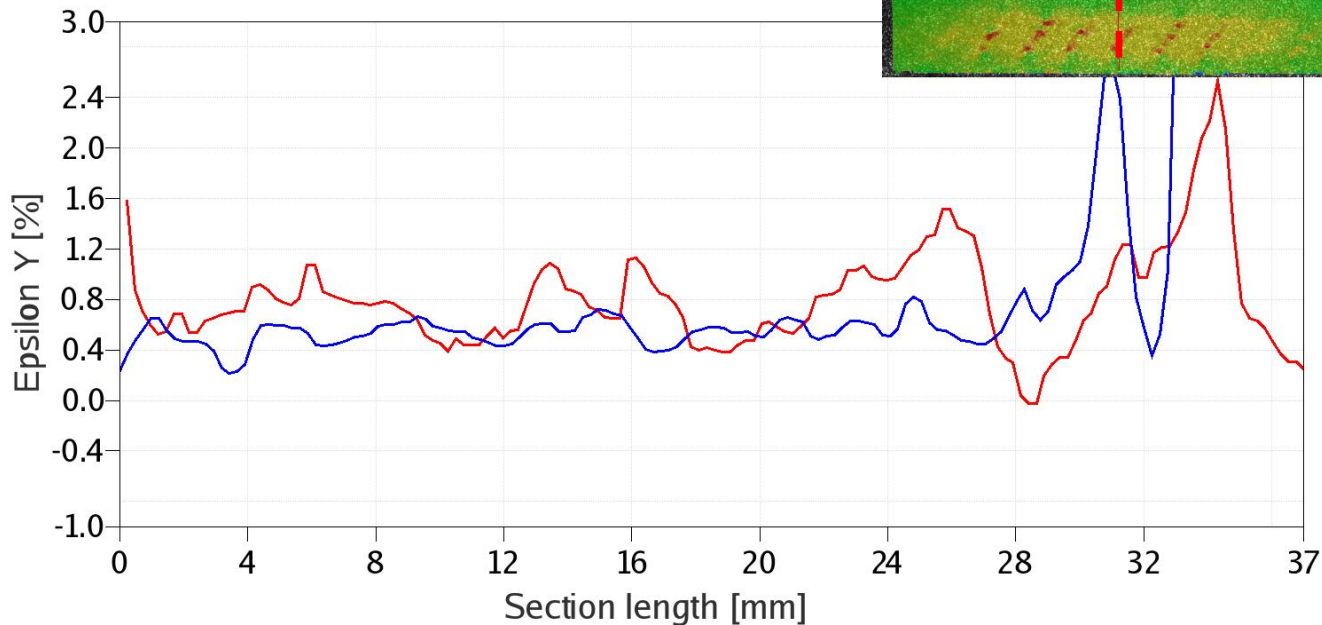
Notched transverse tensile specimen (Vertical strain)

Failure stress:

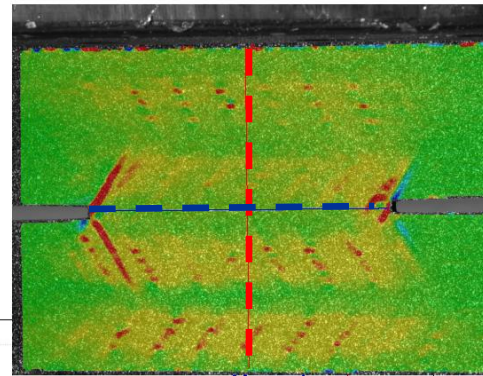
- 462 MPa - straight-sided
- 813 MPa - notched

451 MPa
Stage 85

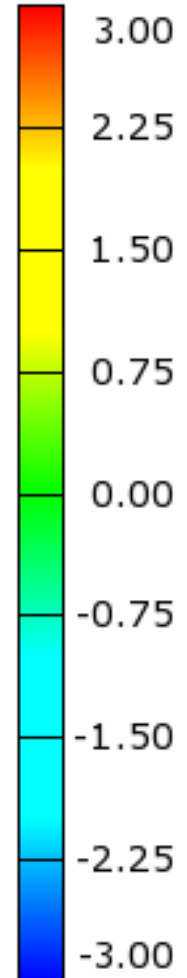
Section lines
— Horizontal
— Vertical



Vertical strain
(Front of specimen)



[%]



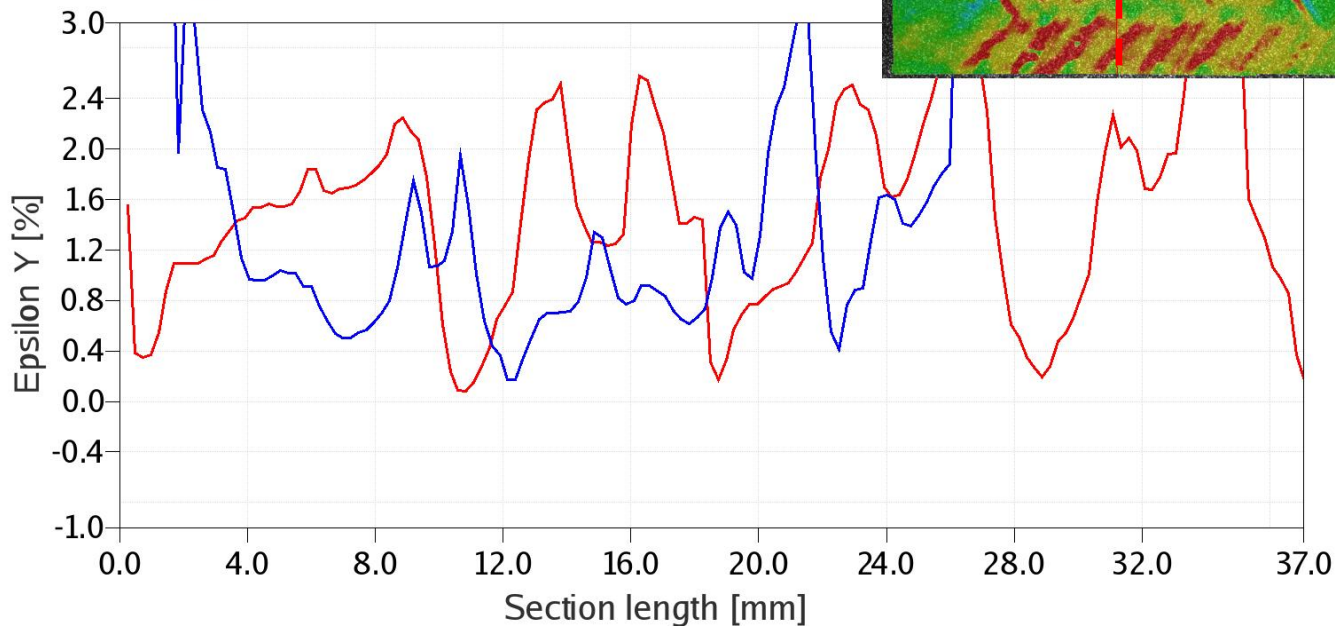
Notched transverse tensile specimen (Vertical strain)

