Mesh Independent Modeling and Moiré Interferometric Examination of the Accumulation of Damage in Composites with Open-Holes

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Composites Testing and Model Identification
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Overview

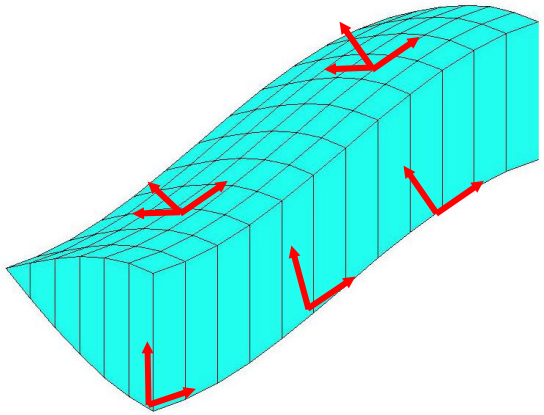
- Previous research led to a comparison of strain redistribution around a hole in a composite material (considered to be vital for strength prediction).
  - Moiré inteferometry was used to examine the specimen
    - Cursory look only.
  - The B-Spline Analysis Method (BSAM) with mesh independent damage capability was used to model the specimen.

- A more detailed look at the experimental behavior was desired.
  - Moiré was again used.

- Unfortunately, at the time of writing, we were not able to complete the BSAM modeling for comparison.

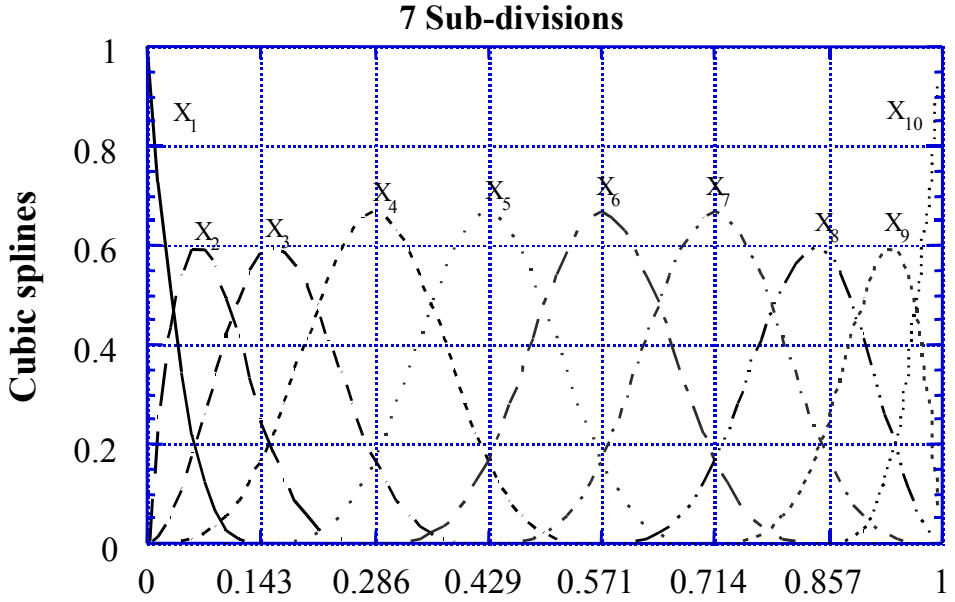
B-Spline Analysis Method (BSAM)

Superelement (Cluster)

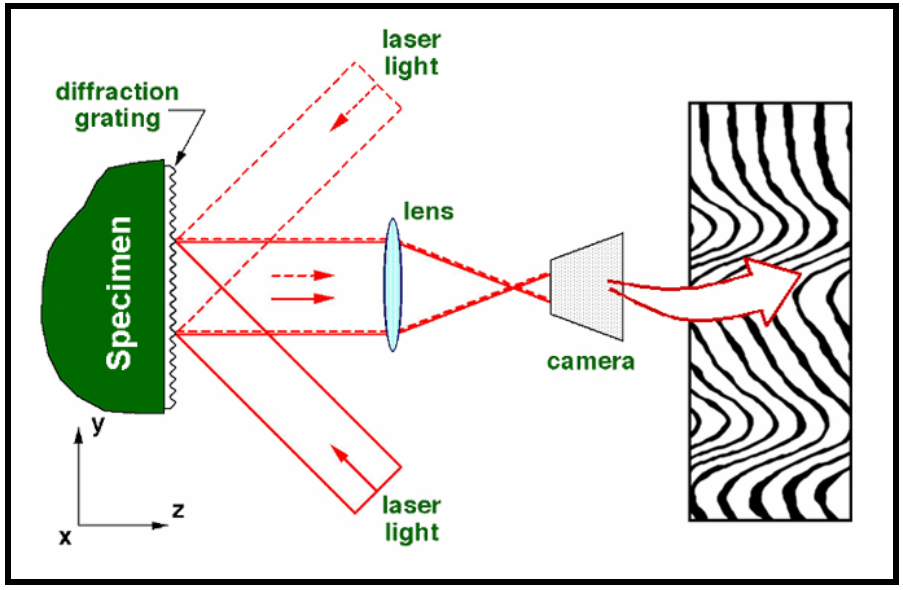


- Displacement-based method with overlapping B-spline approximation functions.
- Continuity of displacements, *strains* & *stresses* within homogeneous domains (subregions).

- Homogeneous
- Laminated
- Global –Local Laminated
- Mesh Independent Internal Discontinuities



Moiré Interferometry



$$U(x,y)=\frac{1}{f}N_x(x,y)$$

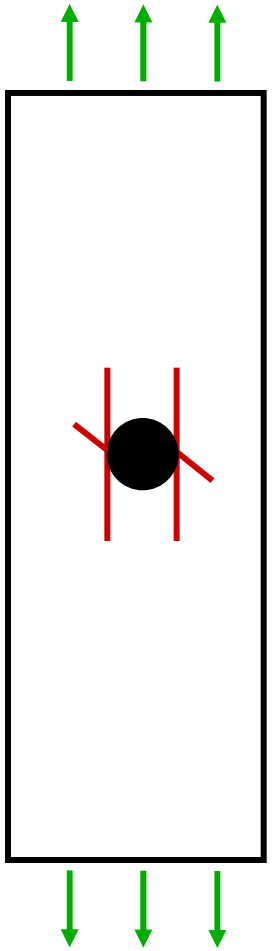
$$V(x,y)=\frac{1}{f}N_y(x,y)$$

$$\varepsilon_x=\frac{\partial U}{\partial x}=\frac{1}{f}\left[\frac{\partial N_x}{\partial x}\right]$$

$$\varepsilon_y=\frac{\partial V}{\partial y}=\frac{1}{f}\left[\frac{\partial N_y}{\partial y}\right]$$

$$\gamma_{xy}=\frac{\partial V}{\partial x}+\frac{\partial U}{\partial y}=\frac{1}{f}\left[\frac{\partial N_y}{\partial x}+\frac{\partial N_x}{\partial y}\right]$$

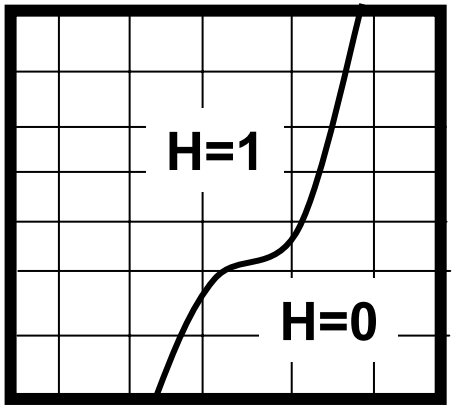
Mechanism-Based Strength Prediction



- Discrete damage modeling
  - transverse cracking
  - delaminations
  - how many cracks to model?
  - which cracks to model?
- How to model the damage?
  - remeshing (Shephard)
  - meshless methods (Belytscko)
  - ☑ step function enrichment (Belytscko)

Step Function Enrichment

Moes, Dolbow & Belytschko, 1999, *Int. J. Num. Meth. Eng.*



$$W = H\,W(u_1,v_1,w_1) + (1-H)\,W(u_2,v_2,w_2)$$

H(x) – step functions with a jump over crack surface

u,v, and w are continuous functions

$$u = \sum_n u_n X_n, \quad v = \sum_n v_n X_n, \quad w = \sum_n w_n X_n$$

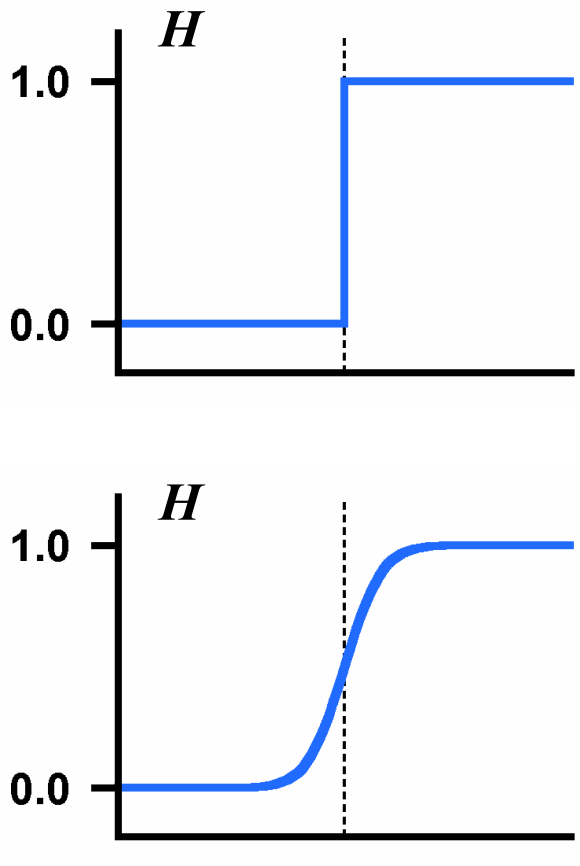
Near zero volume elements

Requires Modified integration schemes

Restricted to linear elements

Mesh Independent Crack Modeling

by using higher order shape functions



The numerical implementation contains **only the original approximation functions and their products**, thus the Gaussian integration is carried out within the **original mesh**

