Failure Criterion Development for Composite Materials Loaded Transverse to Fiber Direction

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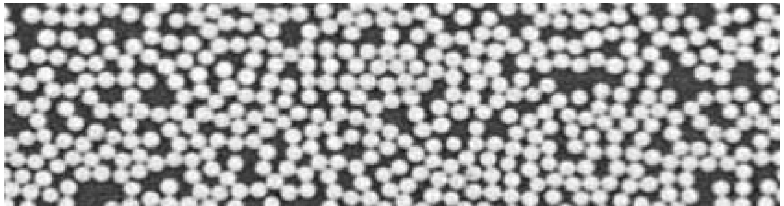
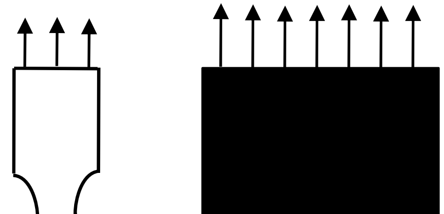
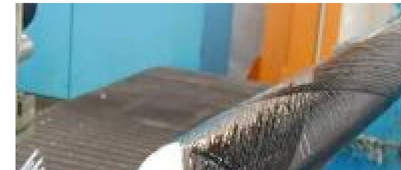
Outline

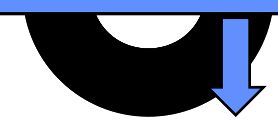
- Introduction
  - Objective
- Experimental Techniques and Results
  - Transverse failure => Cruciform specimen testing
- Analytical Techniques and Results
  - Fiber-matrix debond criteria
  - Matrix failure criteria
- Summary and Conclusions
- Questions

Introduction
Transverse Failure Initiation

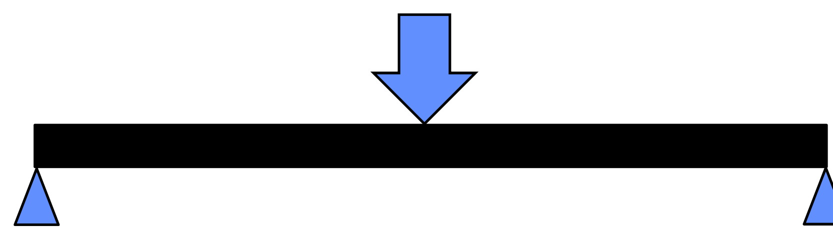




OBJECTIVE

Develop a micromechanics based failure criteria for transversely loaded composite materials



Attempted Criterion Development
- 2-D analysis for 3-D problem
- RVE represents composite
- Edge effects neglected
- Failure modes treated separately



2 competing mechanisms

free edge effect

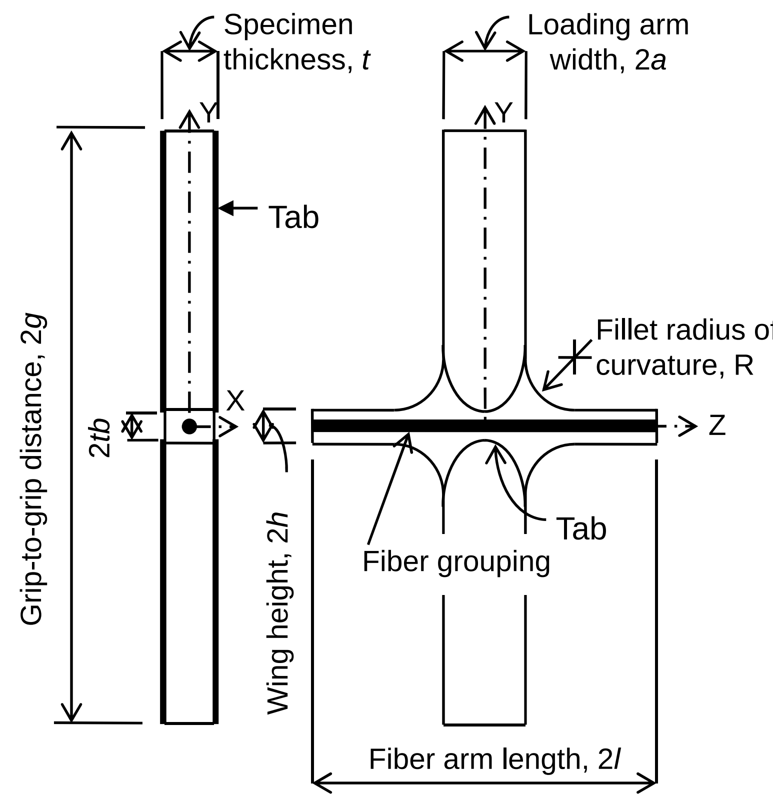
Introduction
Transverse Failure Initiation

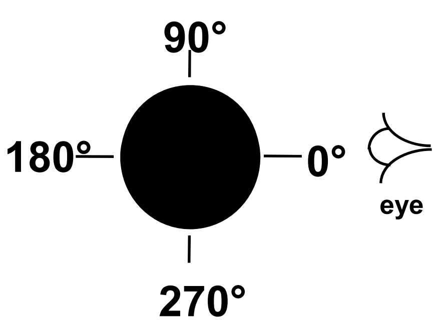
Matrix Cavitation

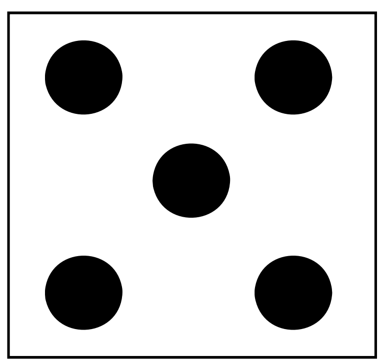
- **forms under tensile tri-axial stress state**
- **develops micro-voids => volume dilatation**

Fiber-matrix Debonding

- **matrix pulls apart from fiber**
- **typically forms in load direction in top or bottom half of fiber**