Failure stress:

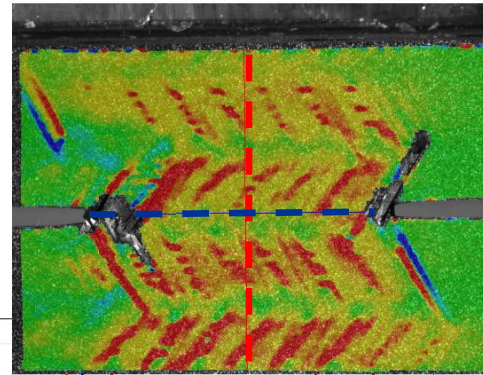
- 462 MPa - straight-sided
- 813 MPa - notched

729 MPa
Stage 162

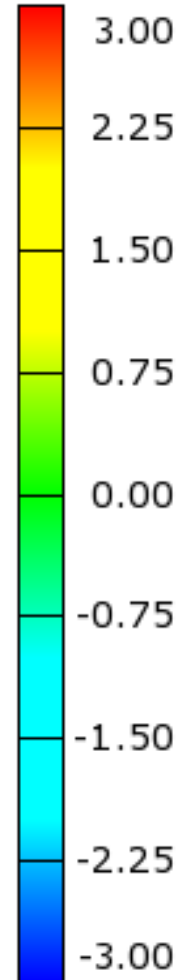
Section lines
— Horizontal
— Vertical



Vertical strain
(Front of specimen)



[%]



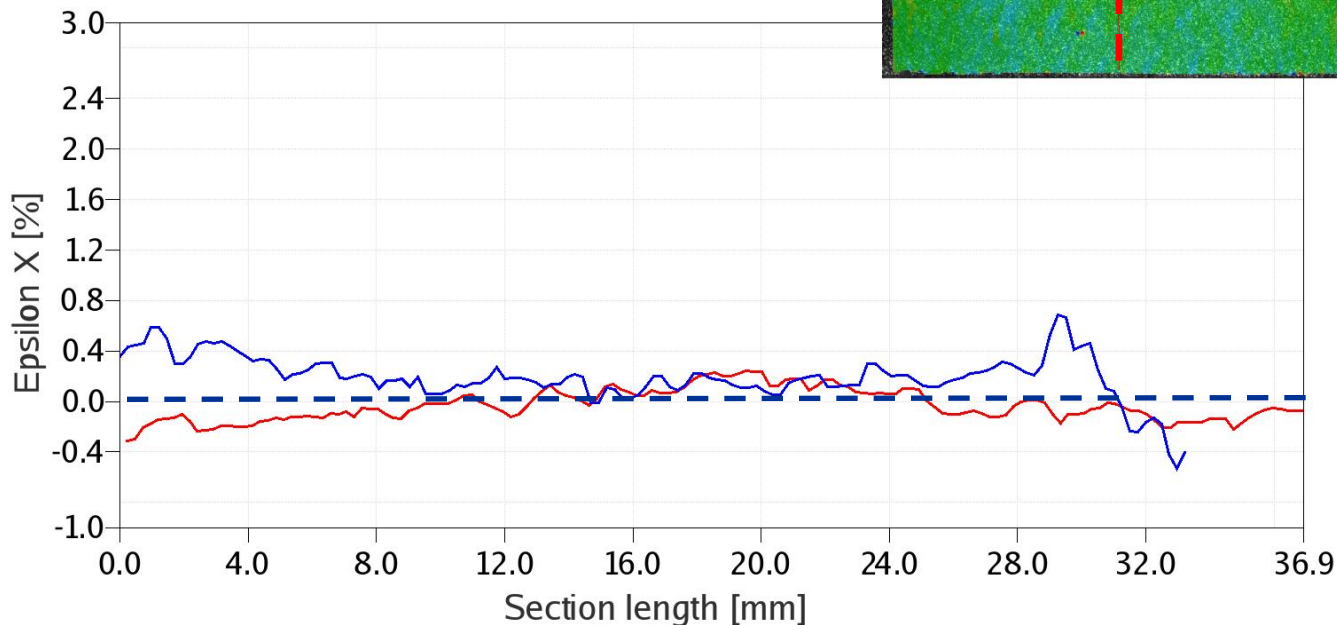
Notched transverse tensile specimen (Horizontal strain)

Failure stress:

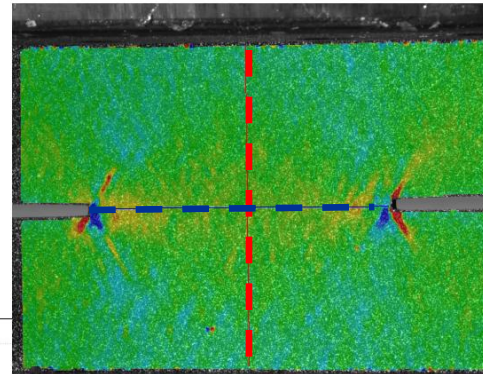
- 462 MPa - straight-sided
- 813 MPa - notched

351 MPa
Stage 64

Section lines
— Horizontal
— Vertical



Horizontal strain
(Front of specimen)



[%]



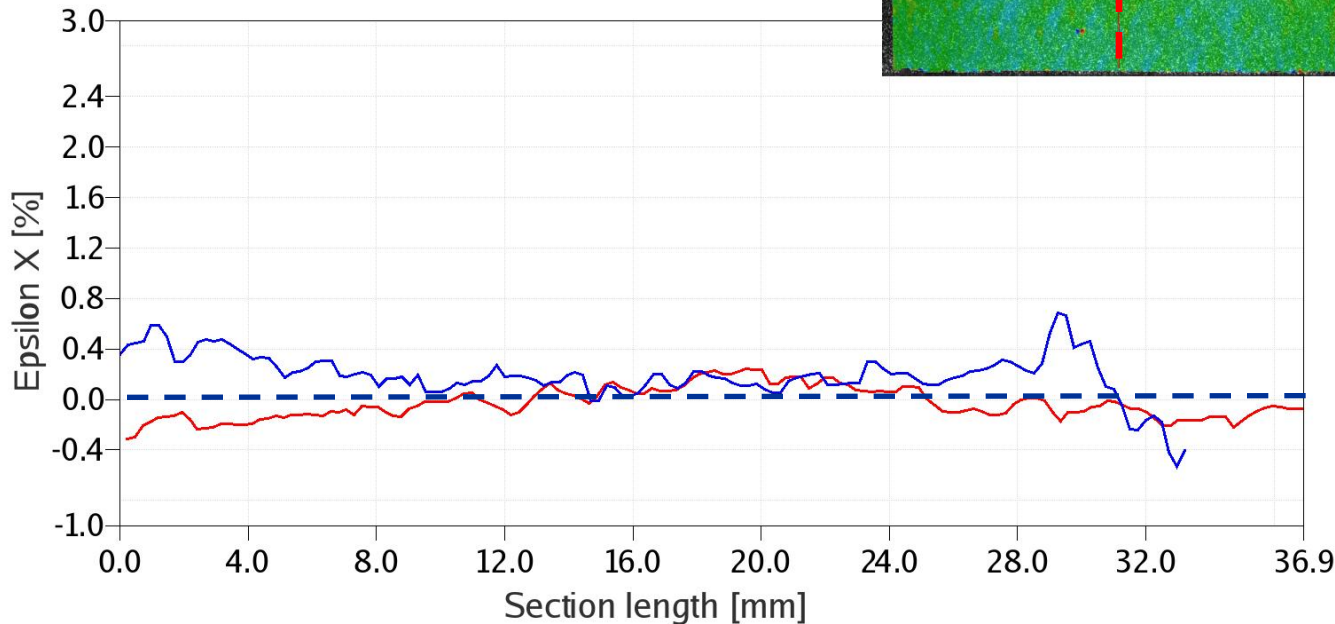
Notched transverse tensile specimen (Horizontal strain)