$$H = \sum_n h_n X_n$$

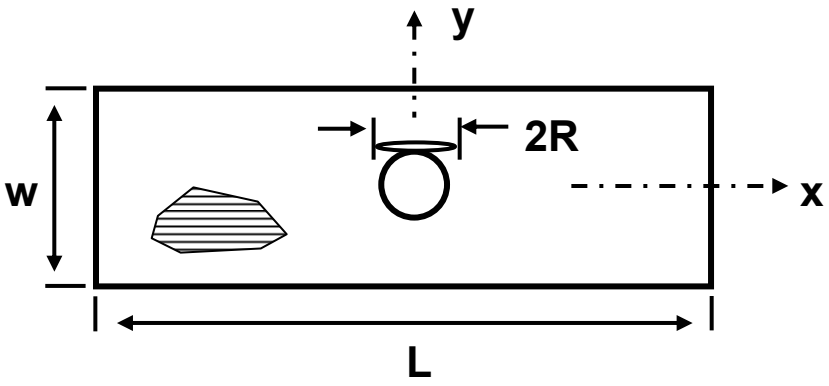
$X_n(\mathbf{x})$ – *displacement approximation shape functions*

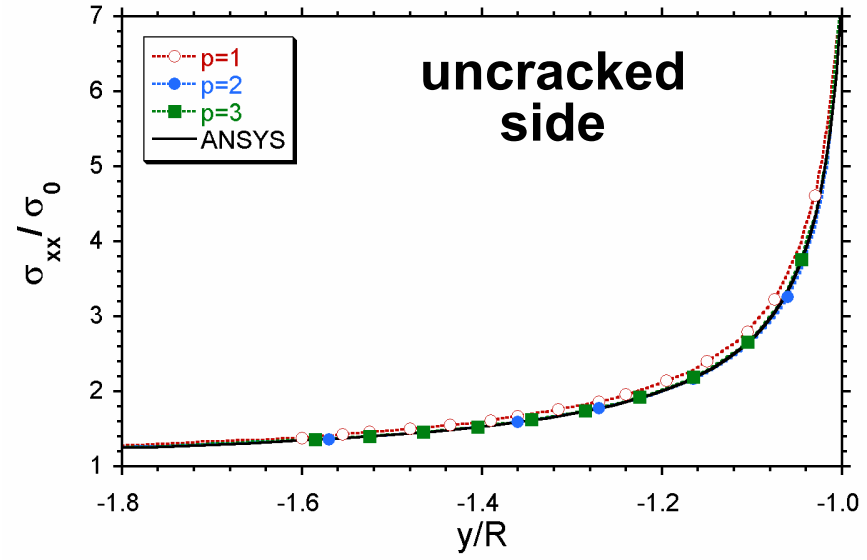
h_n – *coefficient defined by crack surface location*

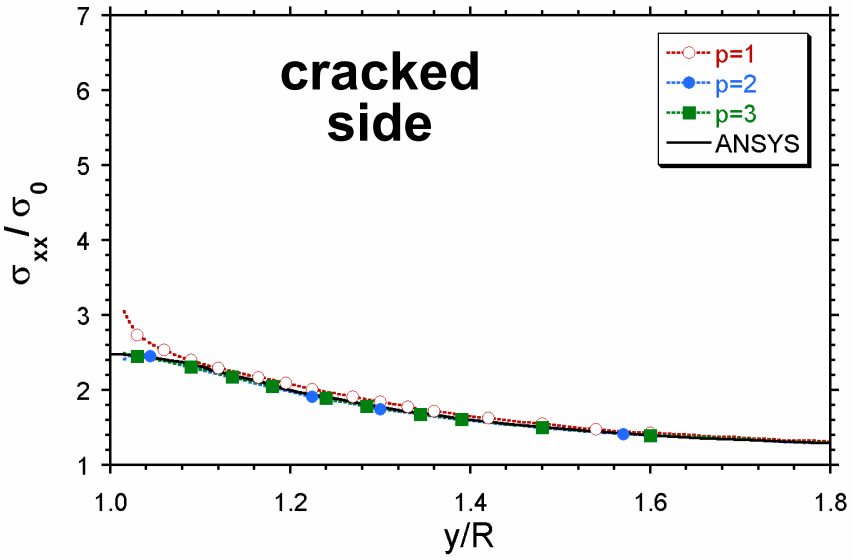
Iarve, 2003, *Int. J. Num. Meth. Eng.*

Mesh Independent Crack Modeling
(0° open-hole tensile coupon)

- **BSAM mesh independent crack modeling approach**
  - **varying degrees of approximation order**
  - **finite element method verification through explicit crack meshing**

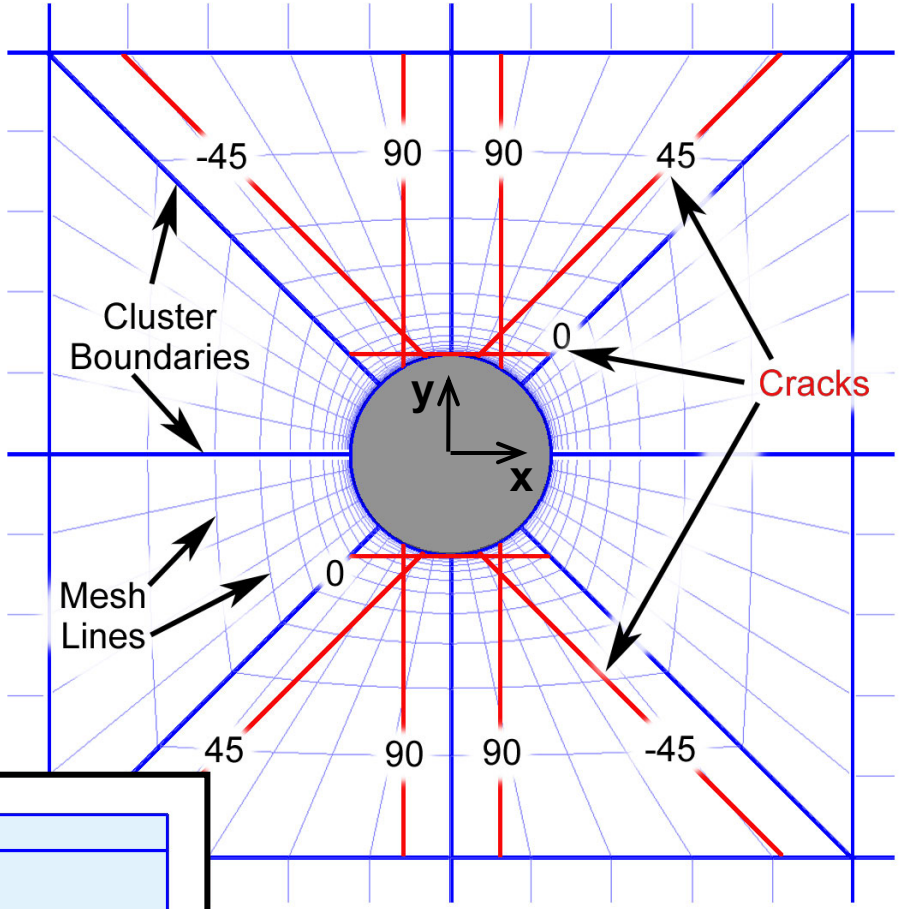


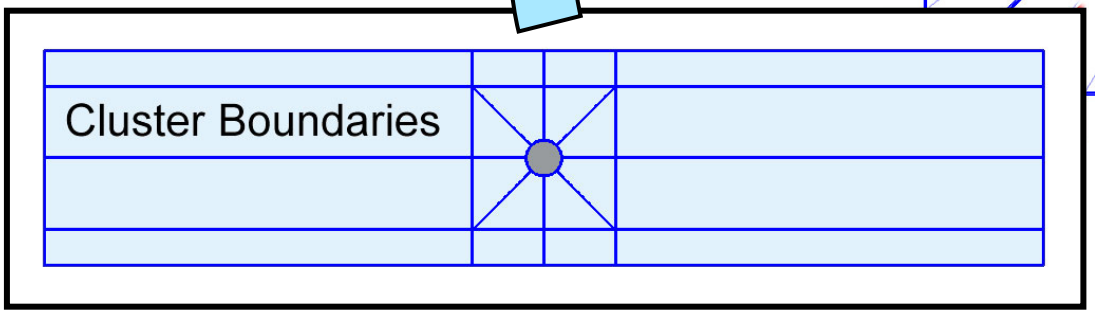




Previous Research Results of Explicitly Modeled Cracks in a $[0/+45/90/-45]_s$ Laminate

- **Specimen modeled with cracks in similar locations to actual damage sites ...**
  - **no damage**
  - **0°, 45°, 90°, & -45° ply cracks**
  - **45°, 90°, & -45° ply cracks**
  - **0° ply cracks**
    - **anti-symmetric**
    - **symmetric**
  - **45° ply cracks**
  - **90° ply cracks**
  - **-45° ply cracks**





