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Failure analysis of composite structures using multicontinuum technology: a mesh sensitivity study

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Two Fundamental Tenets

1. In a heterogeneous composite material, failure occurs at the ***constituent material level***.

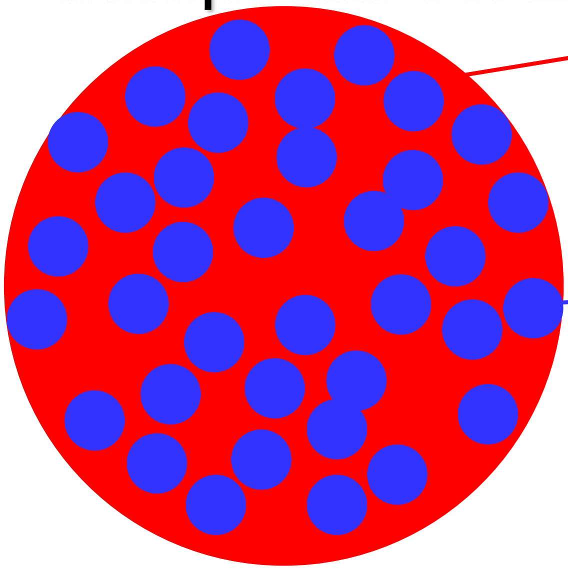
2. ***Failure of a constituent material*** is best predicted by the ***stresses within the constituent material***, not the homogenized composite stresses.

Question

How can we bring this ***constituent level stress information*** into the finite element analysis of large composite structures and still maintain a high level of efficiency?

The Multicontinuum Concept

Composite RVE



matrix *average* stress state

$$\sigma_{ij}^{m} = \frac{1}{V_m}\int_{D_m} \sigma_{ij}\, dv$$

fiber *average* stress state

$$\sigma_{ij}^{f} = \frac{1}{V_f}\int_{D_f} \sigma_{ij}\, dv$$

$$D_c = D_m \cup D_f$$

composite *average* stress state

$$\sigma_{ij}^{c} = \frac{1}{V_c}\int_{D_c} \sigma_{ij}\, dv$$

We retain the identity of the constituents and refer to their coexistence as a "multicontinuum".

$$\sigma^{c} = \frac{V_m}{V_c}\sigma^{m} + \frac{V_f}{V_c}\sigma^{f}$$

The Multicontinuum Concept

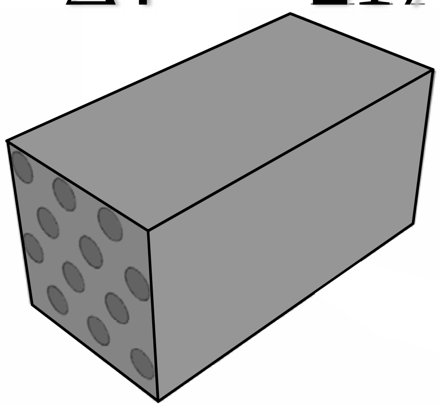
In **traditional continuum mechanics** (as applied to structures made from fiber-reinforced composite materials), attention is focused on the development of relationships between the various **composite average quantities** (e.g. stress, strain).

In contrast, **Multicontinuum Theory** focuses on

- the development of relationships between the various constituent average quantities,
  - → *Micro-mechanical finite element model of the RVE*
- the development of relationships that link the composite average quantities to the constituent average quantities.
  - → *MCT decomposition*

Why Constituent Average Stress States?