Failure stress:

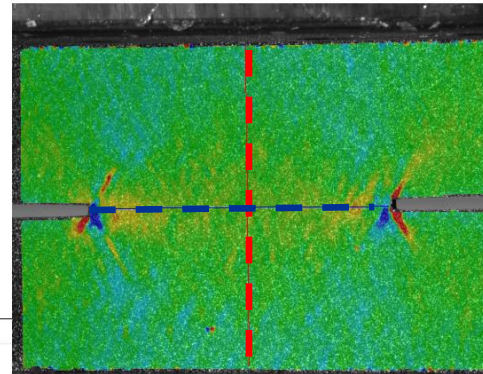
- 462 MPa - straight-sided
- 813 MPa - notched

351 MPa
Stage 64

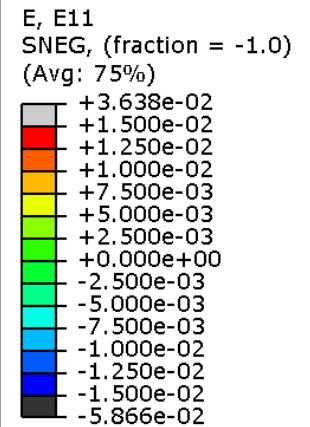
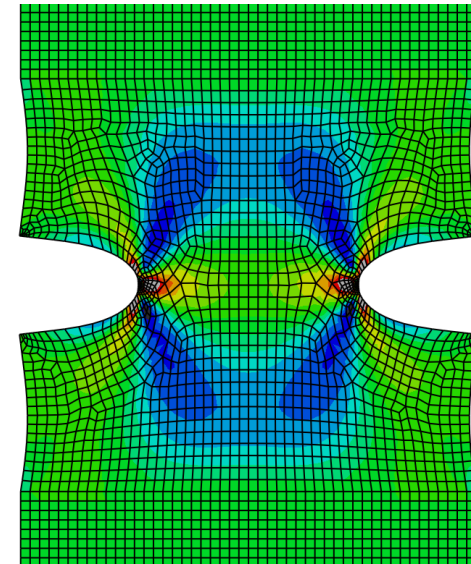
Section lines — Horizontal
— Vertical



Horizontal strain
(Front of specimen)



FE simulation
(Aluminum)



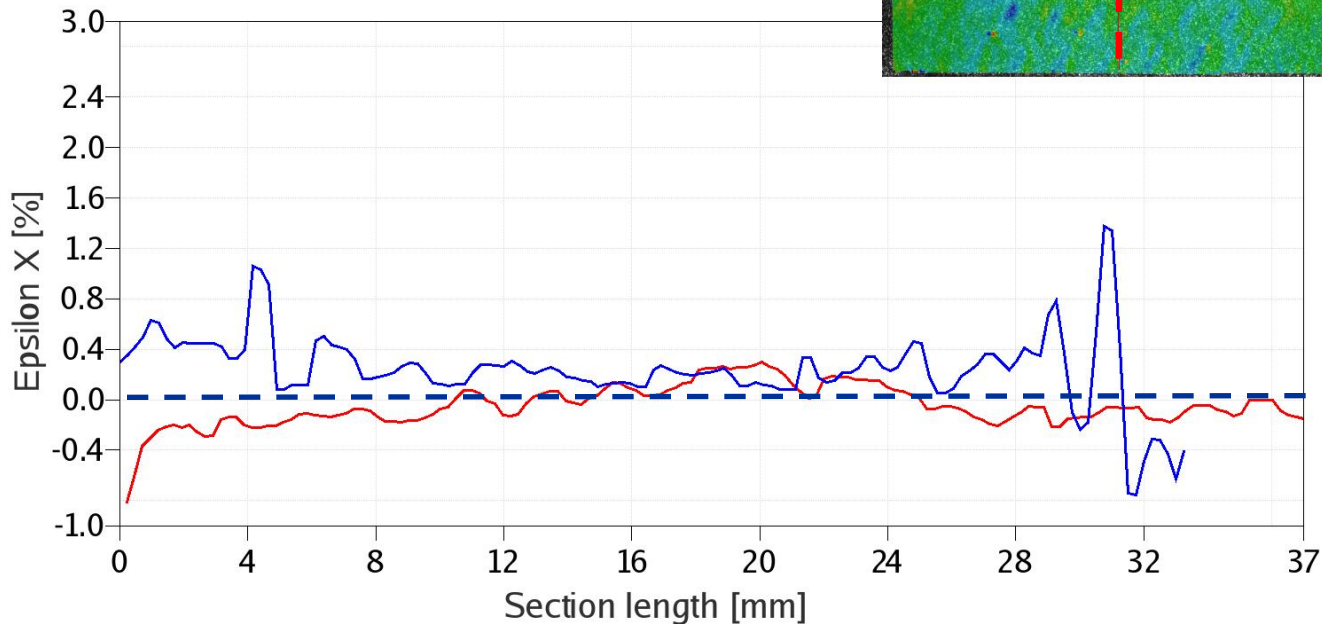
Notched transverse tensile specimen (Horizontal strain)

Failure stress:

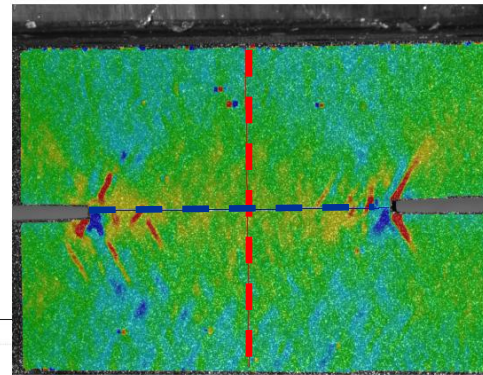
- 462 MPa - straight-sided
- 813 MPa - notched