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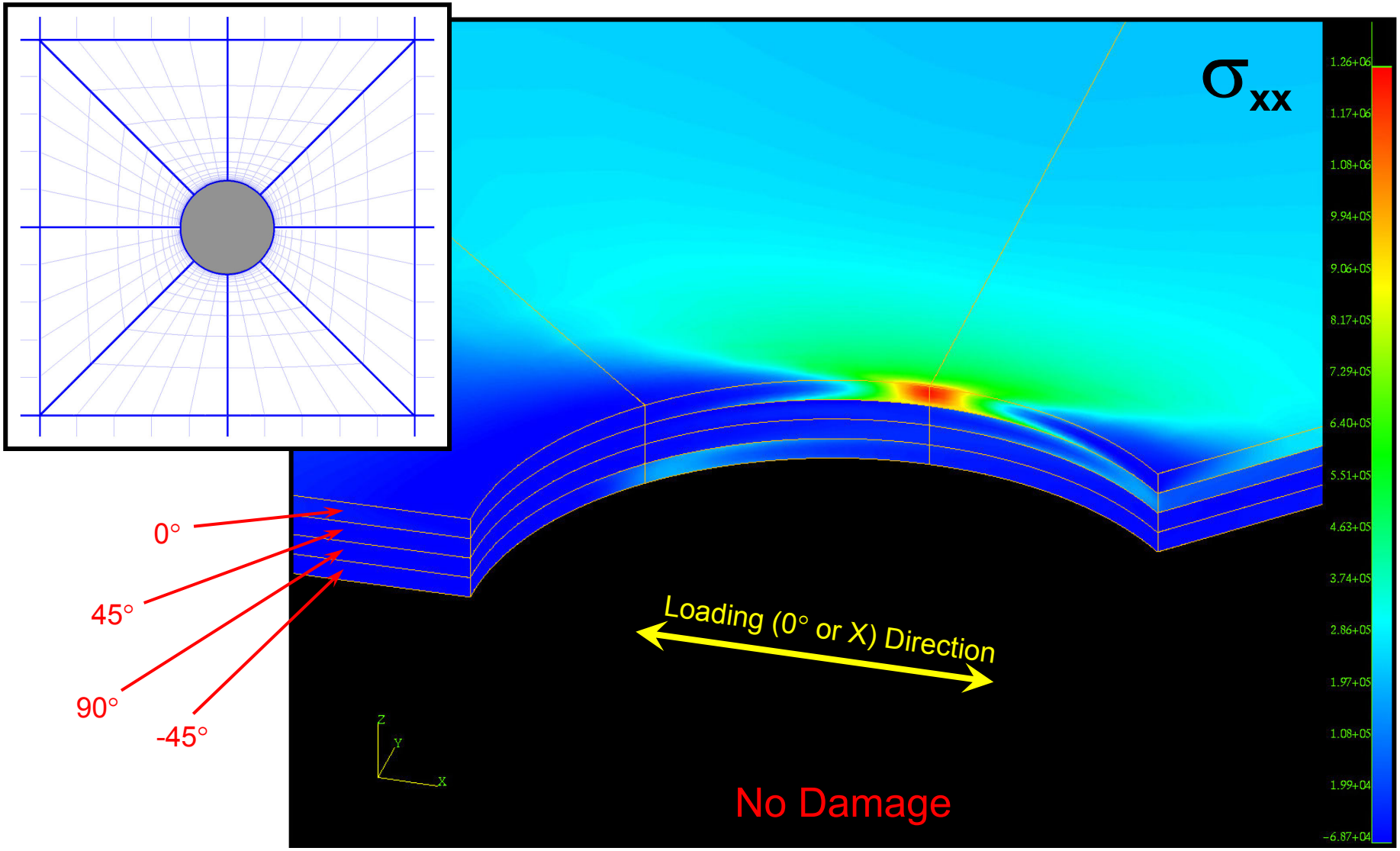

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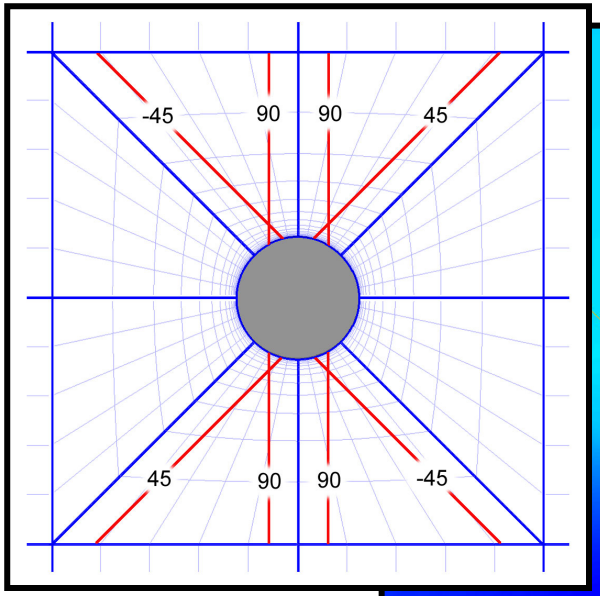