Example: Unconstrained cooling of a composite



$\Delta T = -217°C$

all $\sigma_{ij}^{c} = 0$

MCT decomp.

matrix average stress state

$\sigma_{22}^{m} = \sigma_{33}^{m} = -17.25\ MPa$

$\sigma_{11}^{m} = -44.5\ MPa$

fiber average stress state

$\sigma_{22}^{f} = \sigma_{33}^{f} = 25.87\ MPa$

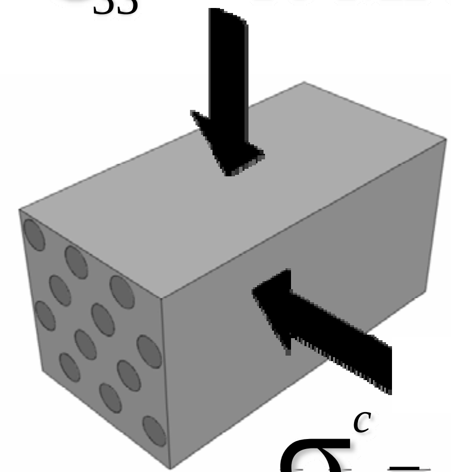
$\sigma_{11}^{f} = 66.75\ MPa$

The constituent average stress states are inherently triaxial !

Why Constituent Average Stress States?

Example: Composite under biaxial compression

$\sigma_{33}^{c} = -10$ MPa



$\sigma_{22}^{c} = -10$ MPa

all other $\sigma_{ij}^{c} = 0$

MCT
decomp.

matrix average stress state

$\sigma_{22}^{m} = \sigma_{33}^{m} = -8.7\ MPa$

$\sigma_{11}^{m} = -5.73\ MPa$

fiber average stress state

$\sigma_{22}^{f} = \sigma_{33}^{f} = -10.9\ MPa$

$\sigma_{11}^{f} = 3.8\ MPa$

The constituent average stress states are inherently triaxial !

MCT Decomposition

homogenized composite strain state

ε^c → $^c\mathbf{T}^m(\mathbf{C}^c, \mathbf{C}^m, \mathbf{C}^f, \alpha^c, \alpha^m, \alpha^f, \phi^m)$ → ε^m

transfer function (Hill, 1963)

matrix average strain state

linearized about as many different *discrete damaged states* as desired

$$\varepsilon^c = \phi^m \varepsilon^m + \phi^f \varepsilon^f$$

fiber average strain state

matrix *average* stress state

$$\sigma^m = \mathbf{C}^m(\varepsilon^m - \theta\,\alpha^m)$$

fiber *average* stress state

$$\sigma^f = \mathbf{C}^f(\varepsilon^f - \theta\,\alpha^f)$$

MCT Material Characterization

Step 1.

Optimize the ***in situ* constituent properties** so that the micromechanical finite element model matches the measured properties of the composite material

in situ constituent properties

$$\left.\begin{matrix} \mathbf{C}^m, \boldsymbol{\alpha}^m \\ \mathbf{C}^f, \boldsymbol{\alpha}^f \end{matrix}\right\} \rightarrow$$

Micromechanical Finite Element Model of RVE

$$\rightarrow \left\{ \mathbf{C}^c, \boldsymbol{\alpha}^c \right.$$

homogenized composite properties

measured composite properties $\left\{ E_{11}^c, E_{22}^c, E_{33}^c, G_{12}^c, G_{13}^c, G_{23}^c, \nu_{12}^c, \nu_{13}^c, \nu_{23}^c \right.$

In Situ Constituent Properites vs. Bulk Constituent Properties

Idealized vs. Actual Microstructure
Defects in Microstructure
Interphase Properties
Curing Differences
Refinement level and regularity of F.E. model

Idea: Adjust constituent properties to compensate for errors and uncertainty in the micromechanical finite element model.

MCT Material Characterization

Step 2.