451 MPa
Stage 85

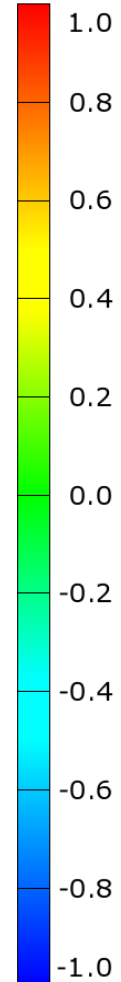
Section lines
— Horizontal
— Vertical



Horizontal strain
(Front of specimen)



[%]



Notched transverse tensile specimen (Horizontal strain)

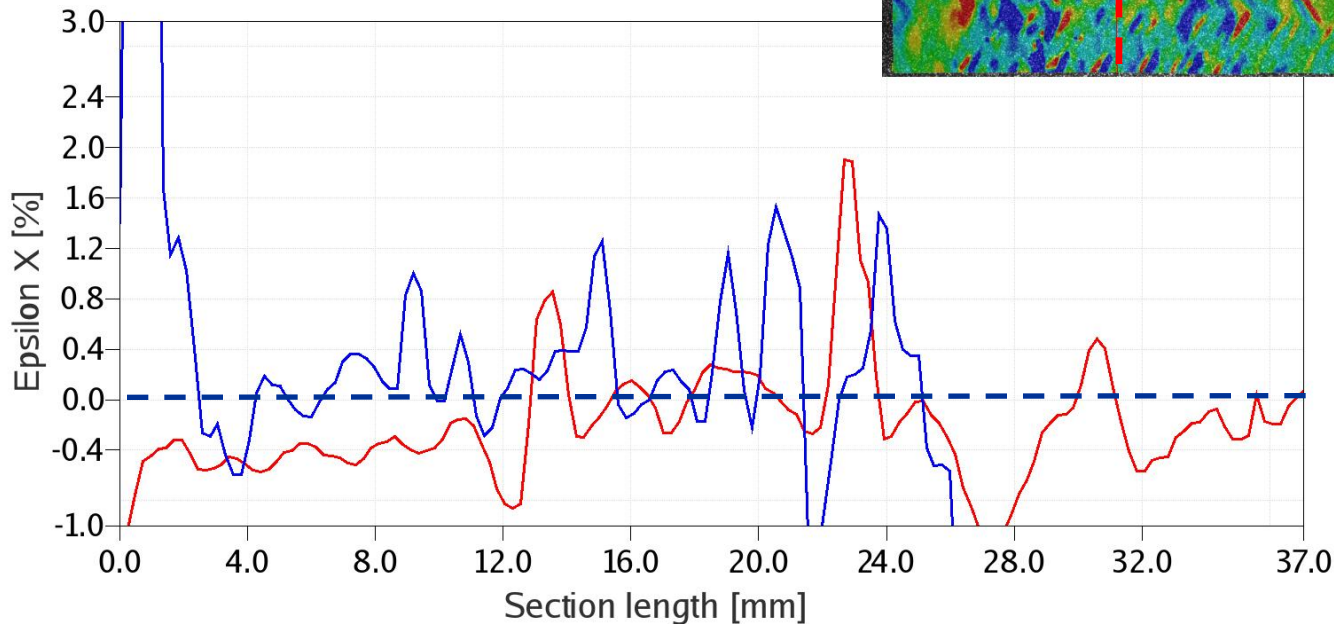
Failure stress:

- 462 MPa - straight-sided
- 813 MPa - notched

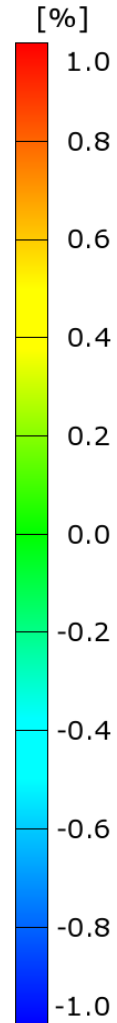
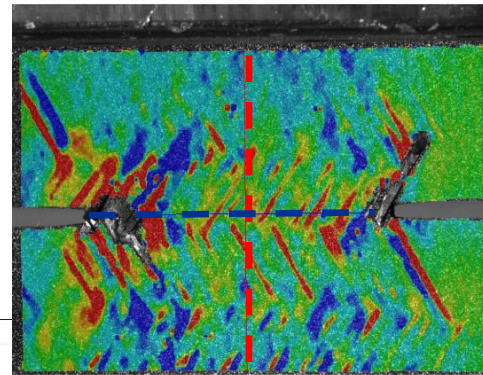
729 MPa