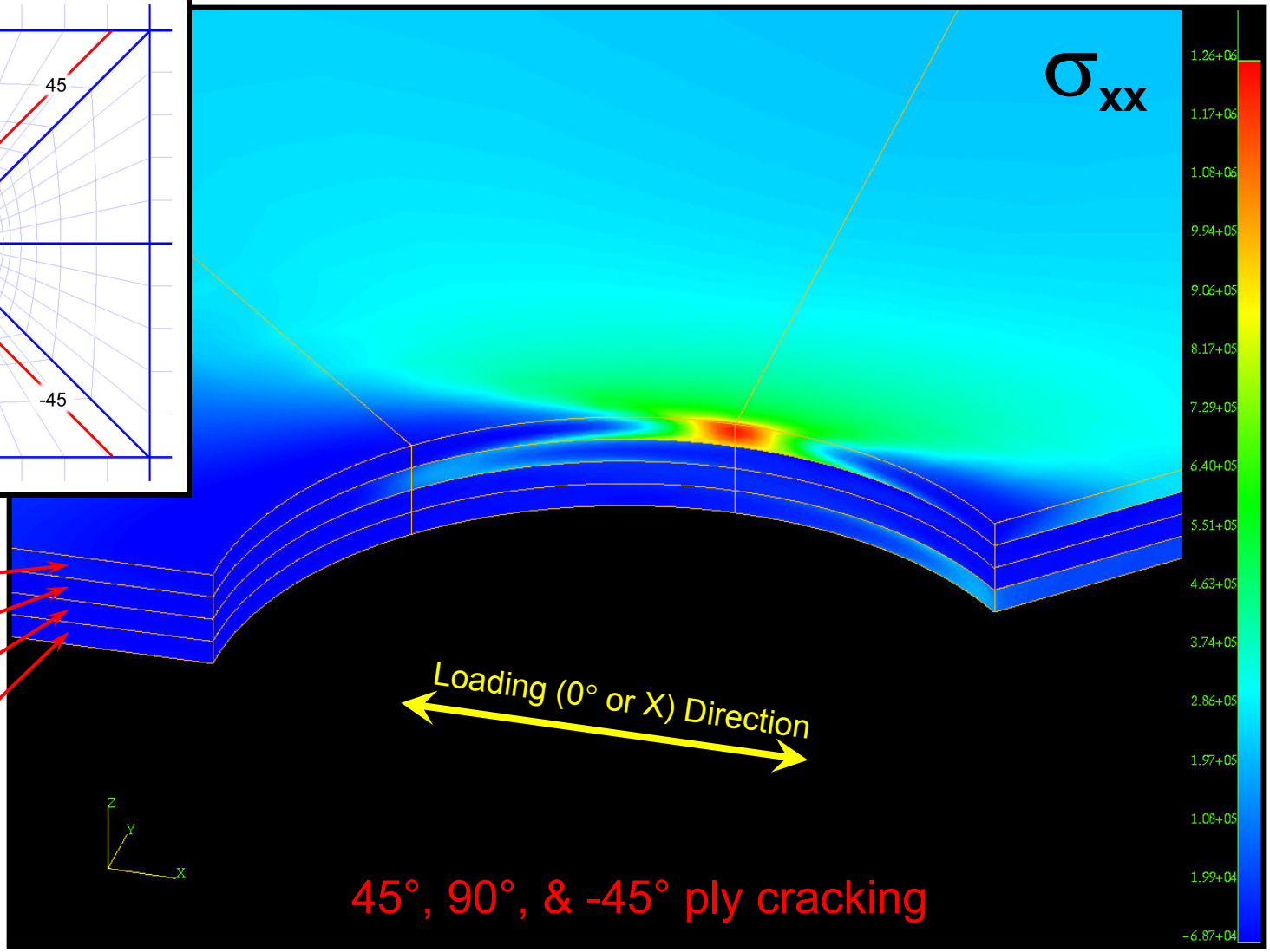

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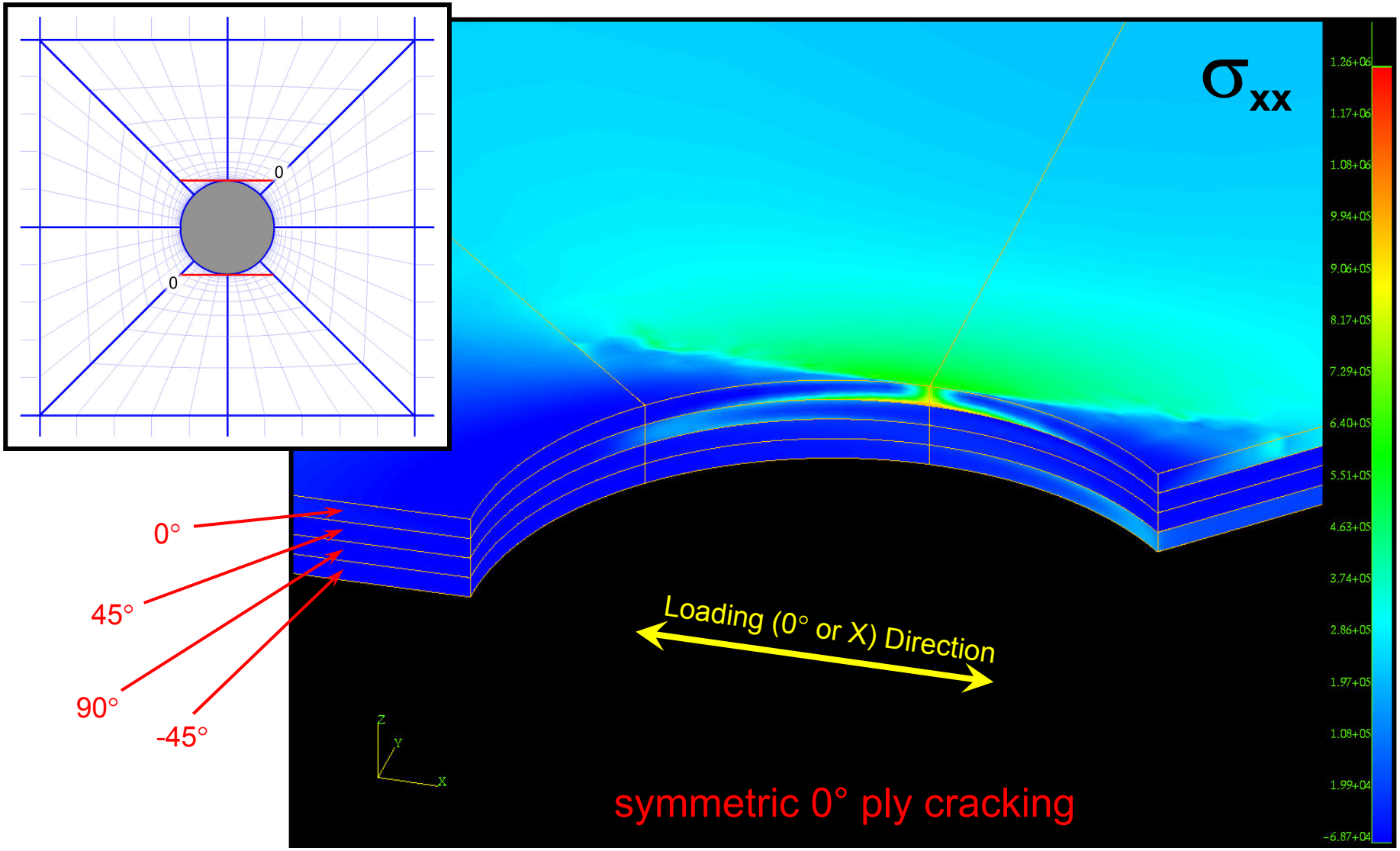

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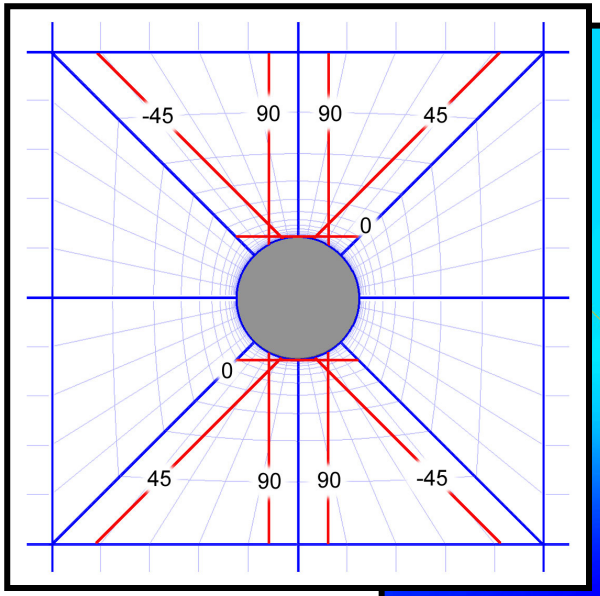
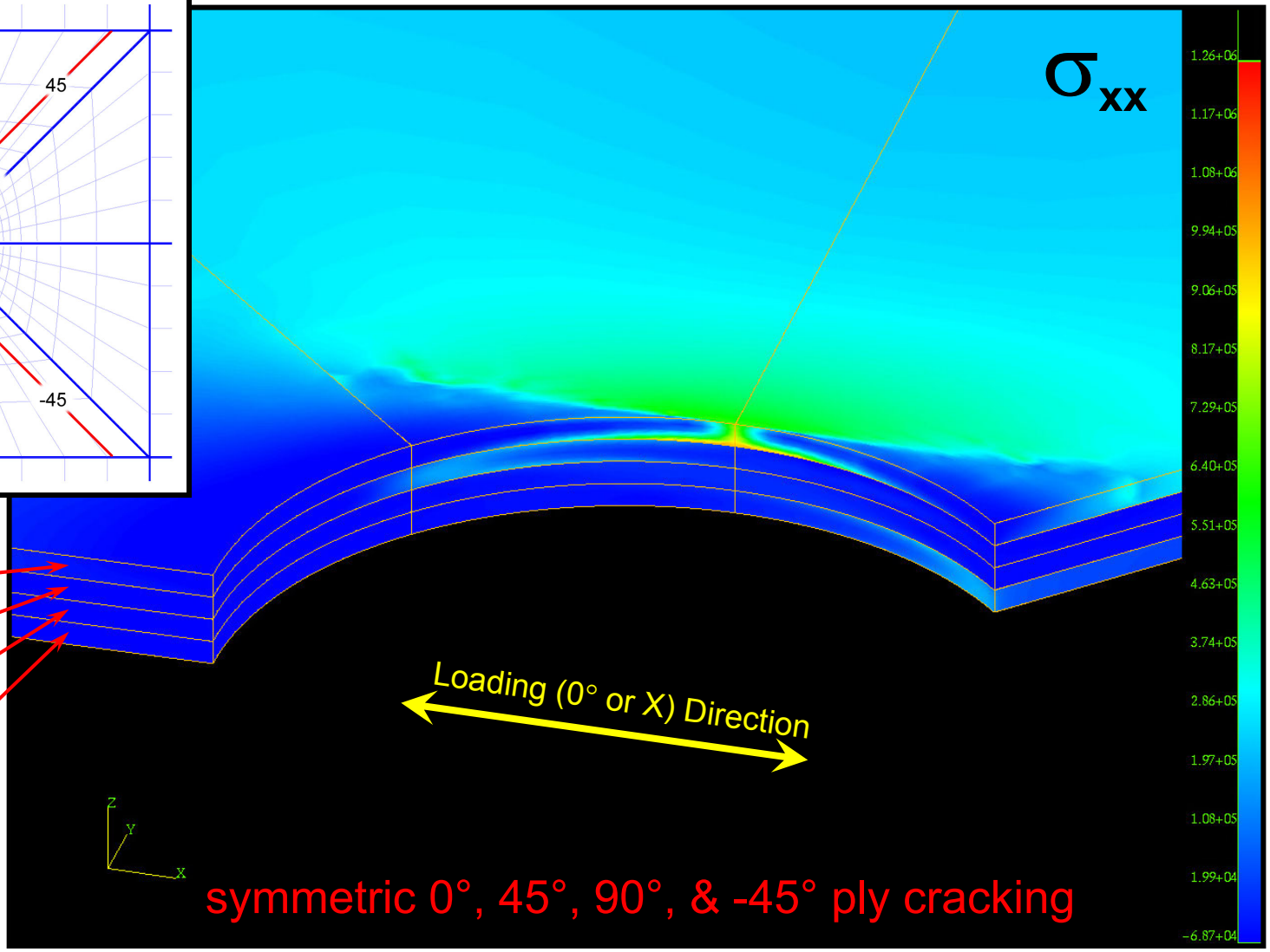
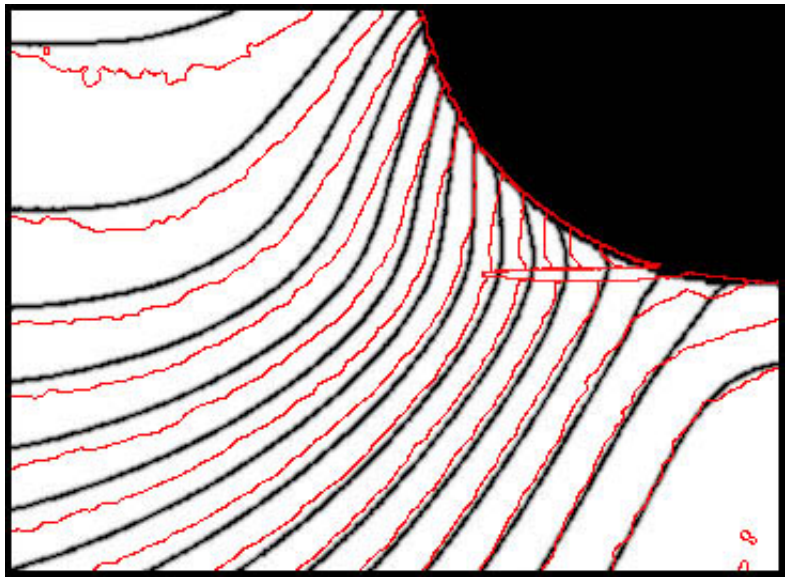