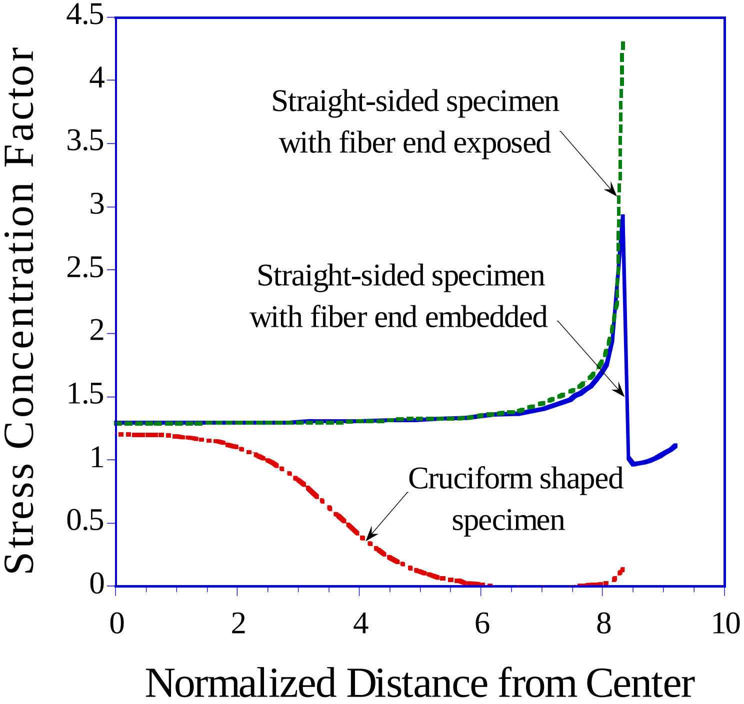


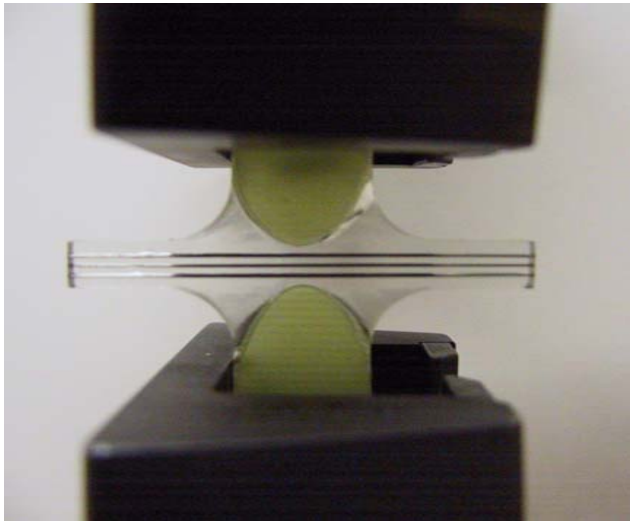


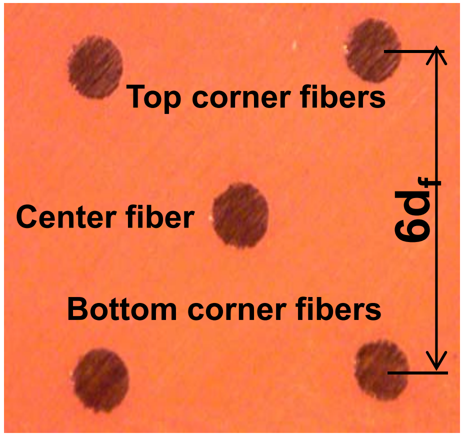
Fiber grouping configuration

Experimental Technique
Specimen Geometry

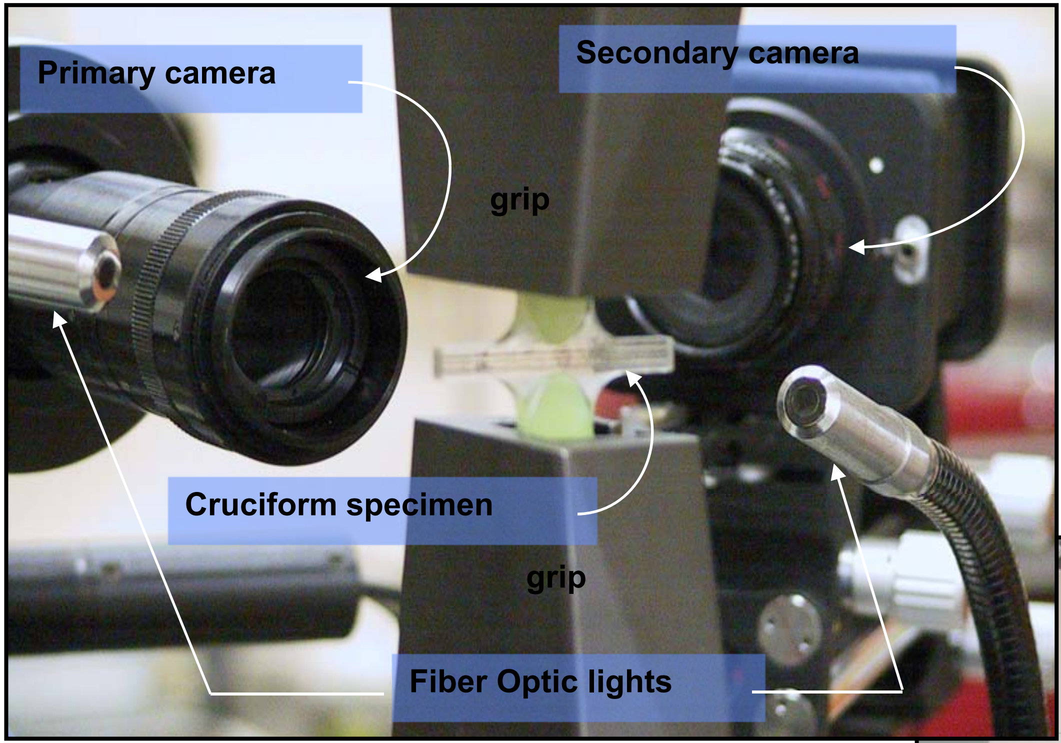
- **Model composite system**
  - **Cruciform Shape specimen geometry**
  - **Stainless steel wires**
    - **0.36 mm diameter**
  - **Transparent matrix systems**



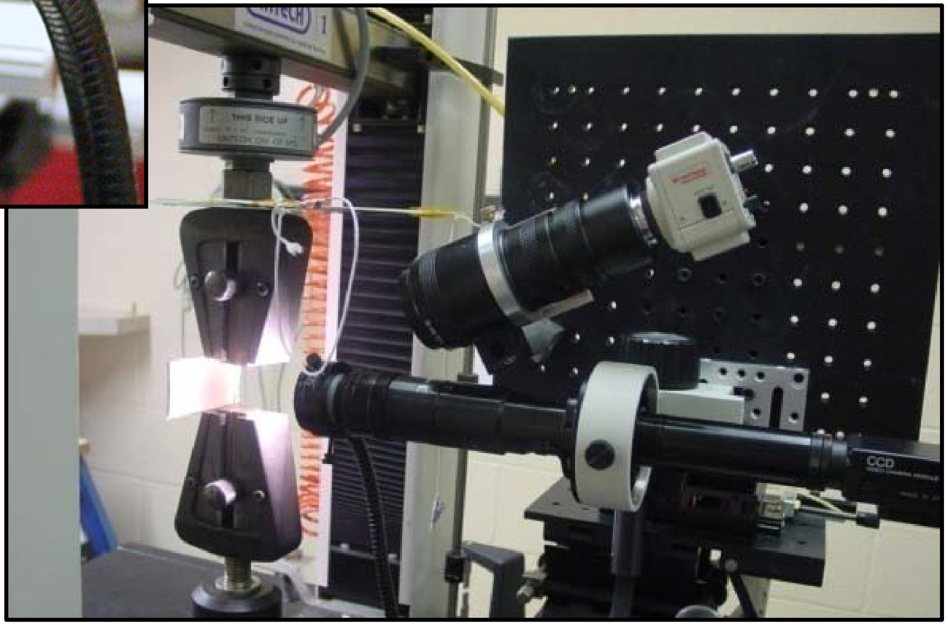




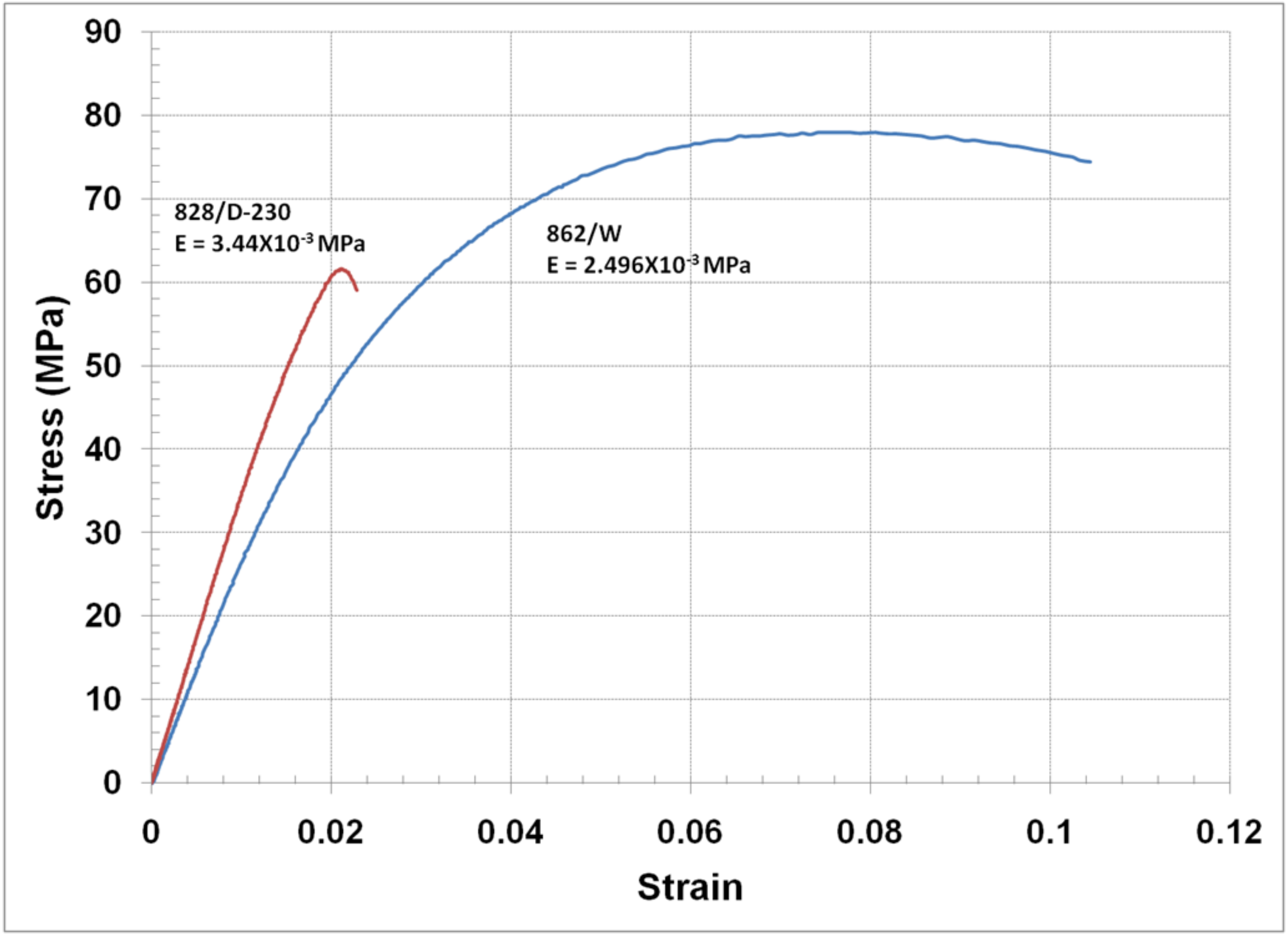
Experimental Technique
Cruciform Specimen Testing



- Direct observation of failure initiation
- Load known at first damage



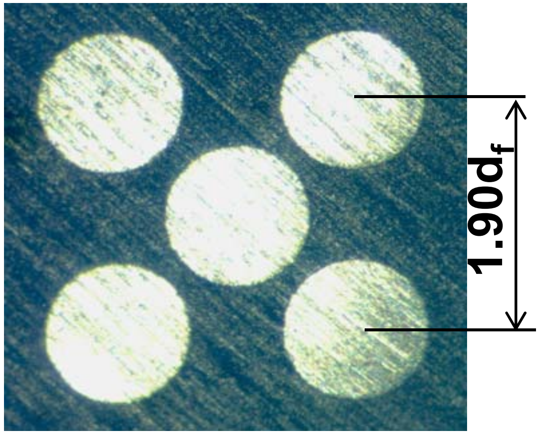
Experimental Technique
Materials



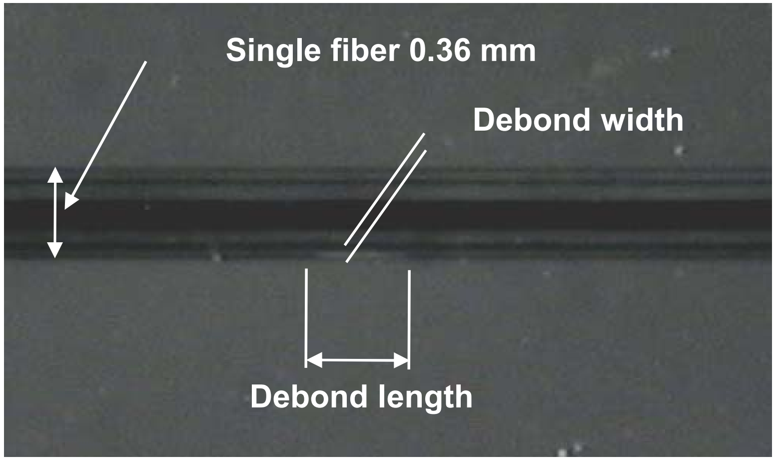
- **Matrix Materials.**
  - 828/Jeffamine-D230 clear two part epoxy room temperature cure
  - 862/W amber two part epoxy high temperature cure
  - Fully characterized