Stage 162

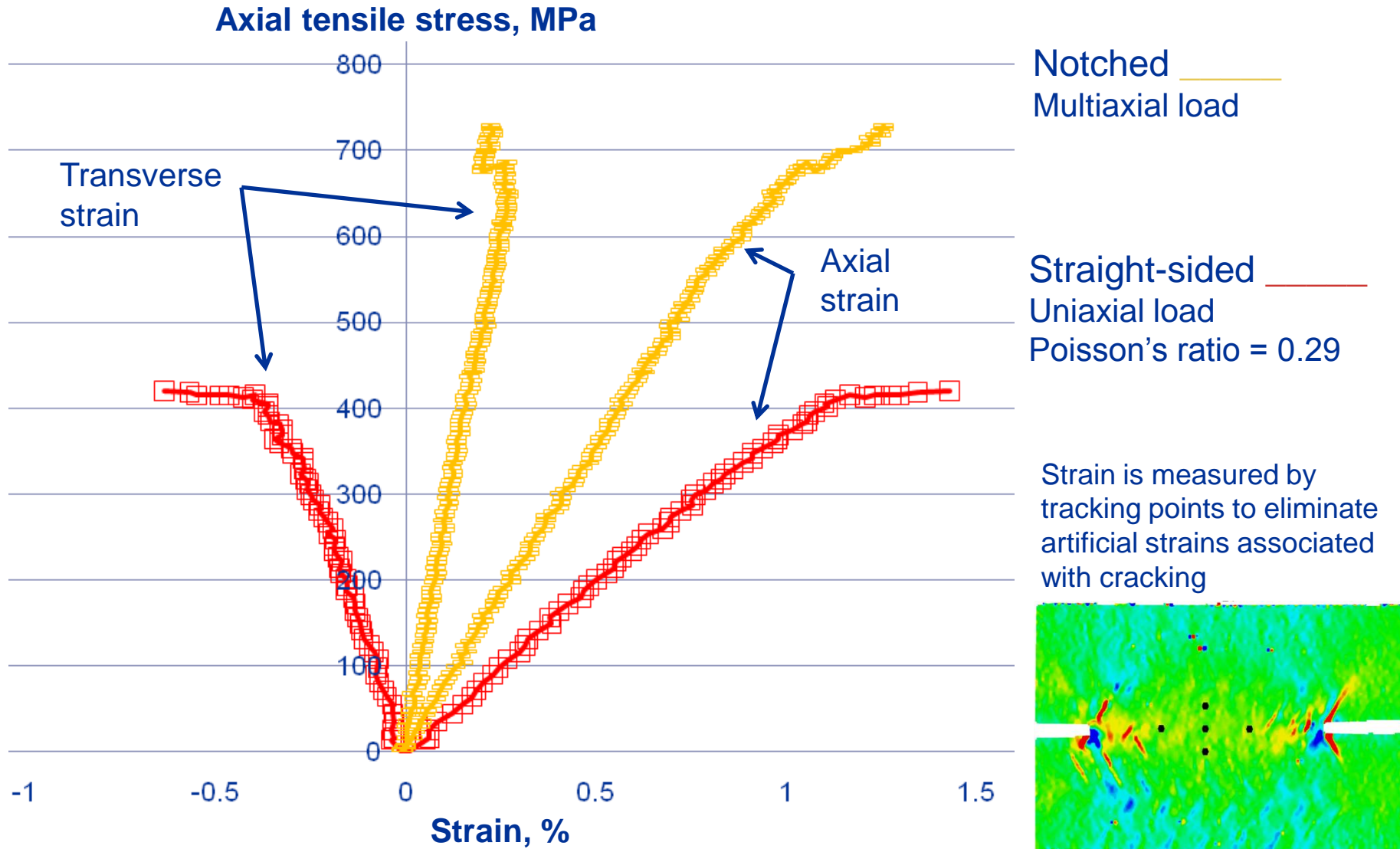
Section lines
— Horizontal
— Vertical

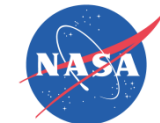


Horizontal strain
(Front of specimen)

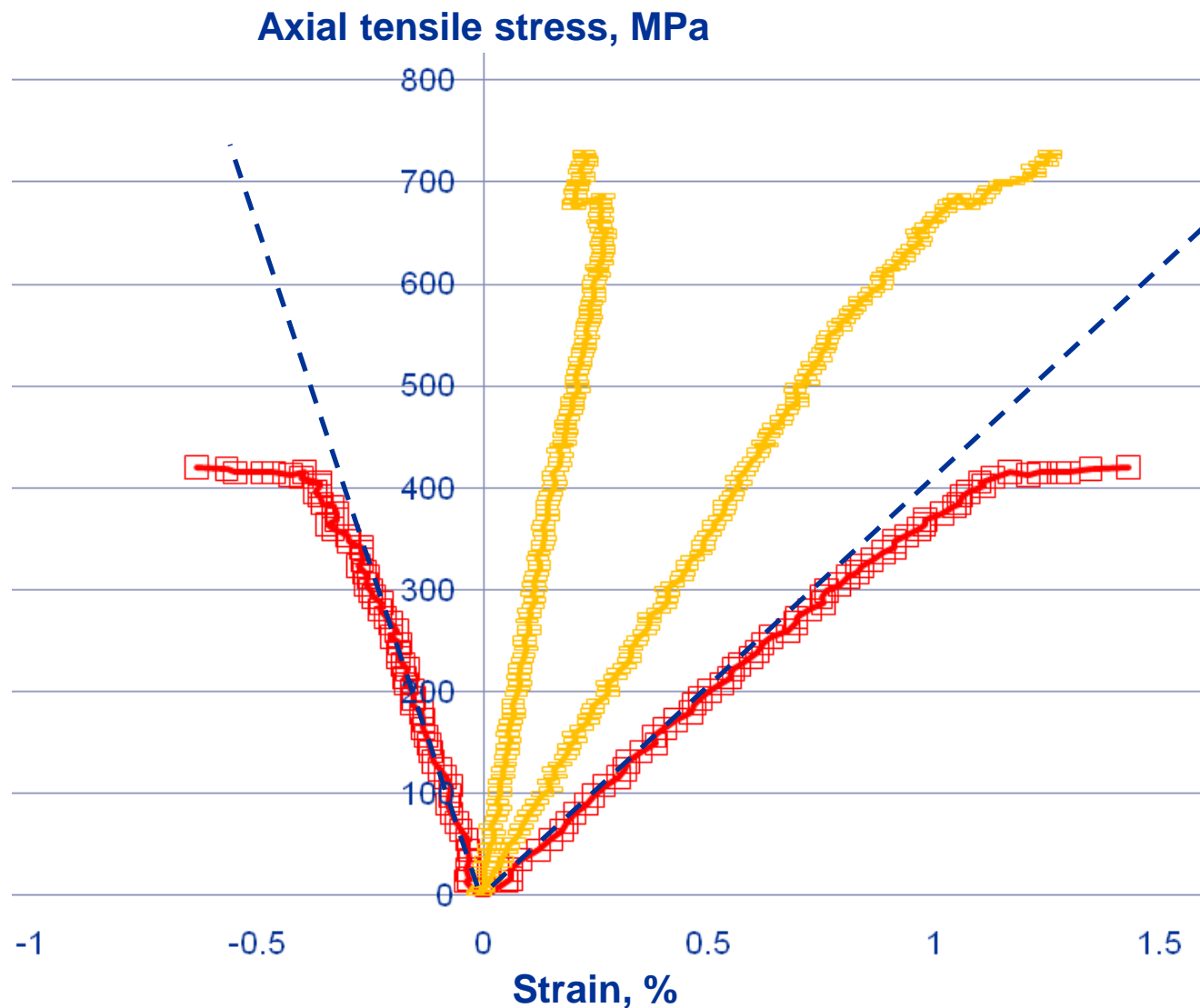


Straight-sided vs notched stress-strain curves





Straight-sided vs notched stress-strain curves

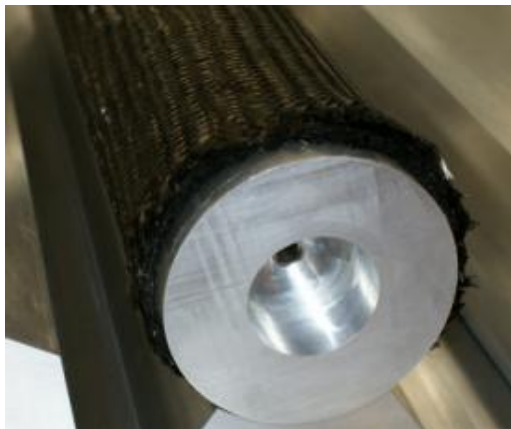


Can we devise a test method that more closely represents uniaxial deformation, but without edge damage?