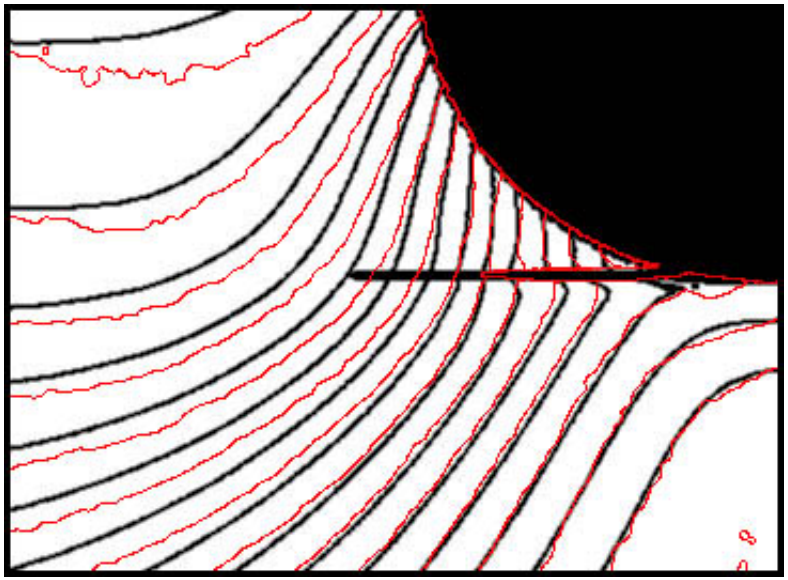


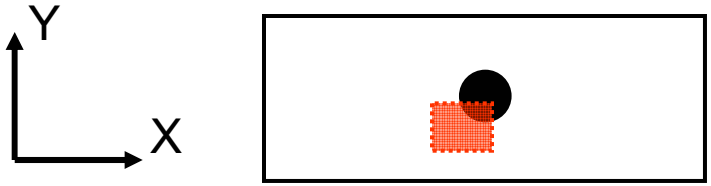
Previous Moiré Results of Transverse (U_y) Displacement Comparison

Moiré results compared with **undamaged** BSAM predictions



Moiré results compared with **damaged** BSAM predictions

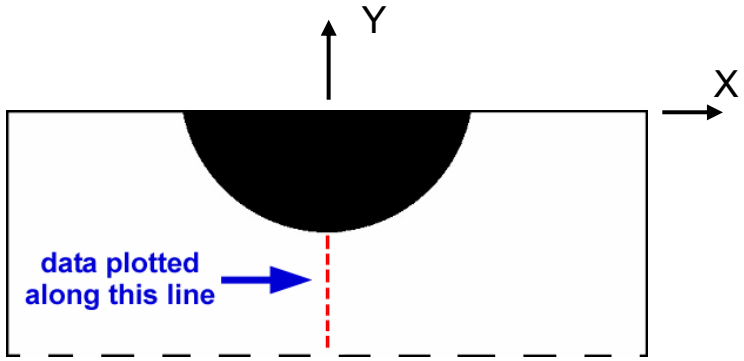


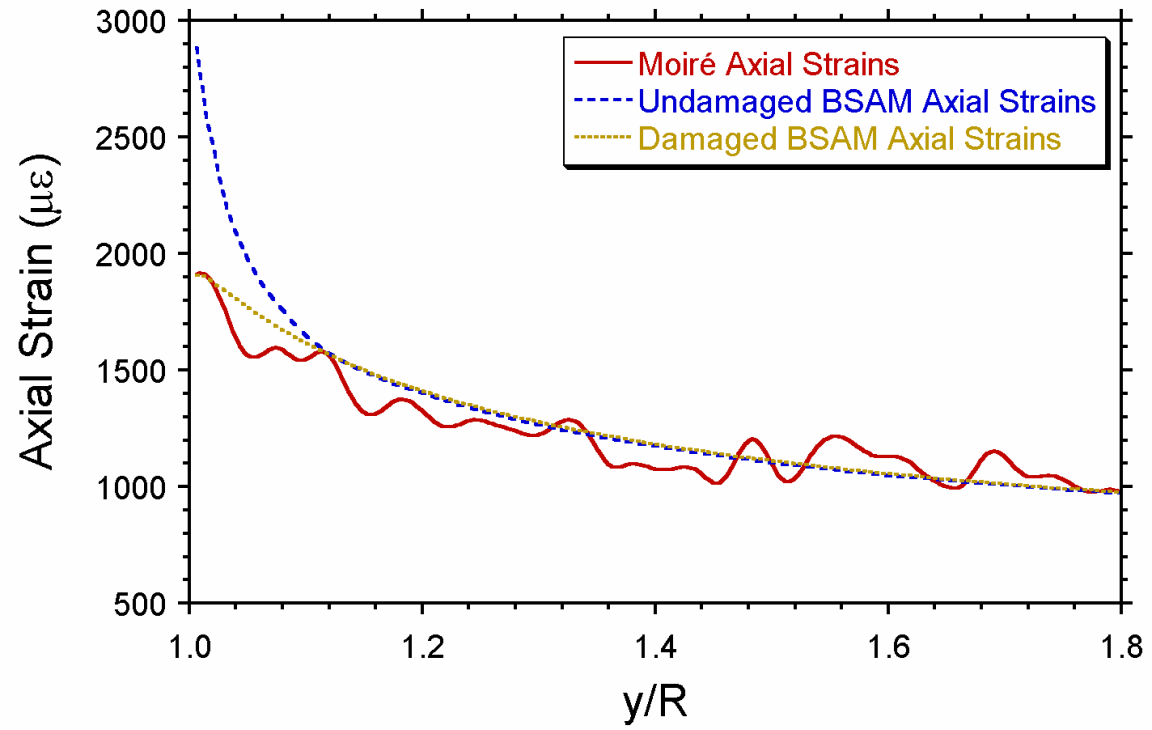


- Moiré contours are in red
- BSAM contours are in black
- Contour interval is 200 nm

Previous Research: Axial Strain Comparison

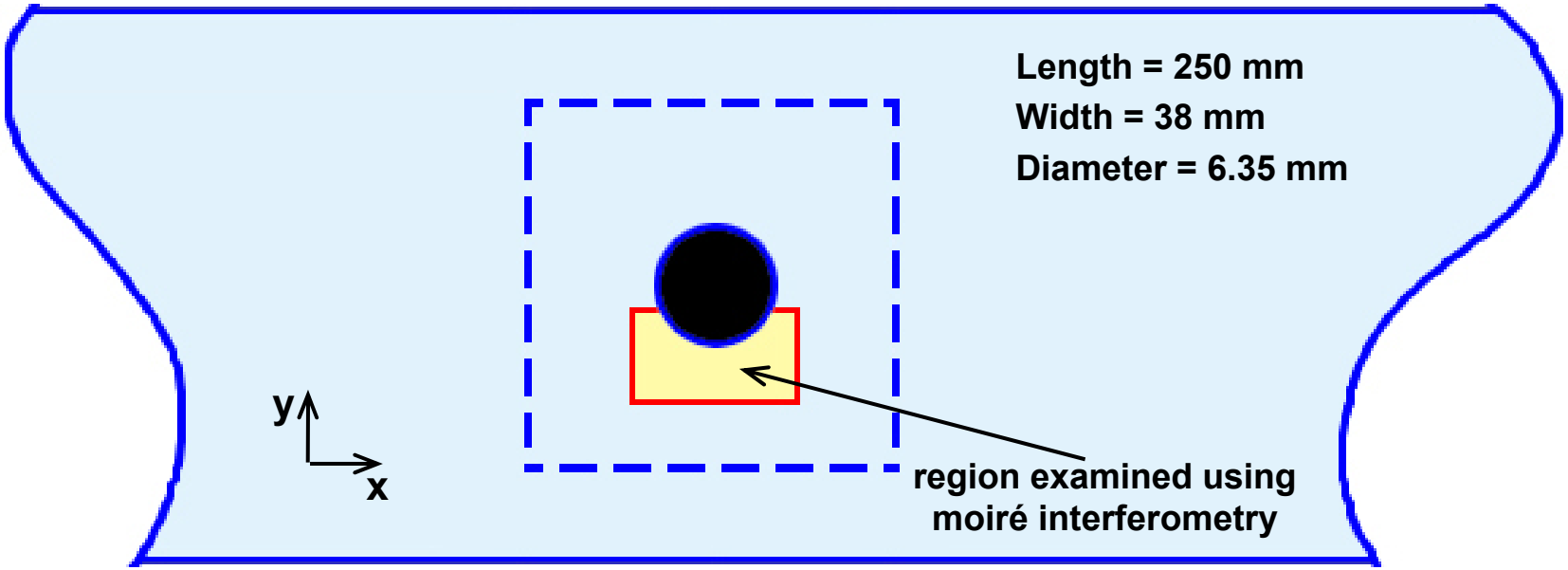
- **Predicted reduction of axial strain matched by strain obtained through moiré**