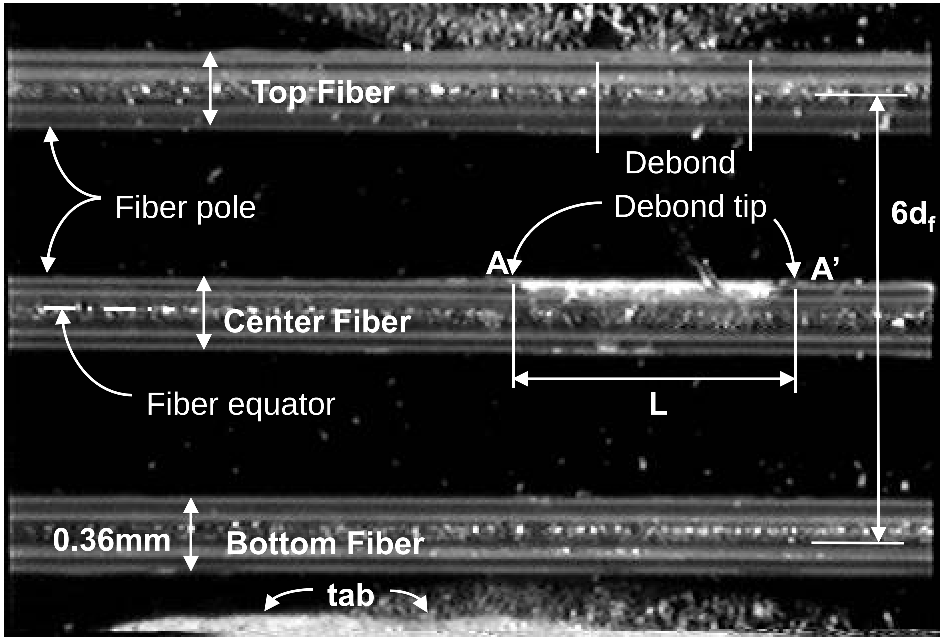
Experimental Technique
Cruciform specimen testing

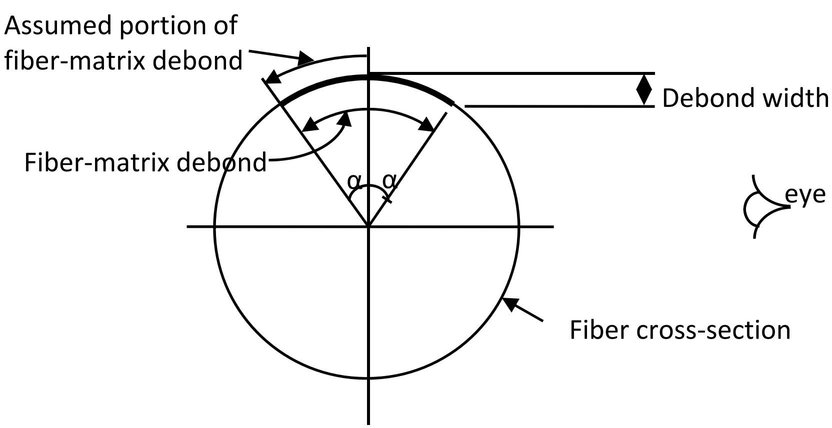
Fiber Spacing	A_f/Area
$1.57d_f$	0.64
$1.75d_f$	0.51
$1.84d_f$	0.46
$1.90d_f$	0.43
$2.0d_f$	0.39
$2.5d_f$	0.25
$6.0d_f$	0.04