Tube specimens

Fabrication by resin transfer molding (RTM)

Preform overbraided on a mandrel



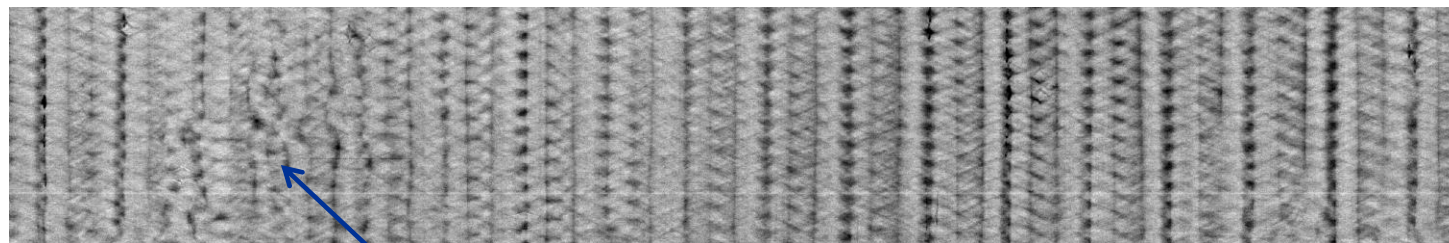
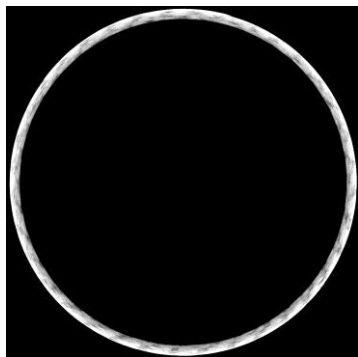
Cured tube dimensions

- Diameter: 3.9 in (9.9 cm)
- Wall thickness: 0.125 in (3.2 mm)
- Length: 24 in (61 cm)

Examination of braid architecture by X-ray computed tomography (CT)

Data is collected as a series of cross-sections

“Unwrapped” CT image shows fiber architecture in individual plies

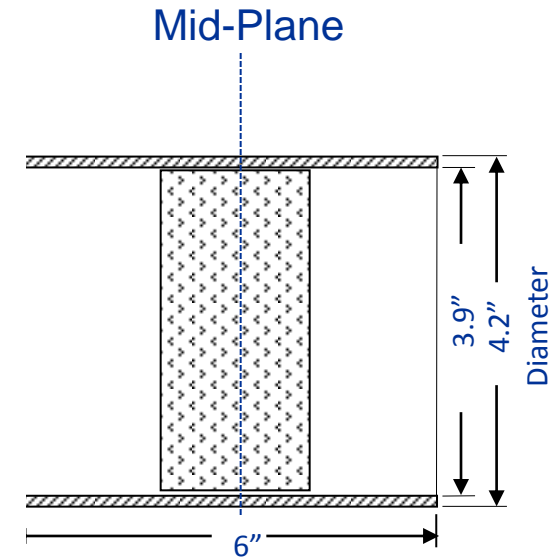
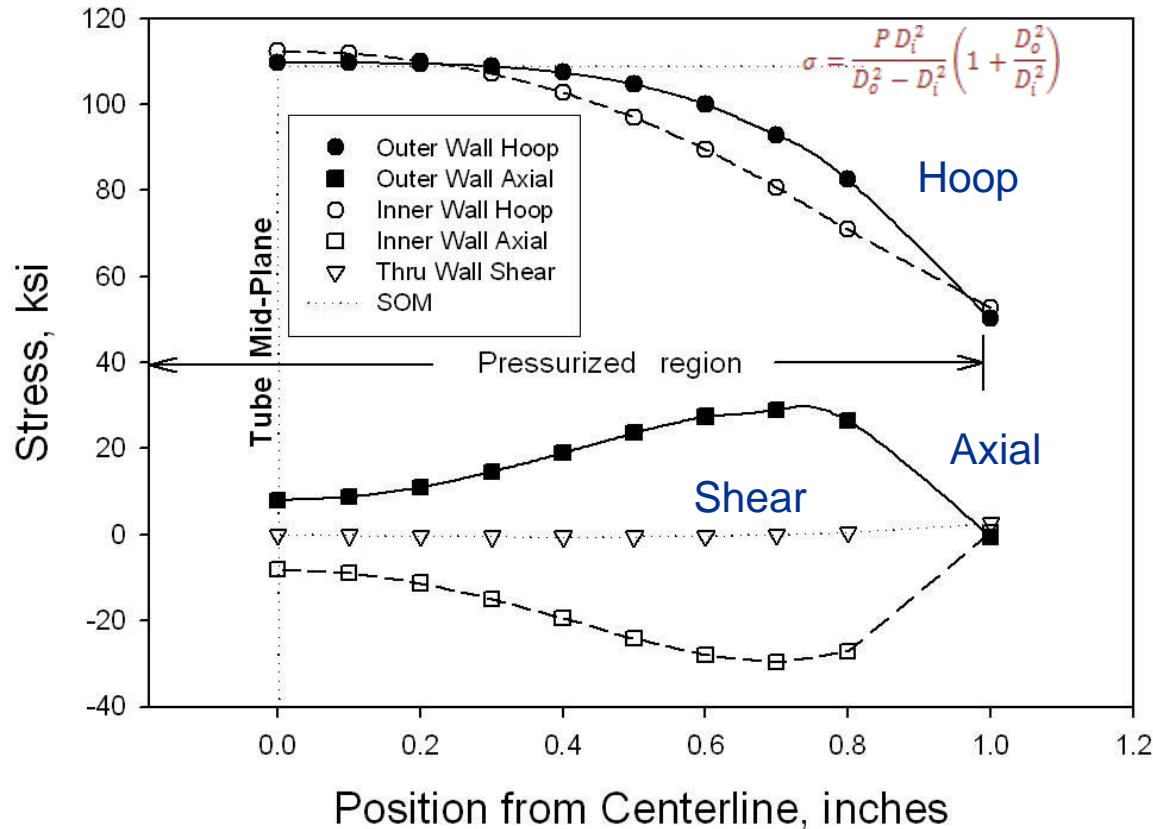