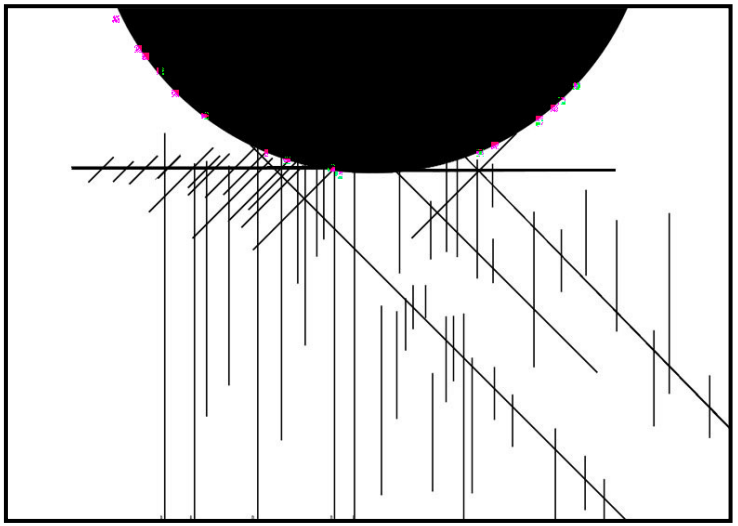
Description of $[0/+45/90/-45]_s$ Laminated Specimen

- Two holes (far apart) were drilled in the specimen (only one examined with moiré interferometry.
- Specimen loaded in uni-axial tension until some damage had been induced ...
  - X-ray revealed crack distribution
  - cracks were visible in all plies.
  - Delaminations were not detected

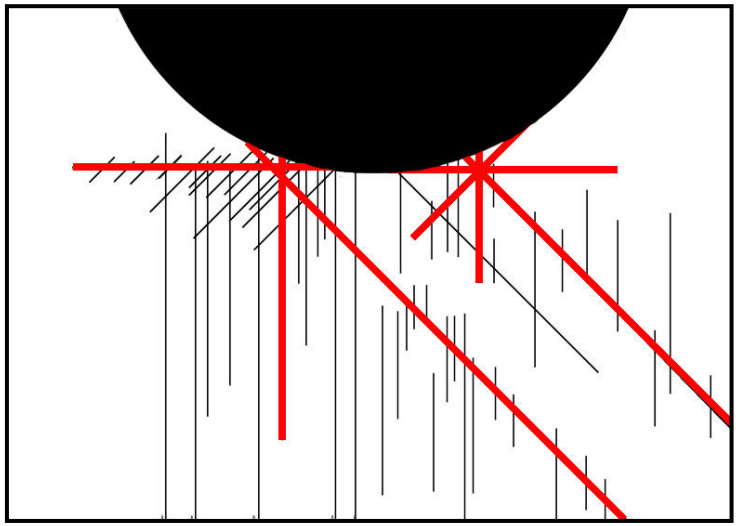


Experimental Testing Procedure

- $[0/+45/90/-45]_s$ specimen loaded in uni-axial tension:
  - 2225 N load increments until failure at 17125 N.
    - final induced the damage pattern shown below (enabled by failure through only one of the 2 holes.
  - 2225 N applied for acquisition of moiré interferometry data.
    - final 2225 N load applied by regripping broken end.
- Moiré Interferometry: fringe patterns captured digitally and analyzed using a phase-shifting algorithm