Determine the coefficients of the constituent failure criteria so that the micromechanical finite element model matches the measured strengths of the composite material

constituent failure criteria

$$\Omega^{m} \geq 1$$

$$\Omega^{f} \geq 1$$

→ Micromechanical Finite Element Model of RVE → measured composite strengths

measured composite strengths $\left\{ S_{11}^{c+},\ S_{11}^{c-},\ S_{22}^{c+},\ S_{22}^{c-},\ S_{12}^{c},\ S_{23}^{c} \right.$

Constituent Failure

matrix failure criterion

If $\Omega^m(\sigma^m) \geq 1$,

Then

$E^m \rightarrow$ *10% of original*

$G^m \rightarrow$ *10% of original*

ν^m *remains unchanged*

↓ ↓

Reduced $\mathbf{C}^m$

fiber failure criterion

If $\Omega^f(\sigma^f) \geq 1$,

Then

$E^f \rightarrow$ *1% of original*

$G^f \rightarrow$ *1% of original*

ν^f *remains unchanged*

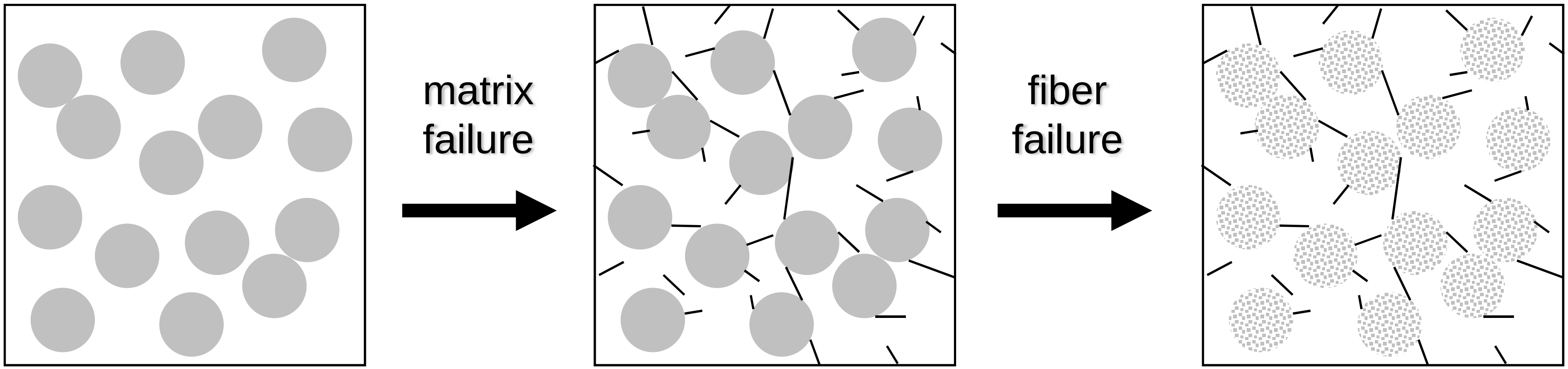
↓ ↓

Reduced $\mathbf{C}^f$

↘ ↙

Reduced $\mathbf{C}^c$

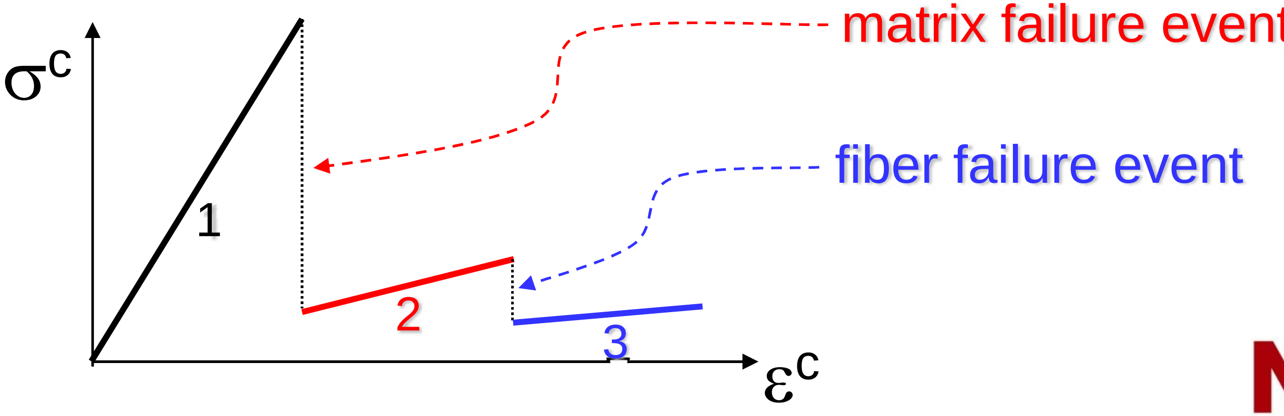
Three Discrete Damaged States



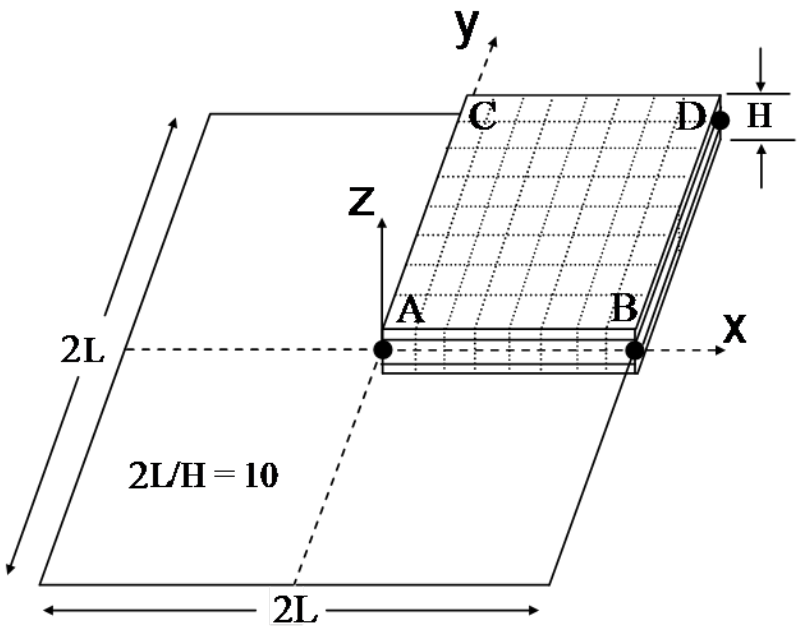
Damaged State 1
undamaged matrix,
undamaged fibers

Damaged State 2
failed matrix,
undamaged fibers

Damaged State 3
failed matrix,
failed fibers



Simply Supported (0/0/90/90/90/90/0/0) w/ Uniform Distributed Transverse Load



Computational Domain (one quadrant)

$0<x<L,\ 0<y<L,\ -H/2<z<H/2$

Simply Supported Edge Conditions

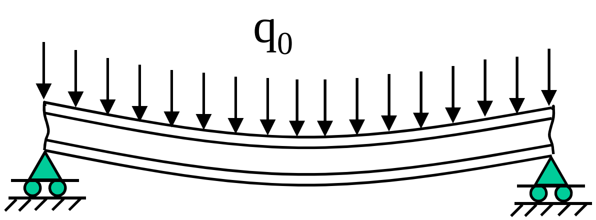
$w(L,y,z) = w(x,L,z) = 0$

$u(0,y,z) = u(x,L,z) = 0$

$v(x,0,z) = v(L,y,z) = 0$

Uniform Distributed Transverse Load

$q(x,y,H/2) = q_0$



Incrementally increase q_0 until global structural failure occurs

T300/PR319

Homogenized Composite Properties (undamaged)