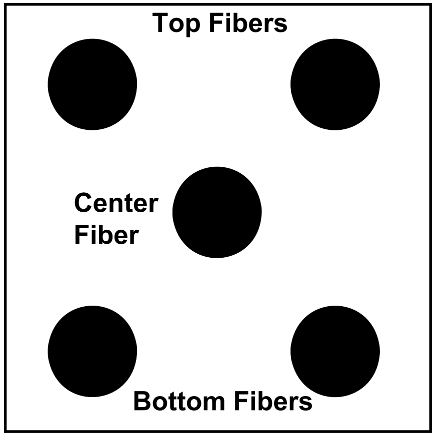


828/D-230 Experimental Results
Cruciform Single Fiber & 6.0d_f Specimens

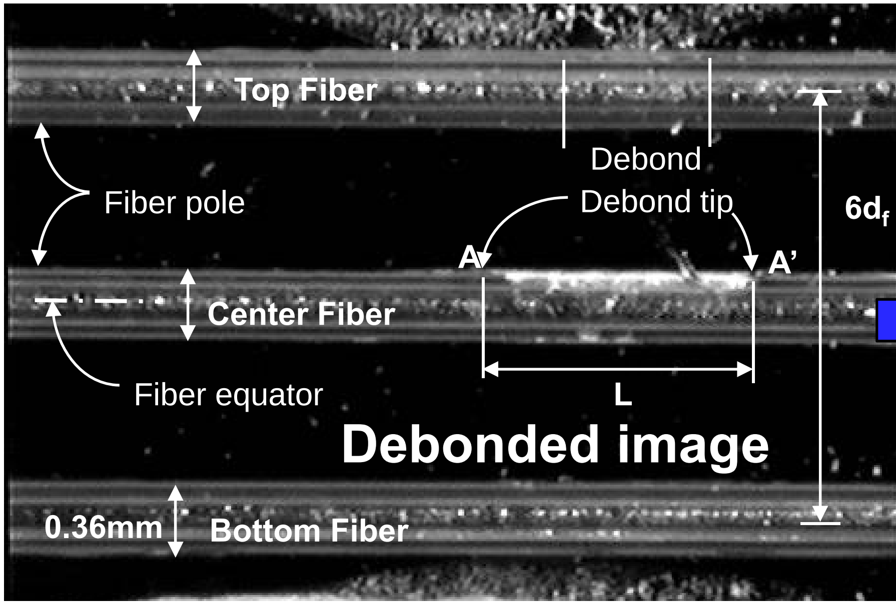


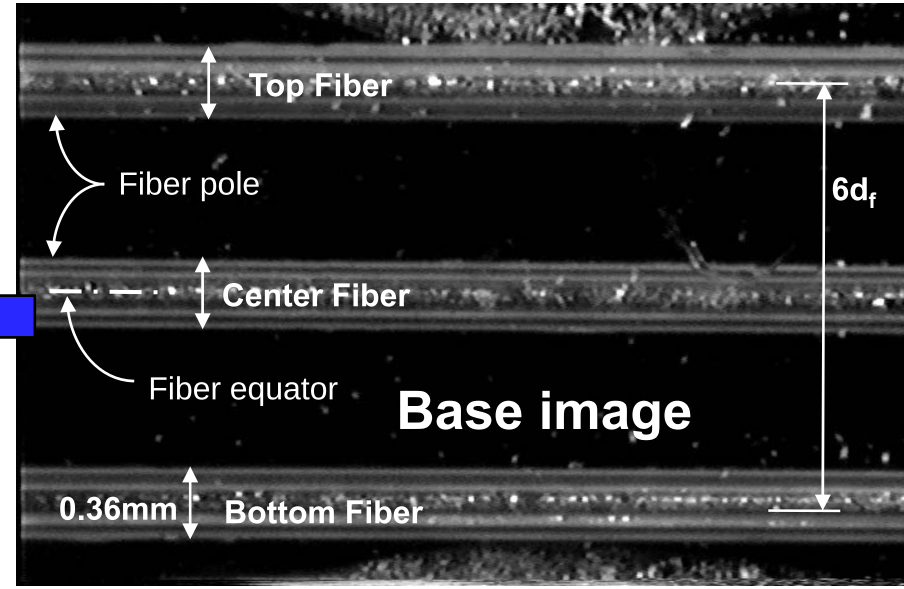




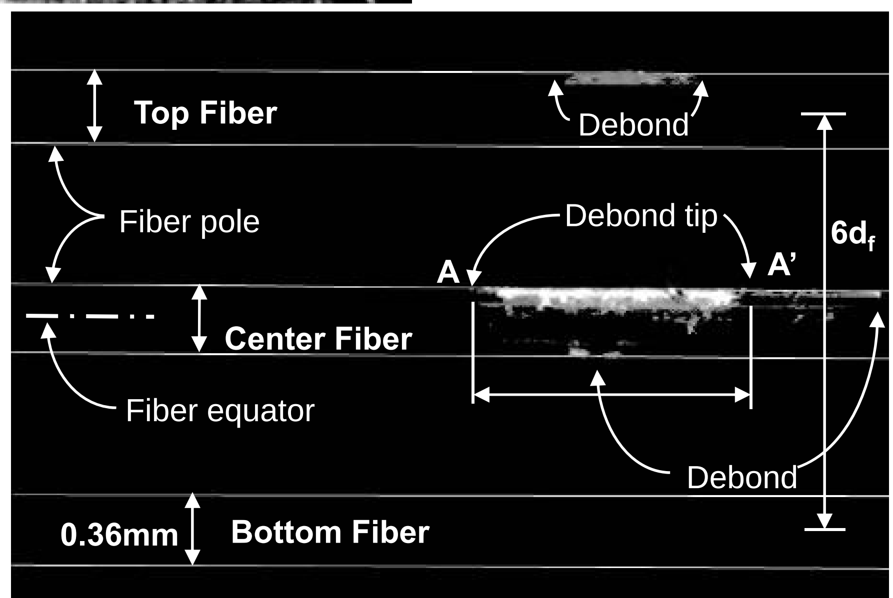


828/D-230 Experimental Results
Image subtraction technique





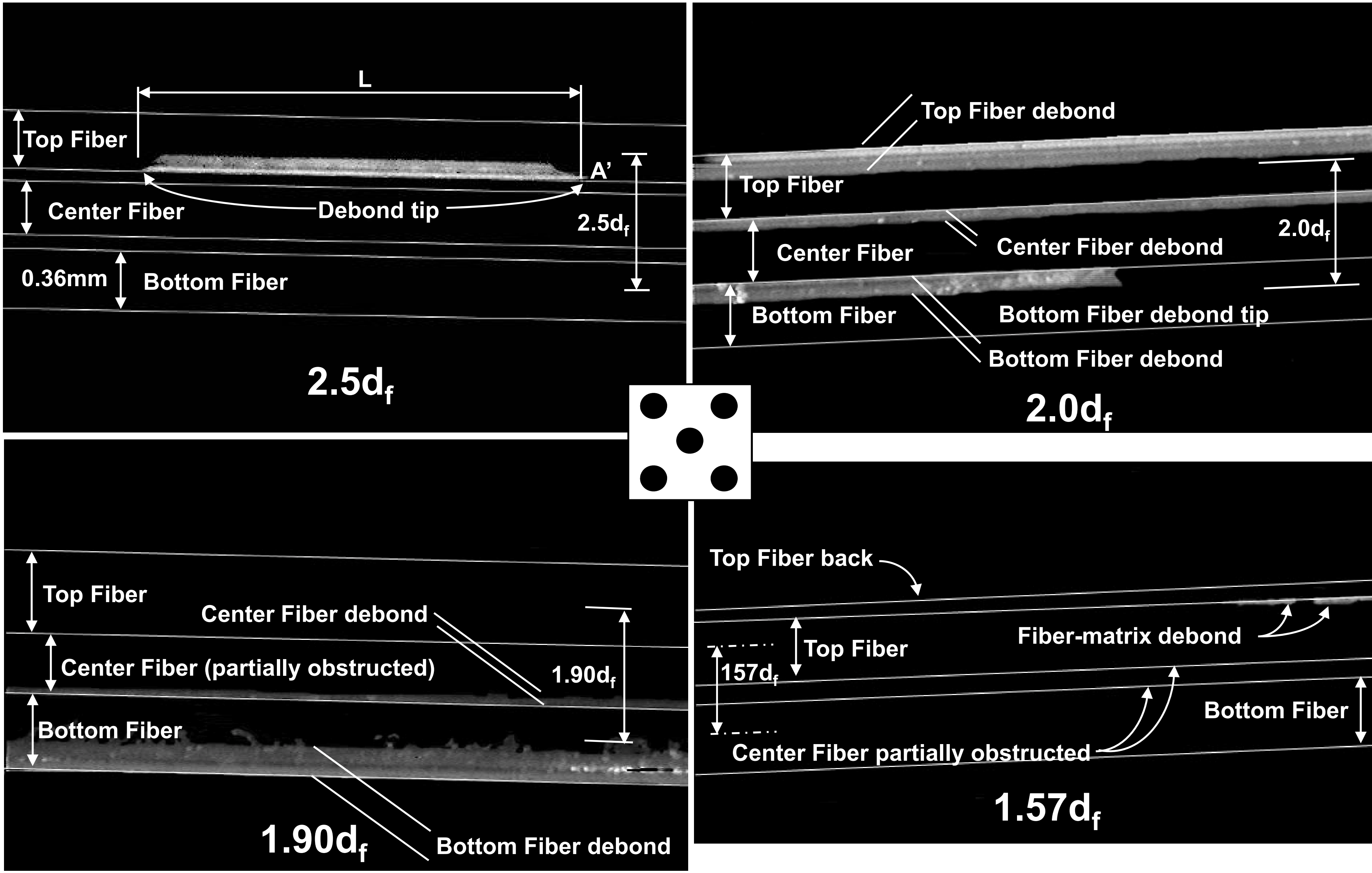
Subtracted image



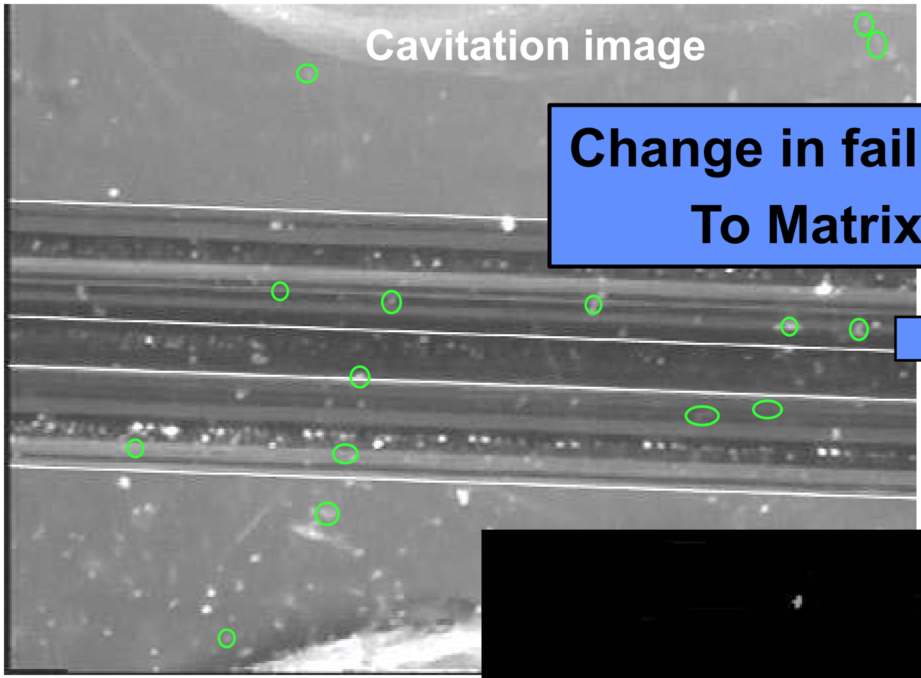
Show 200R1B movie

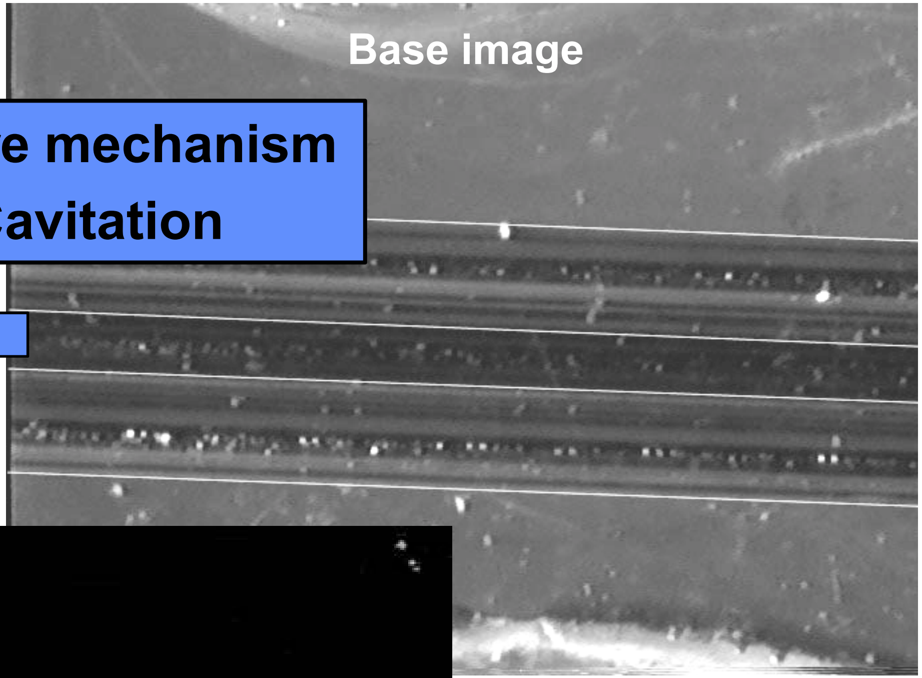
828/D-230 Experimental Results

2.5d_f, 2.0d_f, 1.9d_f & 1.57d_f Specimens

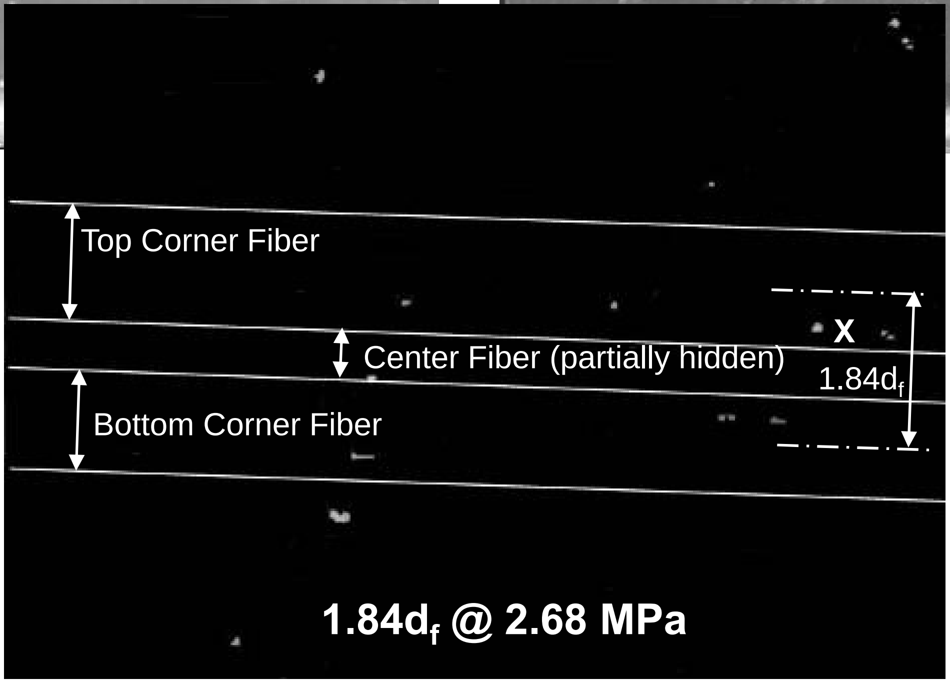


828/D-230 Experimental Results
1.84d_f & 1.75d_f Specimens



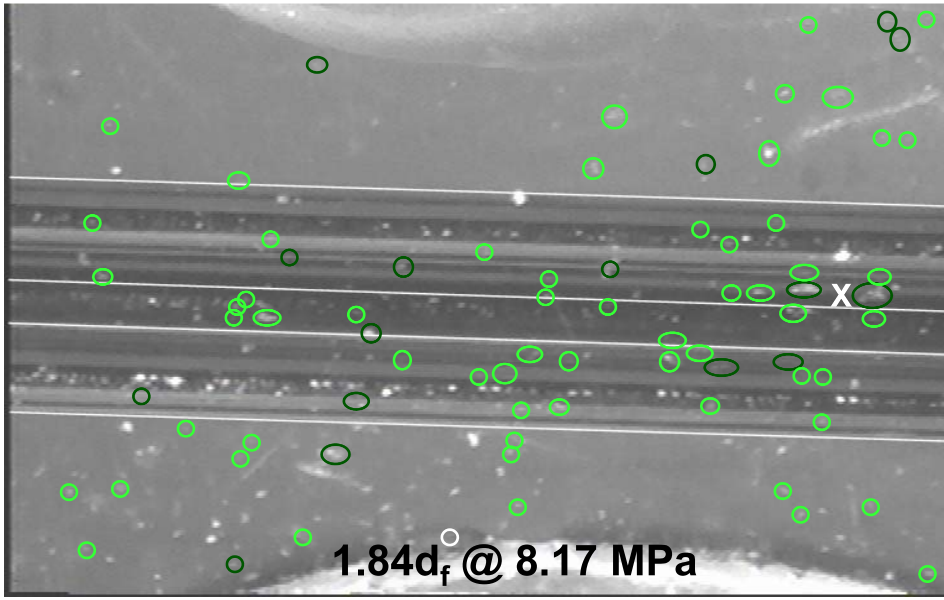