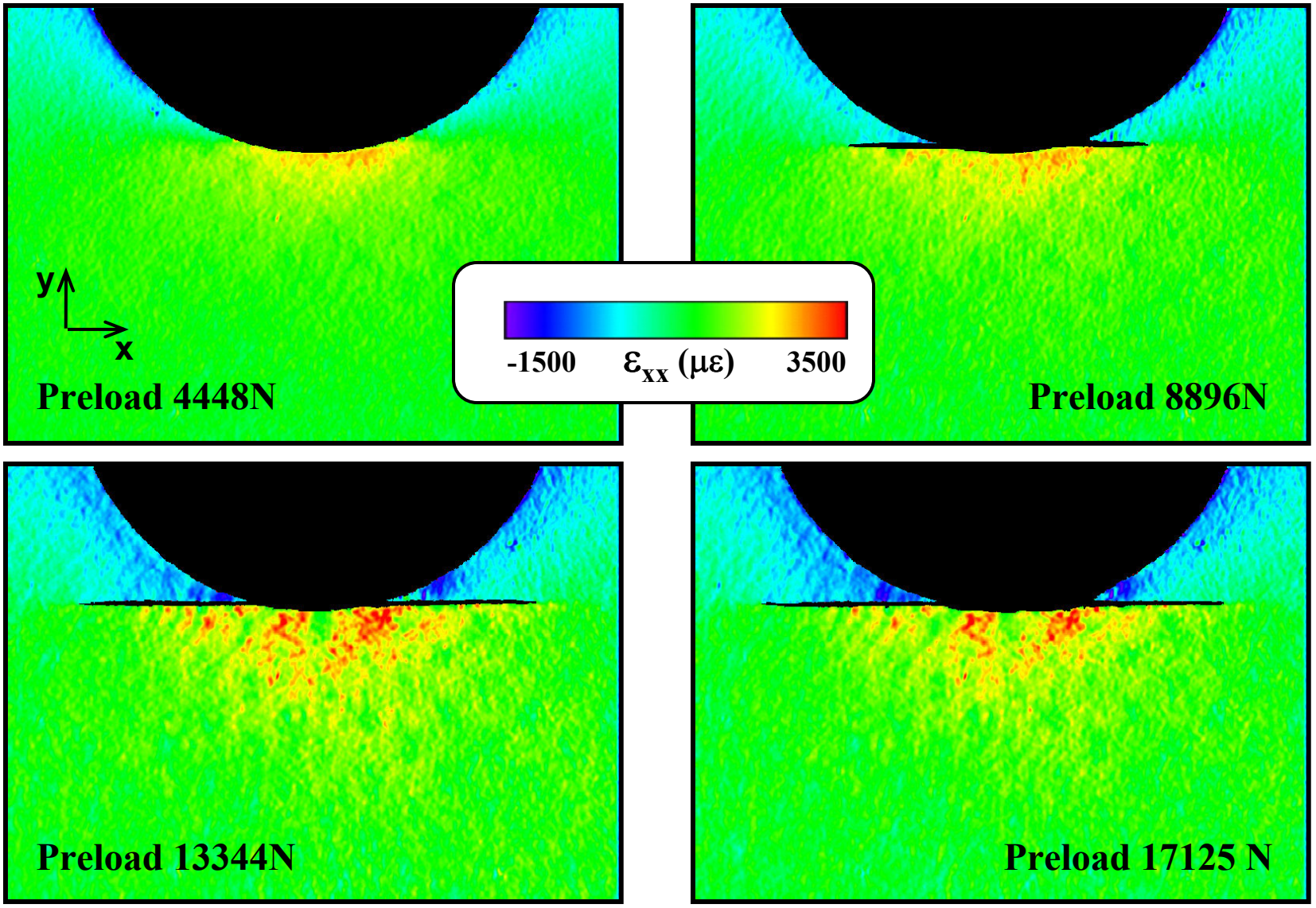


magnified view of the actual damage pattern

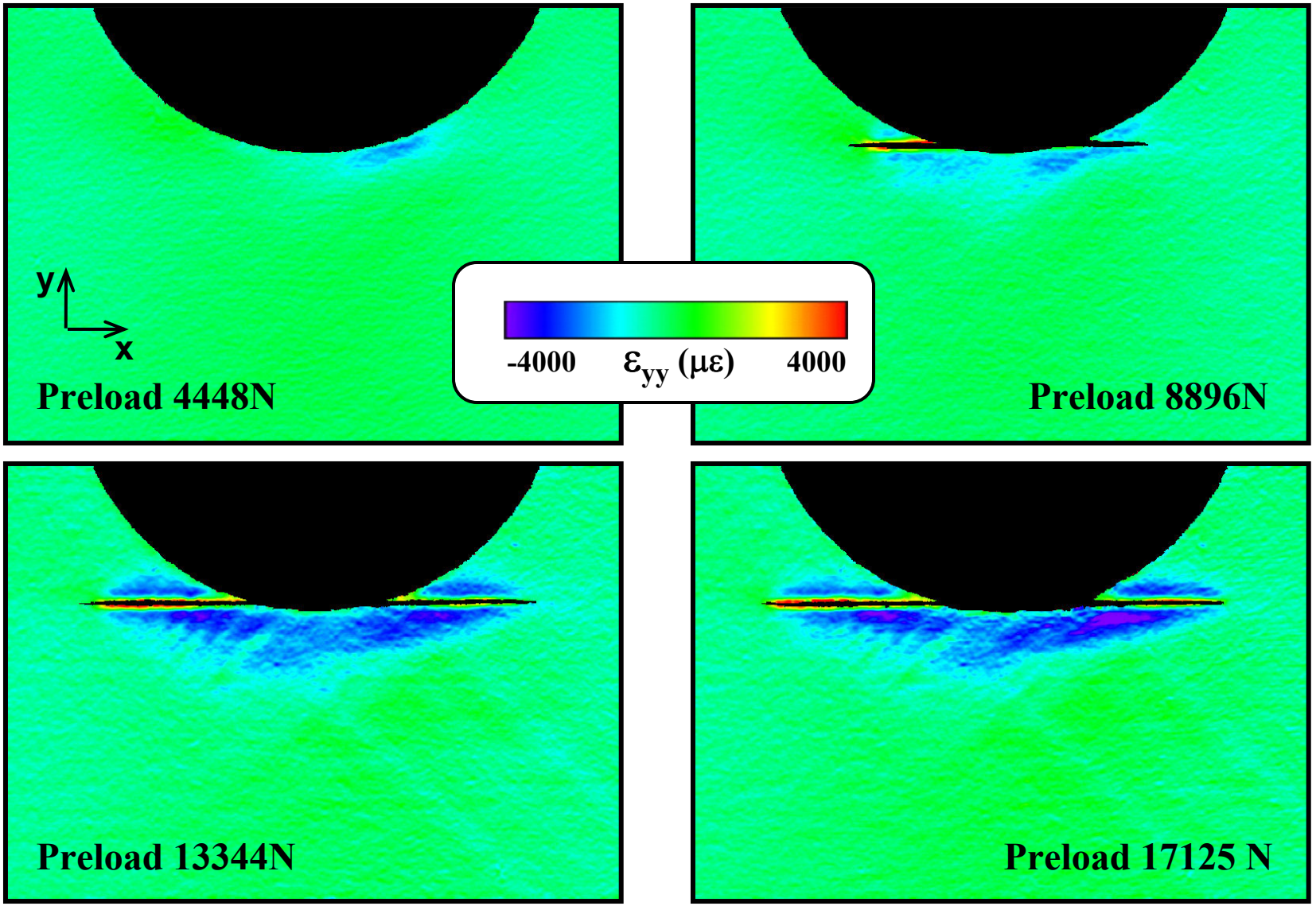


magnified view of the modeled damage pattern

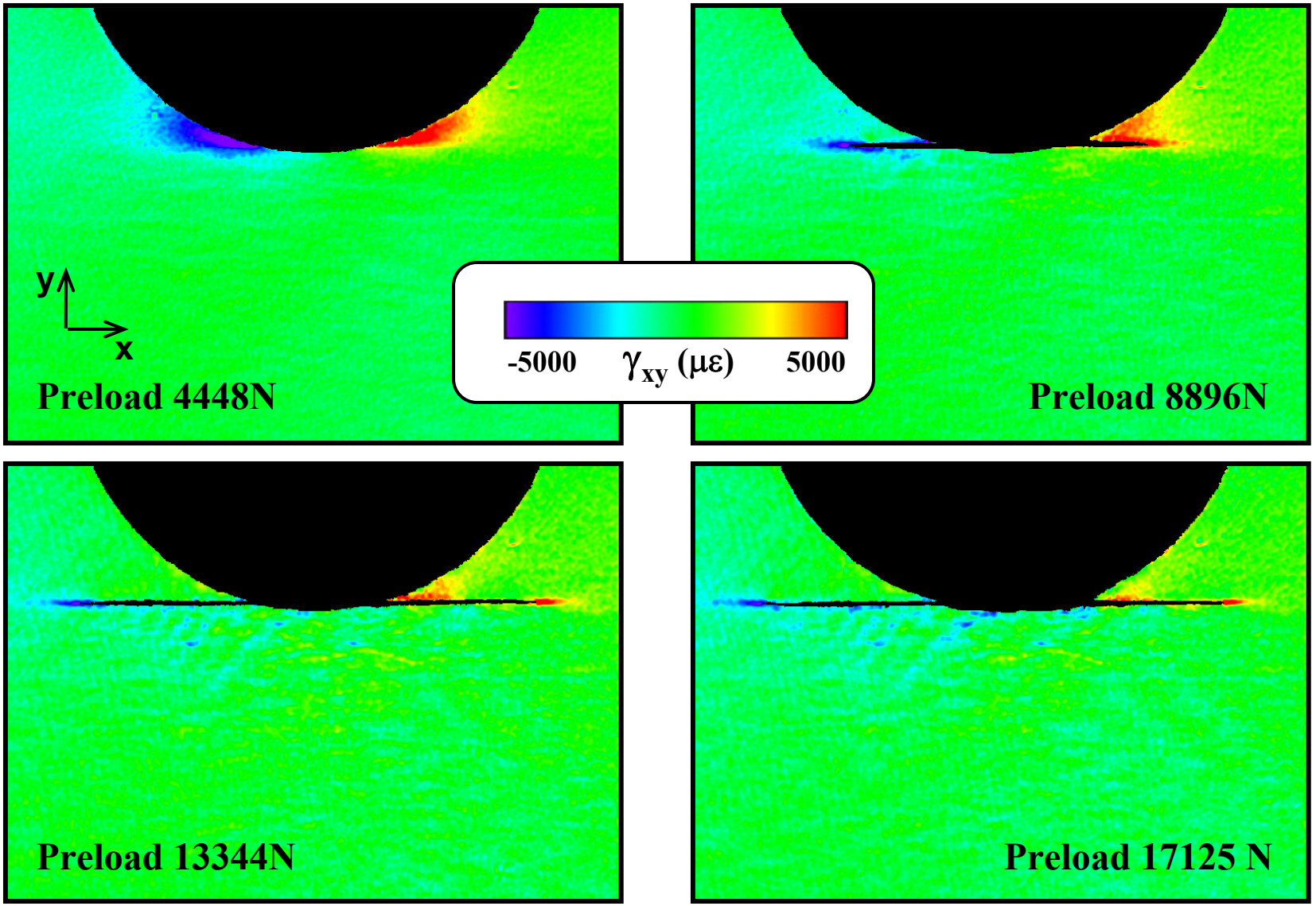
Strains Resulting from 2225 N Load from Various Applied Pre-Loads (ε_{xx} Strain Component)



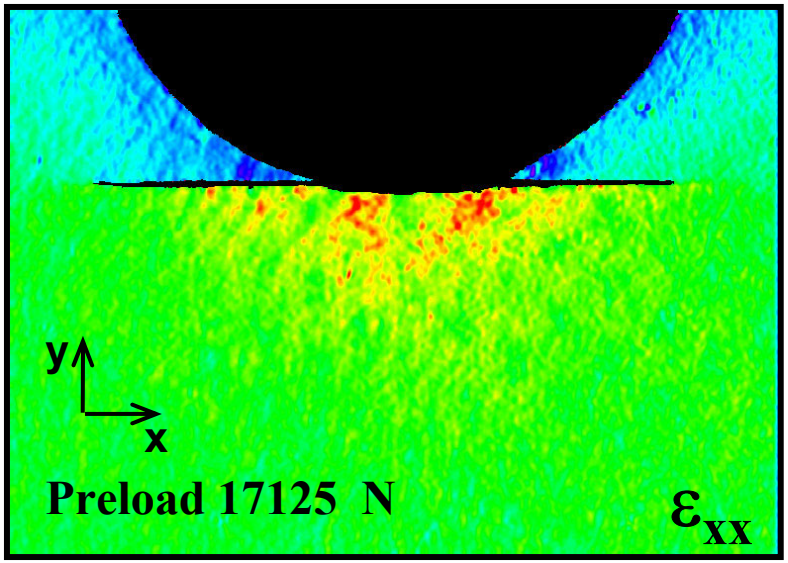
Strains Resulting from 2225 N Load from Various Applied Pre-Loads (ε_{yy} Strain Component)

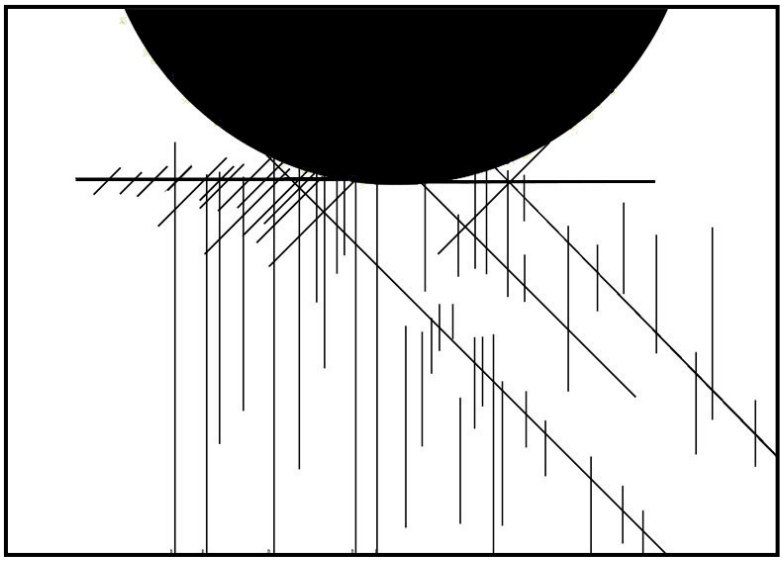


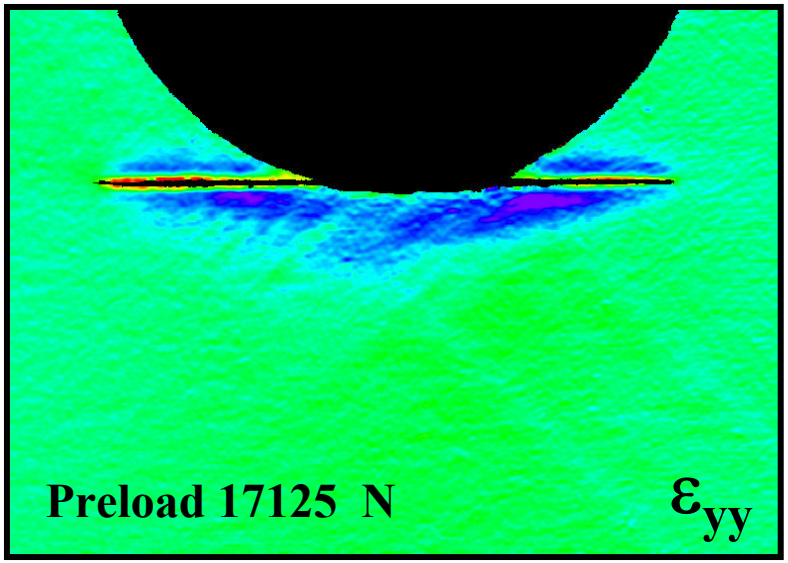
Strains Resulting from 2225 N Load from Various Applied Pre-Loads (γ_{xy} Strain Component)