$E_{11} = 129$ GPa, $E_{22} = E_{33} = 5.615$ GPa

$\upsilon_{12} = \upsilon_{13} = 0.3159$, $\upsilon_{23} = 0.4631$

$G_{12} = G_{13} = 1.329$ GPa, $G_{23} = 1.8607$ GPa

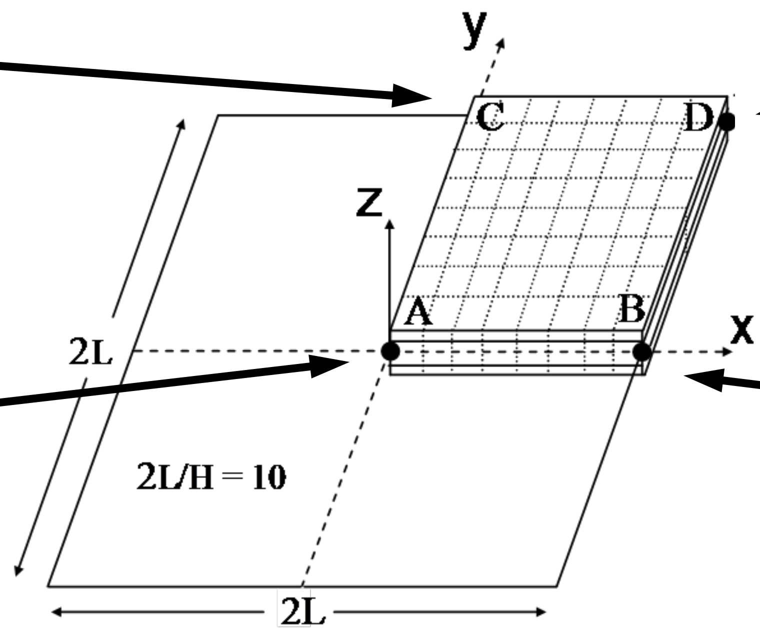
Different regions are dominated by different potentially-damaging stress components

Point **C**

σ_{13} global maxima in inner 90° plies

Point **D**

σ_{12} global maxima in outer 0° plies



Point **A**

σ_{22} global maxima in outer 0° plies

Point **B**

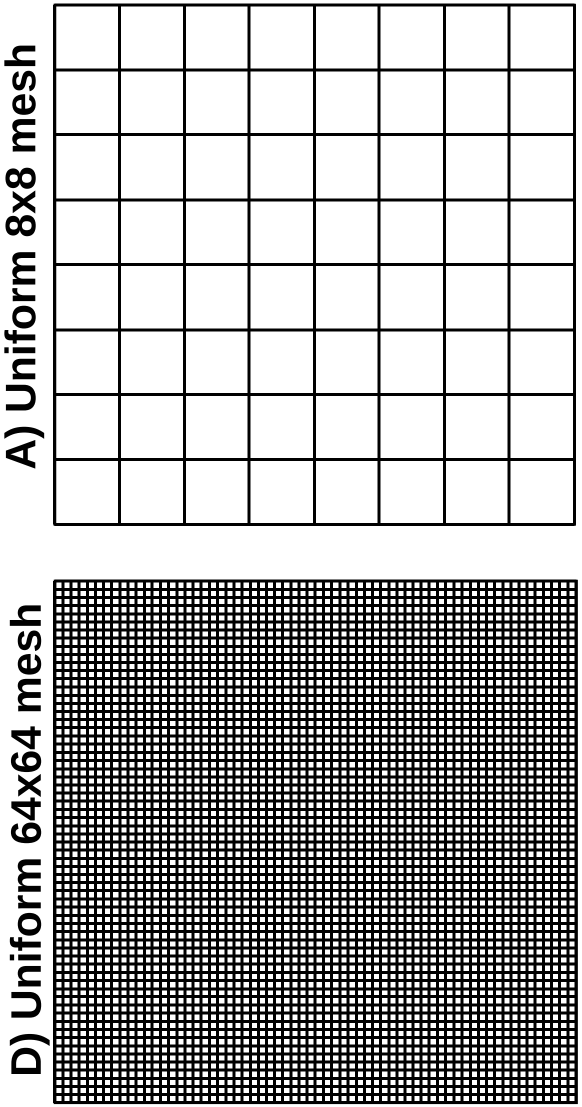
σ_{23} global maxima in inner 90° plies

The epicenter of damage evolution is dependent on the distribution of stress components and the relative strength of the composite material in the various modes of deformation