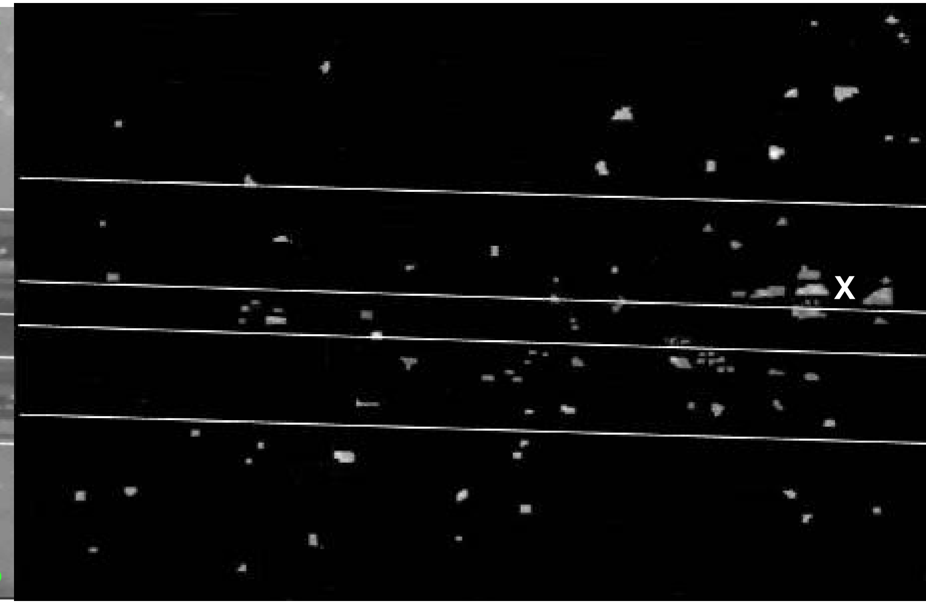
Change in failure mechanism
To Matrix Cavitation

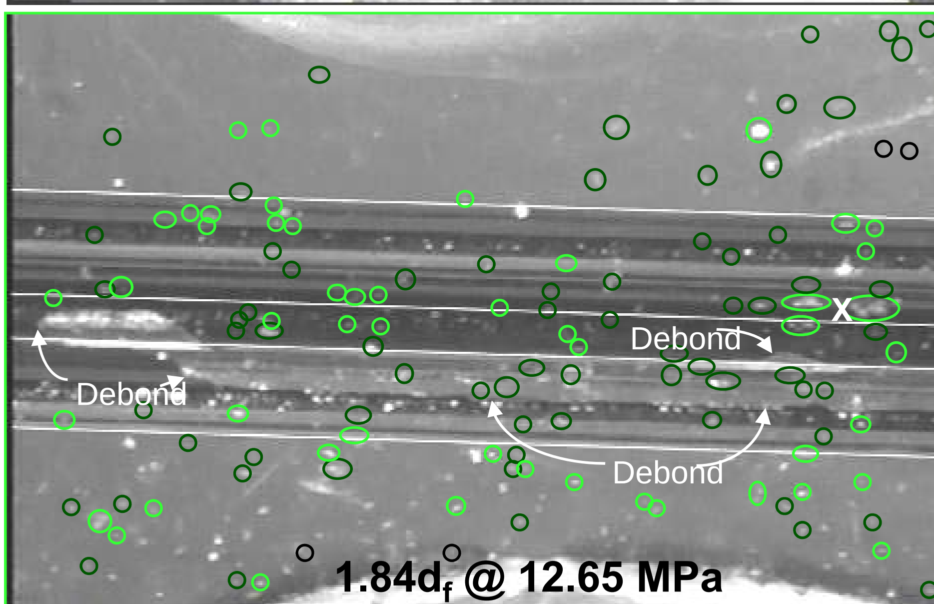


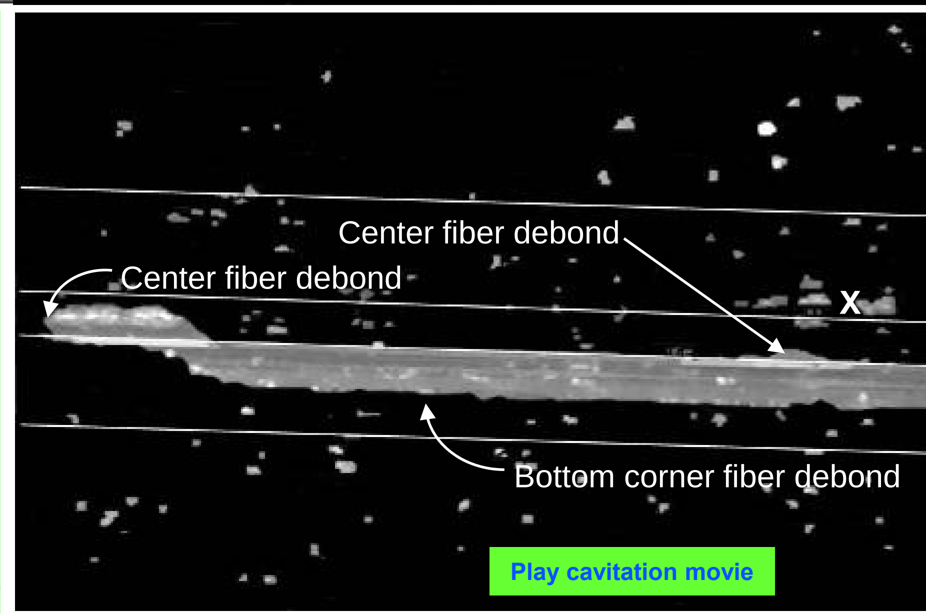
828/D-230 Experimental Results

$1.84d_f$ & $1.75d_f$ Specimens









Experimental Results
Summary

862/W

Fiber Spacing Group	Failure initiation mechanism	Number of specimens tested
SF	debond	6
$6.0d_f$	debond	8
$2.5d_f$	debond	9
$2.0d_f$	cavitation	10
$1.9d_f$	debond	9
$1.75d_f$	debond	11
$1.57d_f$	debond	16

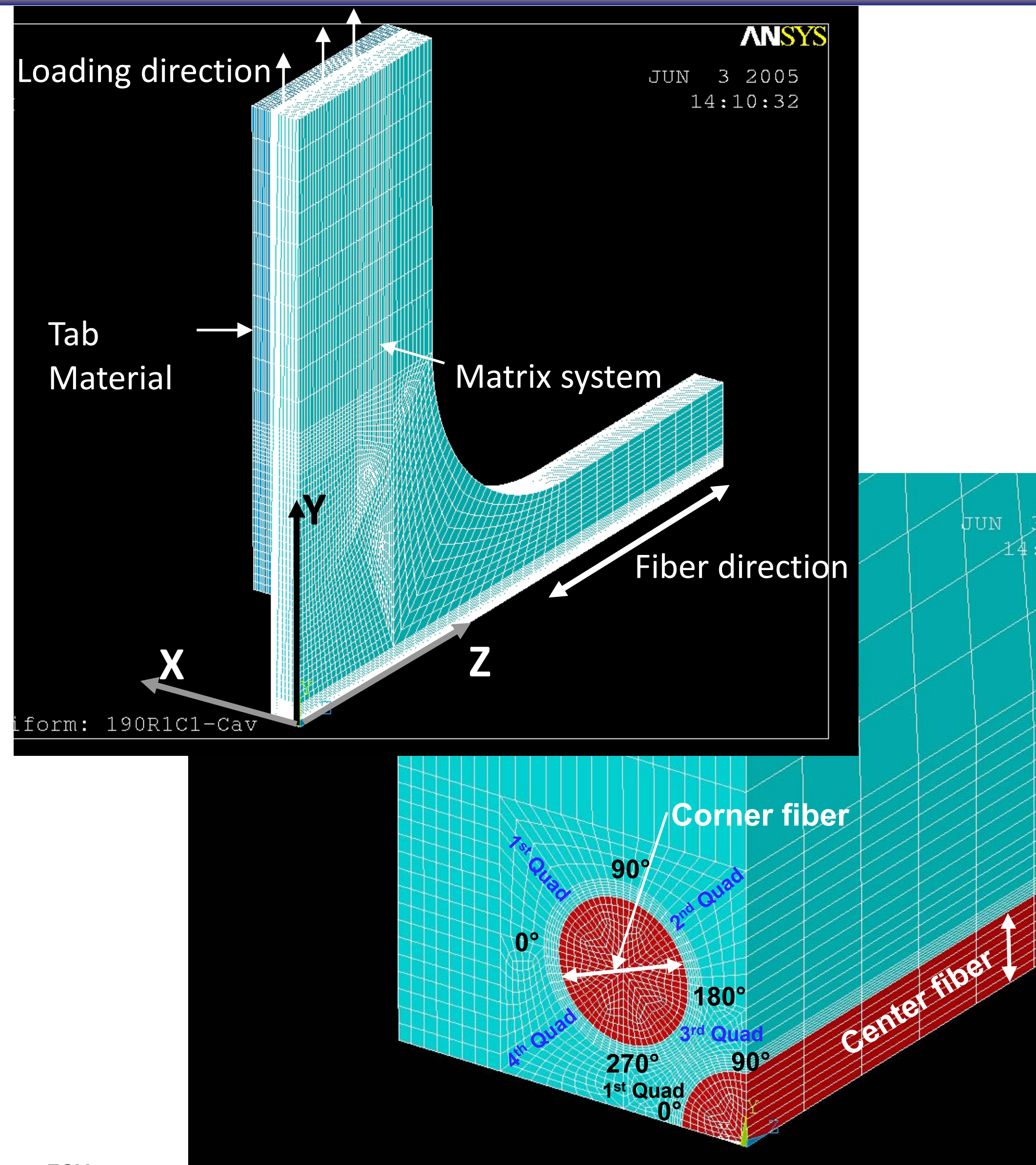
- ***Directly Observed*** **two different failure initiation mechanisms**
- **Recorded load, debond location and made debond measurements at initiation**