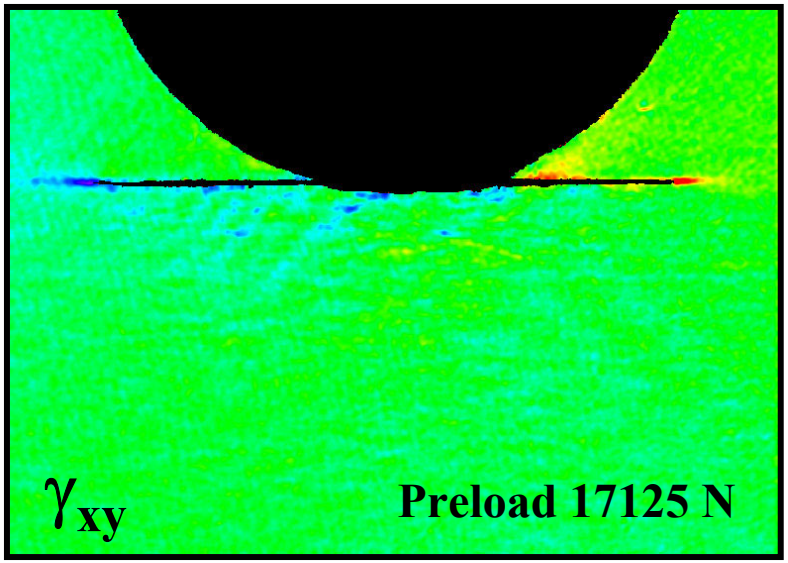


Strains Resulting from 2225 N Load from Various Applied Pre-Loads (ε_{xx} Strain Component)



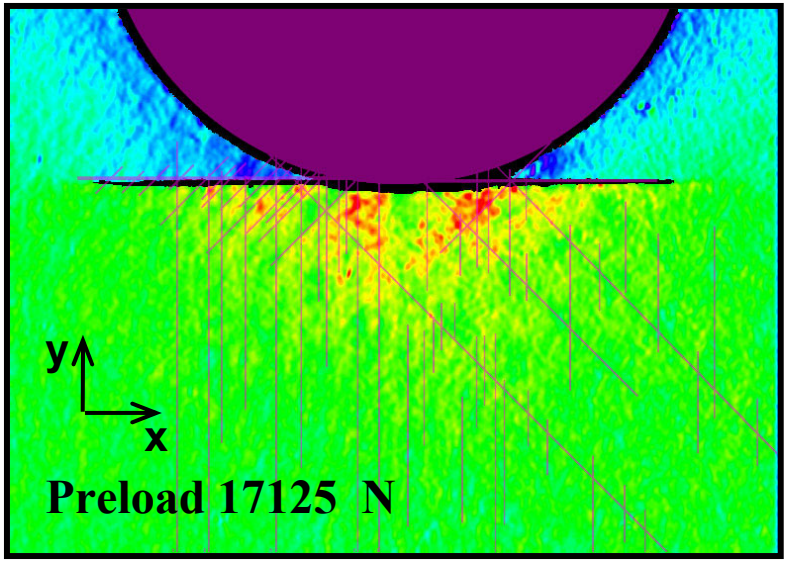


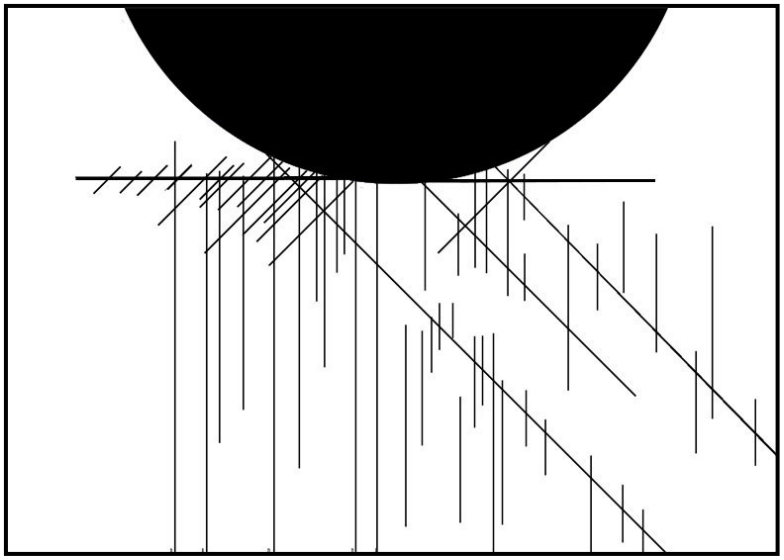


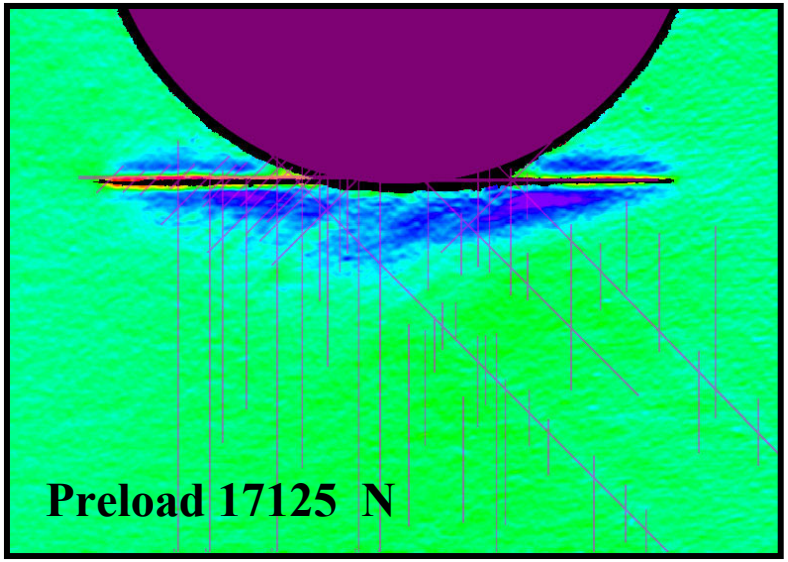


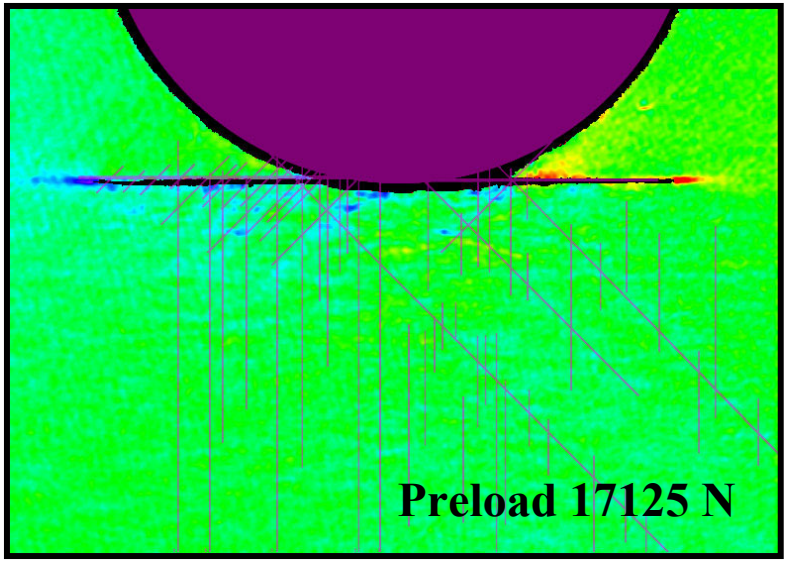
Comparison of Strain Results at Various Loads

(ε_{xx} Strain Component)









Observations from Experimental Testing

- Difficulty with application of moiré grating resulted in a 20% reduction in thickness of both 0-plies
  - Grating material did not properly cure and had to be removed by sanding.
- Drilling of 2 holes and the lucky failure through the hole that was not being examined with moiré, resulted in the ability to test the other hole at very near the failure load with the accumulated damage.
- Strain redistributions due to sub-ply damage were visible on the top of the laminate
  - An unexpected result
- Not very much reduction of the strain in the 0-ply as was expected by previous analysis and moiré experiments.

Future Work

- Incremental X-Ray to plot evolution of damage
  - Approximately 20% finished
- Model as many of the observed cracks as possible using BSAM's mesh independent crack modeling method
  - Ongoing effort: previous BSAM version only allowed 1 crack per ply.
- Predict ultimate strength of the laminate based on redistributed stresses.
  - Likely use a Weibull approach developed by larve.
- Test other composite lay-ups.

Conclusions

- Previous research indicated a great correlation between the modeling effort and a cursory experimental measurement.
  - Obvious reduction in the 0-ply strains.
- Recent moiré testing resulted in very detailed strains at several states of damage evolution.
- 2 Unexpected results
  - sub-layer damage visible on top ply
  - only small reduction in the 0-ply strain, although extensive redistribution due to damage.
- Modeling effort is underway to model as many of the observed cracks as possible