Local distortion of the preform can be detected

Tube testing

Analysis for partial internal pressurization

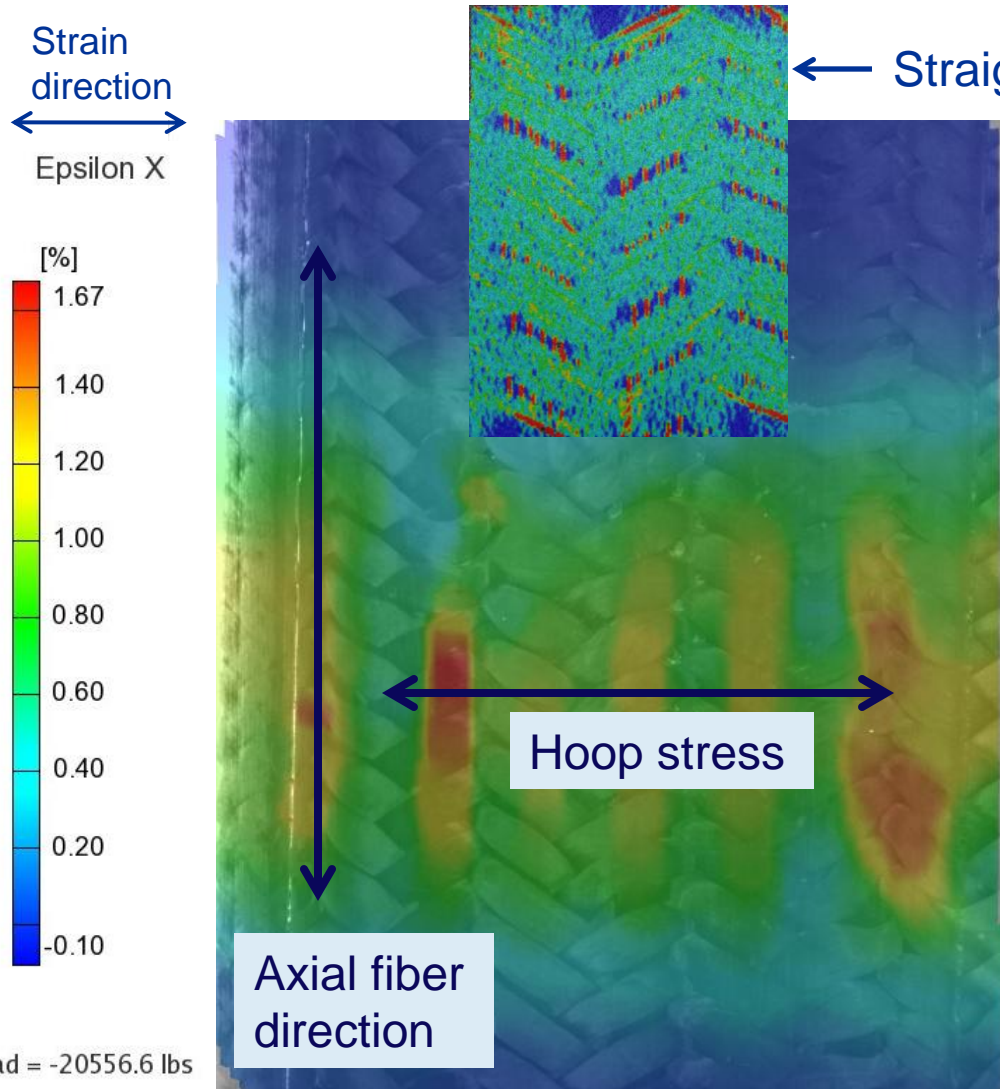
Stresses in a 6 inch tube with 2 inch pressure zone (Isotropic, homogeneous material with composite material modulus)



- Peak stress occurs near the mid-plane
- Small edge stress reduces the chance of edge initiated failure
- Mid-plane stress state is multiaxial with a dominant hoop stress (transverse tensile)

Tube testing

Strain measurement during partial internal pressurization



← Tube with internal pressurization

- Hoop stress = 449 MPa (65.2 ksi)

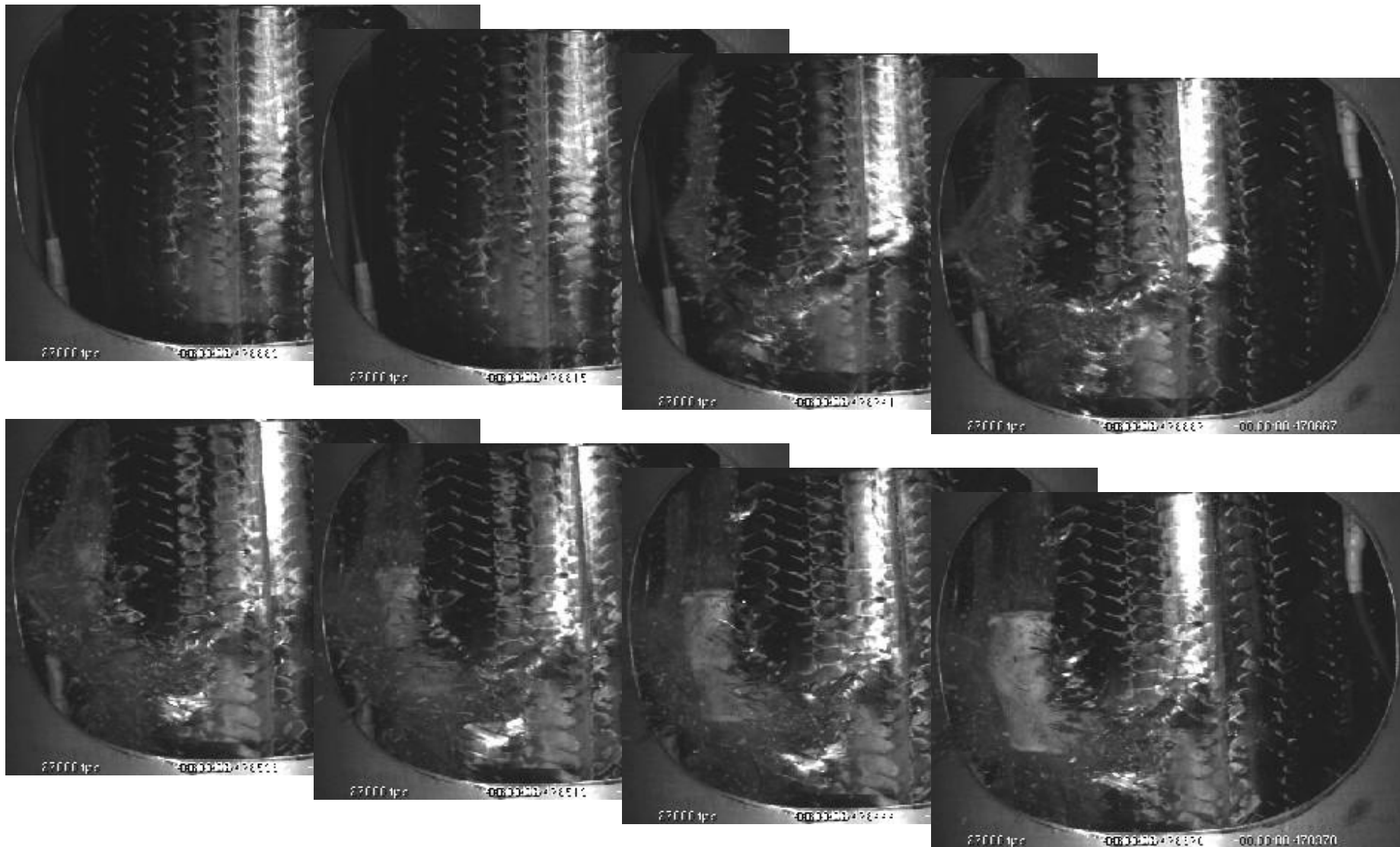
Failure stress:

- Tube (hoop) = 786 Mpa (114 ksi)
- Straight-sided coupon = 462 MPa (67 ksi)

- Apparent high strain regions are likely micro-damage viewed at lower resolution
- More accurate strain measurement procedures are being developed for composite tubes

Tube testing

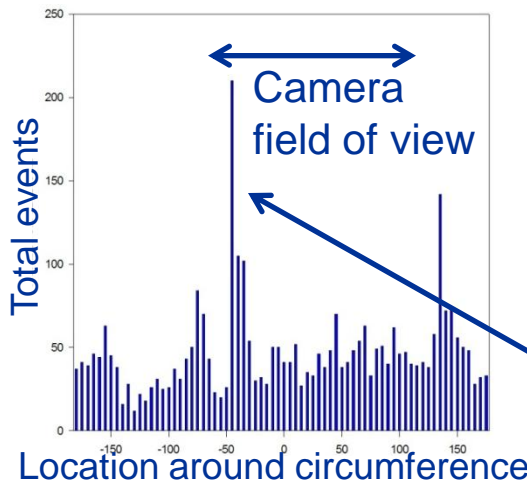
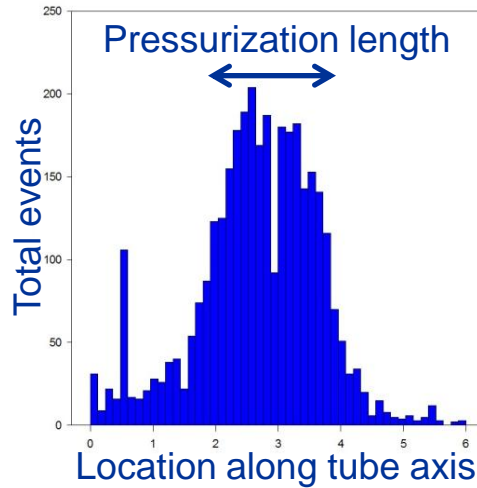
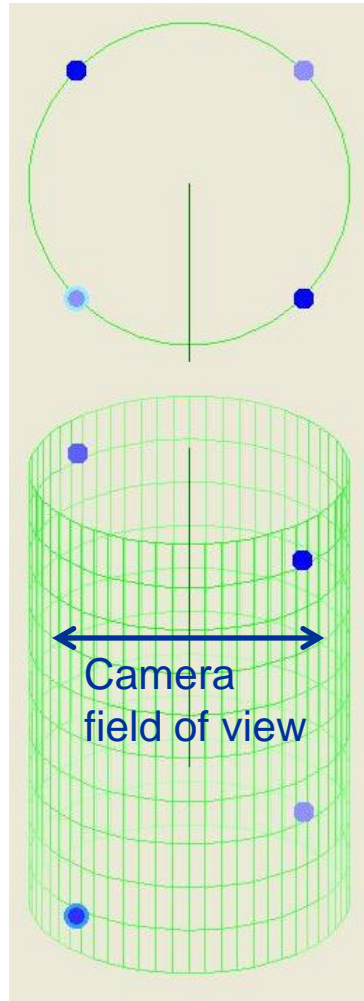
Partial internal pressurization test – image sequence



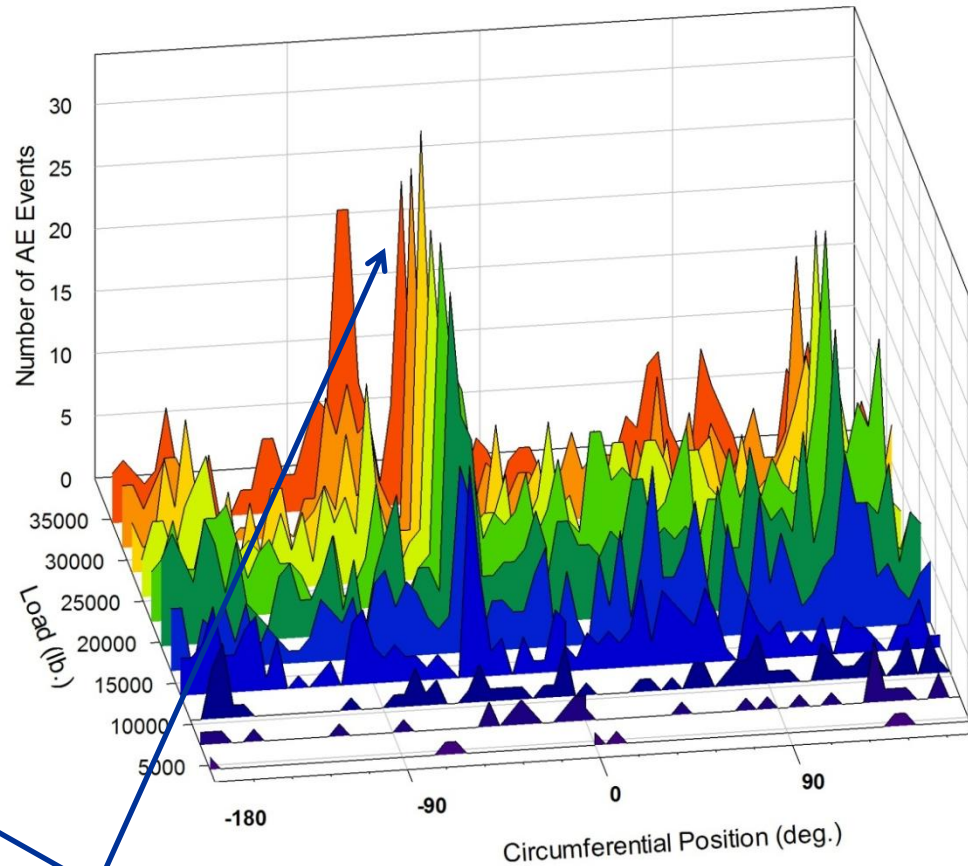
Tube testing

Acoustic emission during partial internal pressurization test

Sensor Locations



Events during 3000 lb load increments



Failure initiation site



Summary

- Straight-sided coupons yield low tensile strength values
 - Edge-initiated failure occurs in transverse and possibly in axial loading
 - Shear failure occurs in transverse loading
- Bowtie and notched coupons provide a more realistic strength
- Notched coupons provide a simple test method for strength
 - Specimens are easy to fabricate
 - The same shape is used for axial and transverse tests (or other orientations)
 - Failure occurs in a tensile mode for transverse tests
 - The effect of the multiaxial stress state needs to be investigated
- Partial internal pressurization of tubes provides a measurement of transverse tensile strength in an nearly uniaxial load condition
 - Failure is free of edge effects
 - The transverse tensile (hoop) stress is uniform near the tube mid-plane
 - Axial and shear stress components are small at the failure initiation site