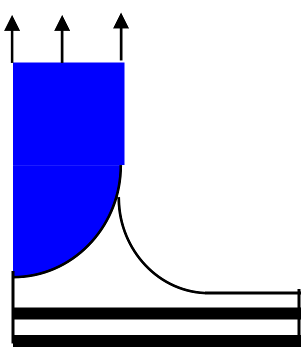
Load, location & measurements needed for criterion dev

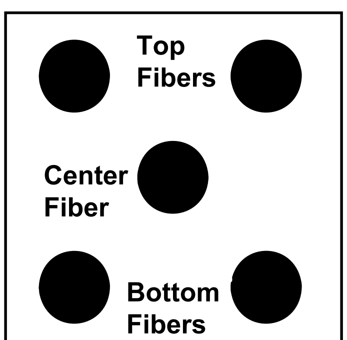
Analytical Results

Cruciform 3-D Finite Element Analysis

- **3-D micromechanical model**
  - **3-D FEA**
    - **combined residual stress and mechanical loading**
  - **ANSYS FEA code**
  - **Utilizing symmetry**
    - **model 1/8 of specimen**
- **Boundary Conditions**
  - **Planes of symmetry constrained – outer surface traction free**
  - **Unit displacement load**



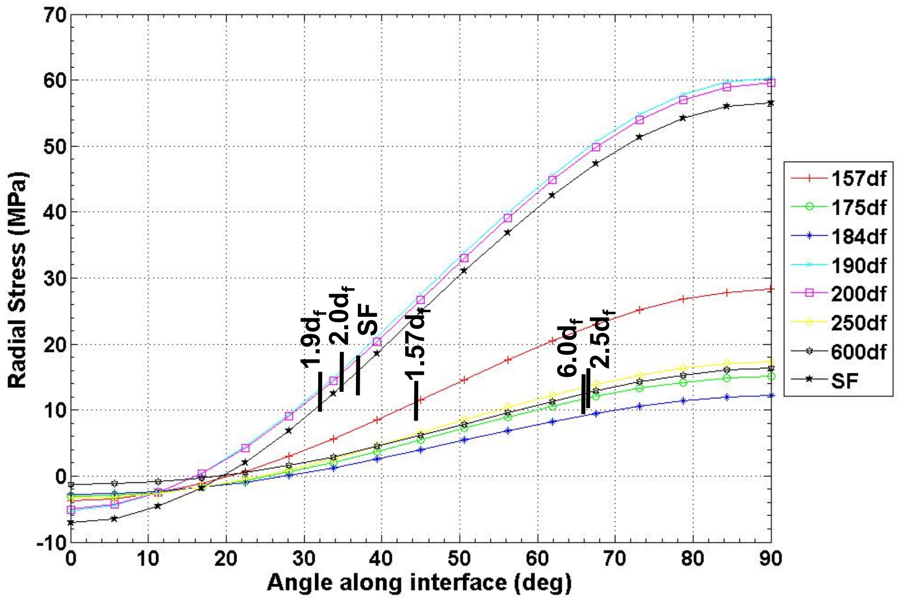


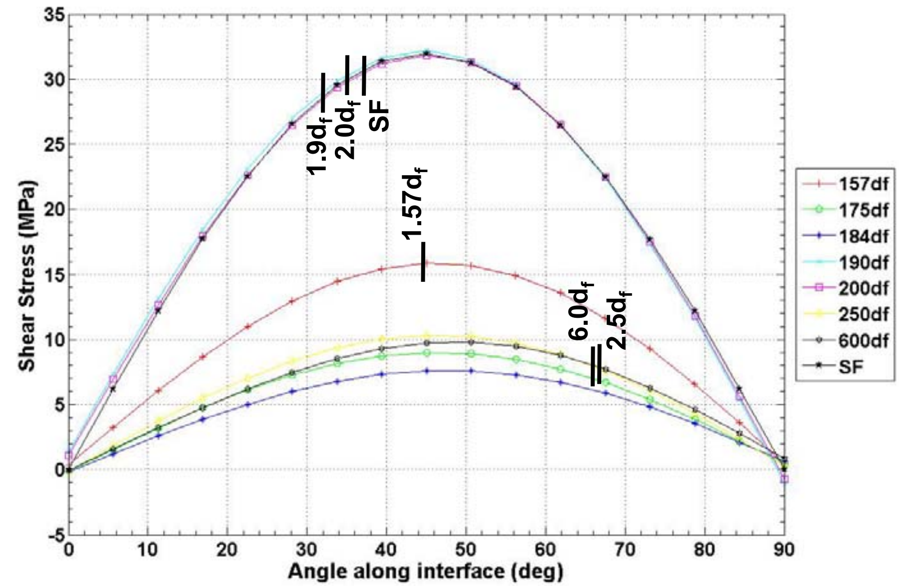


FOV

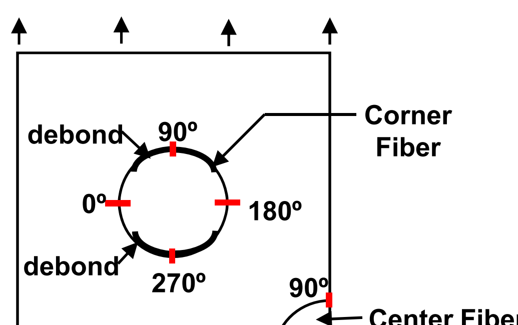
Analytical Results

828 Fiber-matrix debond criteria development





- Observed debond limits encompass regions of fiber-matrix interface having high stresses
- Conclude that interaction exists creating debond
- Analytical results give same indication for 862/W



Analytical Results

Fiber-matrix debond criteria development

- Literature suggest a quadratic interaction debond criterion:

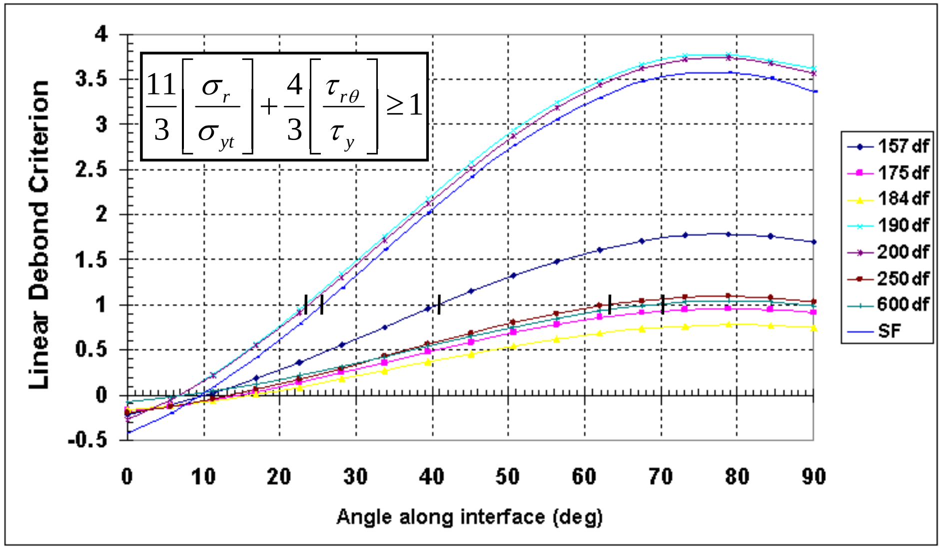
$$A\left[\frac{\sigma_r}{\sigma_{yt}}\right]^2 + B\left[\frac{\tau_{r\theta}}{\tau_y}\right]^2 \geq 1$$

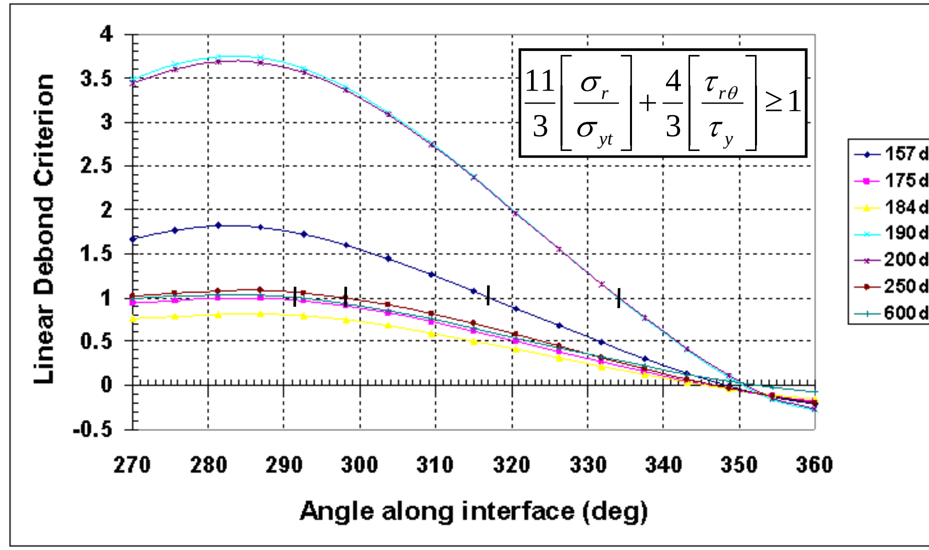
- If compressive interfacial radial stress difficult to debond
  - quadratic criterion would not capture stress state
- Linear interaction debond criterion would capture stress state

$$A\left[\frac{\sigma_r}{\sigma_{yt}}\right] + B\left[\frac{\tau_{r\theta}}{\tau_y}\right] \geq 1$$

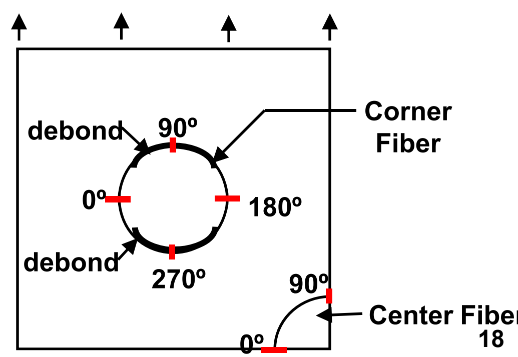
- Constants *A* and *B* are curve fitting parameters
  - could be construed as the radial adhesion and shear adhesion strength of the fiber-matrix interface
- Assumed matrix perfectly bonded to fibers

Analytical Results
828 Fiber-matrix debond criteria





Fiber Spacing	Linear Debond Criterion Debond limits		Experimental Debond limits		%Δ	
	1st Quad	4th Quad	1st Quad	4th Quad	1st Quad	4th Quad
1.57df	42°	314°	44.5°	315.5°	7.7	3.3
1.9df	24°	334°	32°	328°	15.5	10.3
2.0df	24°	334°	35°	325°	20	16.4
2.5df	65°	295°	66.5°	293.5°	10.6	6.4
6.0df	68°	292°	66°	294°	8.3	8.3
SF	26°	-	37°	-	20.8	-



Not trying to predict growth=>overall linear db works better

Analytical Results

828 Fiber-matrix debond criteria-Quadratic vs. Linear

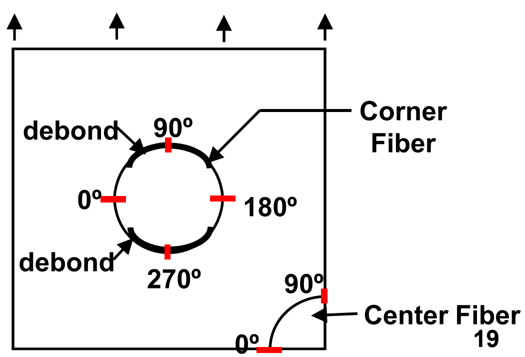
Fiber Spacing	Exp db Limits (deg)	Quadratic db Criterion limits (deg)	%Δ	Linear db Criterion limits (deg)	%Δ
1.57df	44.5	52	16.5	42	***5.5***
1.9df	32	32	***0***	24	13.9
2.0df	35	32	***5.5***	24	20
2.5df	66.5	81	38.3	65	***6.4***
6.0df	[illegible]	[illegible]	[illegible]	68	***8.3***
SF	[illegible]	[illegible]	[illegible]	26	20.8

$$\frac{11}{3}\left[\frac{\sigma_r}{\sigma_{yt}}\right]+\frac{4}{3}\left[\frac{\tau_{r\theta}}{\tau_y}\right]\geq 1$$

Fiber Spacing	[illegible]	[illegible] limits (deg)	[illegible]	[illegible]ear db [illegible]erion limits (deg)	%Δ
1.57df	315.5	306	20.9	316	***1.1***
1.9df	328	326	***3.4***	334	10.3
2.0df	325	326	***1.8***	334	16.4
2.5df	293.5	281	46.8	295	***6.4***
6.0df	294	275	79.8	290	***16.7***

4th Quadrant

- **Quadratic predicts 3 of 5 in 2nd quadrant whereas, linear predicts 3 of 5 in 3rd quadrant**
- **Linear more consistent %Δ**
- **Linear criteria conservative for majority of fiber spacing**



Analytical Results

862 Fiber-matrix debond criteria development

- **Quadratic debond criteria:** $21\left[\frac{\sigma_r}{\sigma_{yt}}\right]^2 + 14\left[\frac{\tau_{r\theta}}{\tau_y}\right]^2 \geq 1$
- **Linear debond criteria:** $4.62\left[\frac{\sigma_r}{\sigma_{yt}}\right] + 1.95\left[\frac{\tau_{r\theta}}{\tau_y}\right] \geq 1$

Fiber Spacing	Exp db Limits (deg)	Quadratic db Criterion limits (deg)	%Δ	Linear db Criterion limits (deg)	%Δ
1.57df	46	30	26.7	47	***2.3***
1.75df	38	12	33.3	36	***3.7***
1.9df	50	16	45.4	37	***24.5***
2.5df					***2.6***
6.0df					***2.6***
SF					***3.6***

$$4.62\left[\frac{\sigma_r}{\sigma_{yt}}\right] + 1.95\left[\frac{\tau_{r\theta}}{\tau_y}\right] \geq 1$$

Fiber Spacing		limits (deg)		limits (deg)	%Δ
1.57df	314	343	39.7	323	***17***
1.75df	322	351	35.8	329	***11.9***
1.9df	310	347	48.1	327	***29.8***
2.5df	308	324	29.6	312	***9.5***
6.0df	309	311	***4.9***	305	10.3

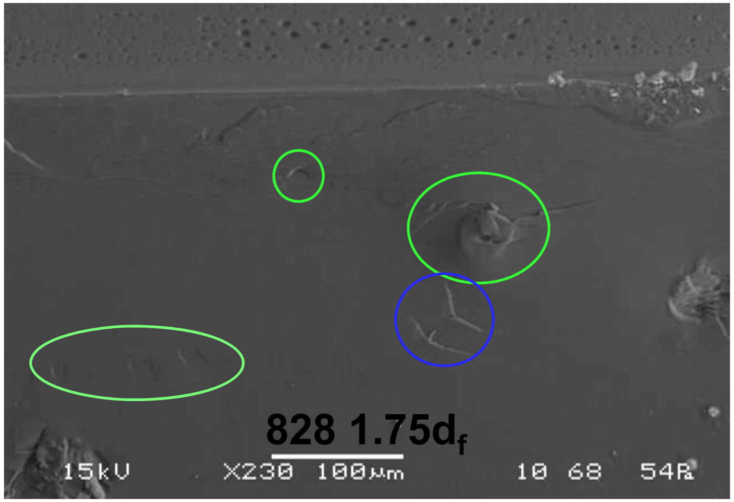
4th Quadrant

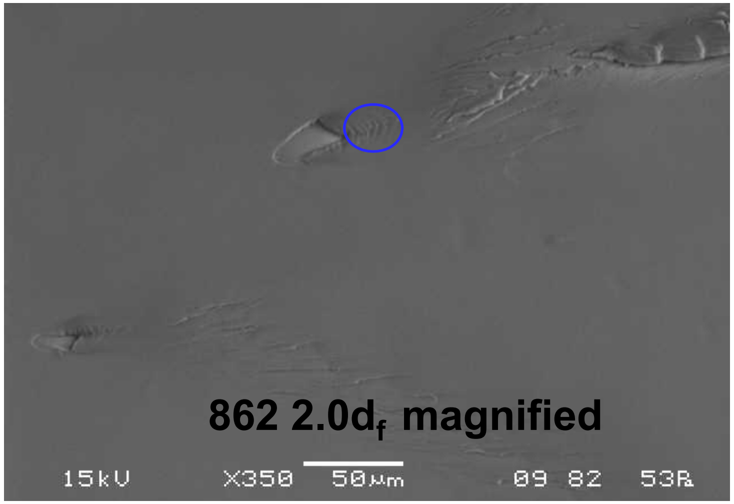
- **Linear criteria more accurate predicting debond**
- ***Works at different fiber spacing and across two material systems***

Analytical Results

Matrix failure criterion development

- **Matrix cavitation only occurs under a tensile tri-axial stress state**
- **Fracture surface analysis at cavitation features indicate a shear stress component present**
- **Occurs in region bounded by approximately 1 fiber diameter beyond corner fibers**





Seem to indicate that shear component highly likely creating unique features

Analytical Results

Matrix failure criterion development

- **Literature search reveals several potential criteria**
  - **Dilatational energy density:** $U_v = \frac{1-2\nu}{6E}(\sigma_1+\sigma_2+\sigma_3)^2$
  - **Stress invariant:** $J_1 = (\sigma_1+\sigma_2+\sigma_3)$
  - **Modified von Mises:**

$$A(\sigma_1+\sigma_2+\sigma_3)+B\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]=1$$

$$A=\frac{(\sigma_{yc}-\sigma_{yt})}{\sigma_{yc}\sigma_{yt}} \qquad B=\frac{1}{(2\sigma_{yc}\sigma_{yt})}$$

  - **Eyring's therory on non-Newtonian flow:** $\tau_0 + Ap = C$

$$A=\frac{\sqrt{2}(\sigma_{yc}-\sigma_{yt})}{(\sigma_{yc}+\sigma_{yt})} \qquad C=\frac{2\sqrt{2}(\sigma_{yc}\sigma_{yt})}{3(\sigma_{yc}+\sigma_{yt})} \qquad p=\sigma_{on}=\frac{\sigma_1+\sigma_2+\sigma_3}{3}$$

  - **Modified-Tresca:** $\tau_s = \tau_s^0 - \mu\sigma_{on}$ $\qquad \mu = \frac{3}{2}\left[\frac{(\sigma_{yc}-\sigma_{yt})}{(\sigma_{yc}+\sigma_{yt})}\right]$

    $\tau_s^0 =$ pure shear

  - **3-D analogy to Mohr-Coulomb:** $\tau_{oct} = \tau_s - \mu\sigma_{on}$ $\qquad \mu = \tan\phi$

    $\tau_s =$ octahedral shear in absence of any pressure

Material under tensile tri-axial stress state fail at lower loading=>after through eval of all criteria only Mod-Tresca & Mohr-Coulomb work

Analytical Results

Matrix failure criterion development

Evaluation of Modified-Tresca and Mohr-Coulomb criteria via independent neat resin tests

Neat resin test	Mod-Tresca (MPa)	τ_s (MPa)	Δ	%Δ	Mohr-Coulomb (MPa)	τ_{oct} (MPa)	Δ	%Δ
Tensile	39.83	30.85	9.25	23.2	33.25	29.08	4.17	**12.5**
Shear	45.61	45.61	0	0	37.24	37.24	0	**0**
Compression	54.04	45.04	9.01	16.7	43.07	42.46	0.61	**1.4**

828/D-230 neat resin evaluation results

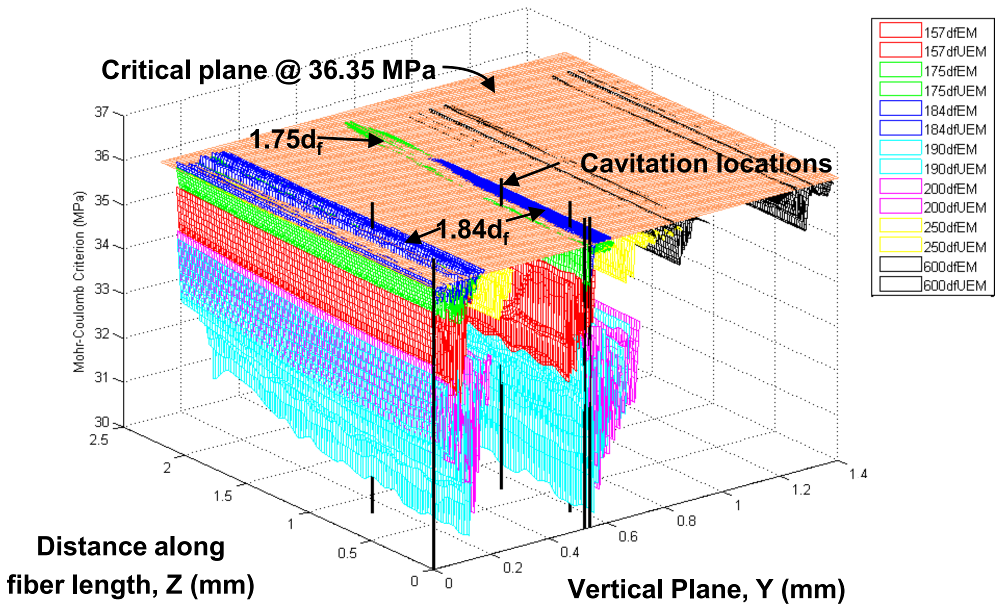
Neat resin test	Mod-Tresca (MPa)	τ_s (MPa)	Δ	%Δ	Mohr-Coulomb (MPa)	τ_{oct} (MPa)	Δ	%Δ
Tensile	56.61	38.94	17.67	31.2	48.1	36.71	11.39	**23.7**
Shear	66.38	66.38	0	0	54.2	54.2	0	**0**
Compression	80.26	61.61	13.65	17	63.85	58.09	5.76	**9**

862/W neat resin evaluation results

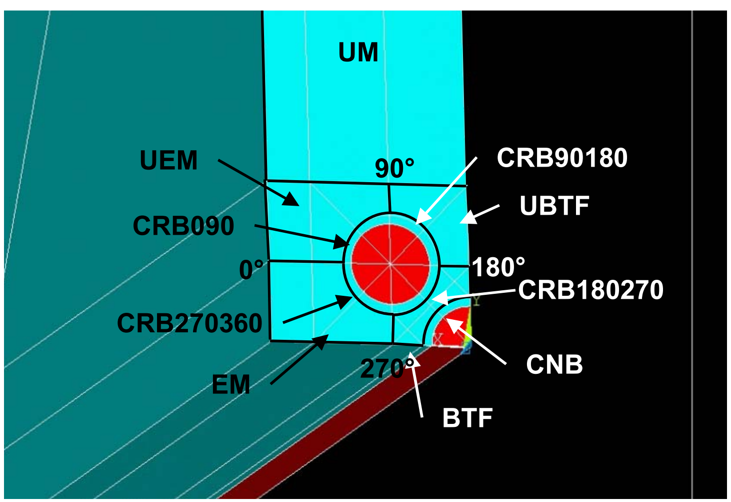
Analytical Results

828/D-230 Matrix failure criterion development results

EM & UEM Matrix Mohr-Coulomb Criterion in YZ plane

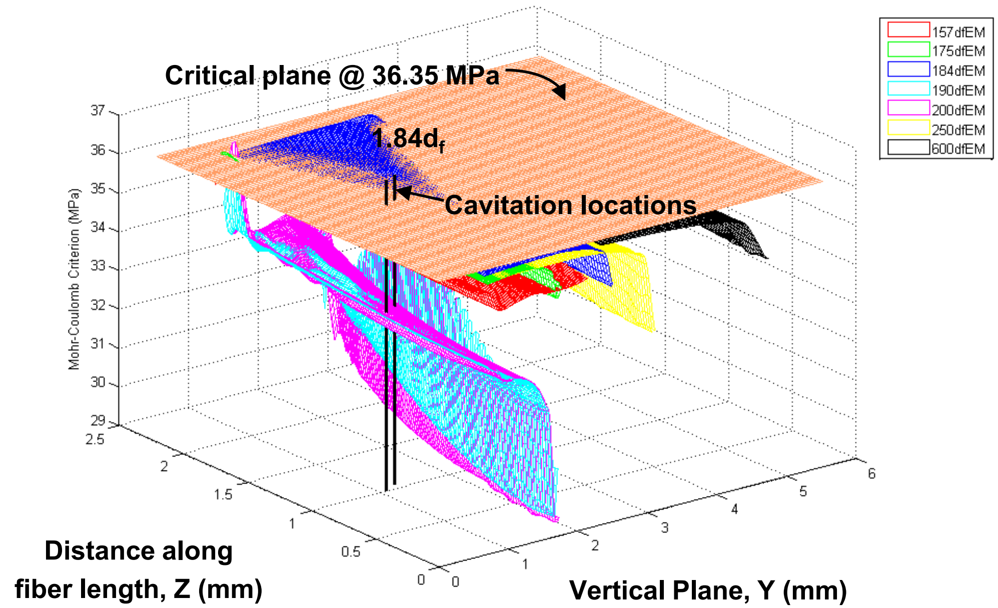


- **The Mohr-Coulomb predicts the fiber spacing and locations of the specimens exhibiting matrix cavitation as their first failure mechanism**
- **All other fiber spacing groups are below the critical value indicating that cavitation does not form**



All volumes were evaluated and these shown along w/BTF & UBTF exceed critical value

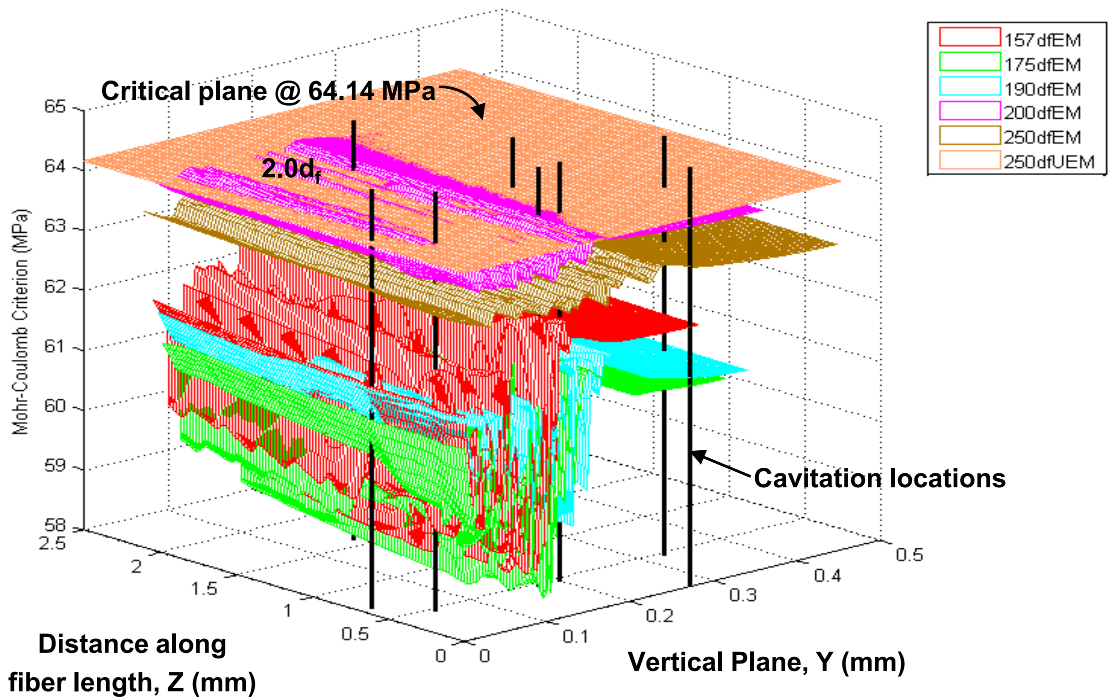
UM Matrix Mohr-Coulomb Criterion in YZ plane

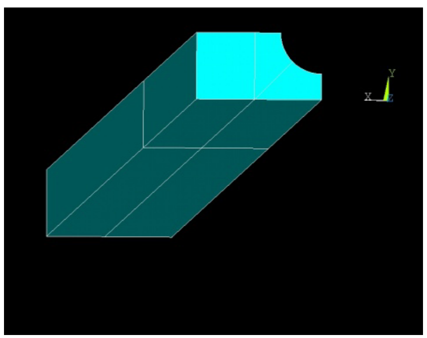


Analytical Results

862/W Matrix failure criterion development results

Exterior Matrix Mohr-Coulomb Criterion in YZ plane





EM volume

- The Mohr-Coulomb predicts the fiber spacing and locations of the specimens exhibiting matrix cavitation as their first failure mechanism
- All other fiber spacing groups are below the critical value indicating that cavitation does not form

Summary and Conclusions

- **Experimental Results**
  - Observed two different failure modes
    - Matrix Cavitation
      - Never before observed
    - Fiber – Matrix debonding
      - Only observed in single fiber cruciform specimens
  - Matrix Cavitation
    - Occurred at 1.84d_f and 1.75d_f in the 828/D-230 system
    - Occurred at 2.0d_f in the 862/W system
  - Fiber – Matrix Debonding
    - Occurred in SF, 6.0d_f, 2.5d_f, 2.0d_f, 1.9d_f and 1.57d_f in the 828/D-230 system
    - Occurred in SF, 6.0d_f, 2.5d_f, 1.9d_f , 1.75d_f and 1.57d_f in the 828/D-230 system

- **Analytical Results**
  - Developed Fiber-matrix debonding Criterion
    - Predicts the debond initiation
    - Fiber spacing exhibiting debonding
  - Applied correct matrix failure criterion
    - Predicts the cavitation locations
    - Predicts the fiber spacing exhibiting cavitation
  - Criteria correctly explain experimentally observed failure initiation
    - Same criteria works in both matrix systems

Questions

Questions ?