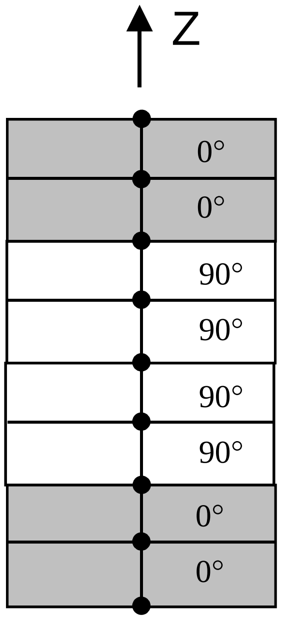
In this particular problem, the strength characterisitics of T300/PR319 make it relatively susceptible to σ_{22} failure at point **A**

Effect of 2-D Mesh Density & Mathematical Model Type

uniform 2-D meshes of 4-node VKFEs



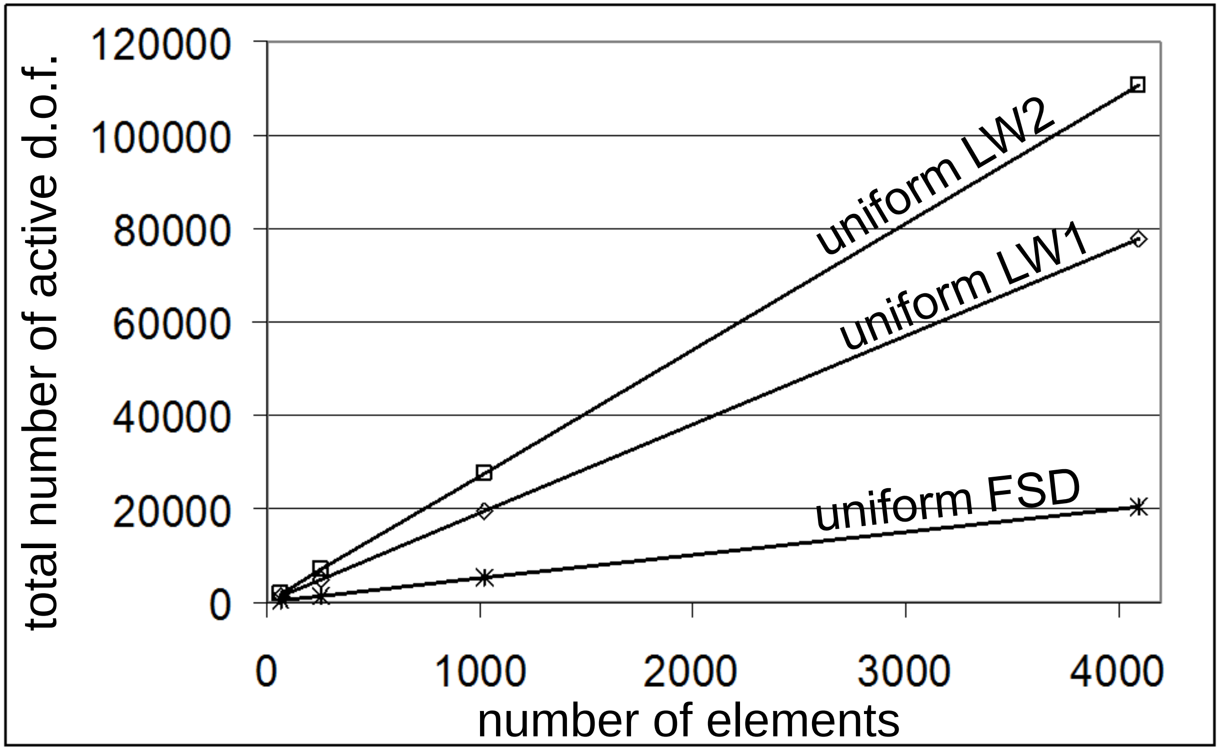
thickness discretization used by layerwise elements: 8 linear layers through laminate thickness



Solutions based on Uniform Mesh Density and Uniform Mathematical Model Type

Problem Size

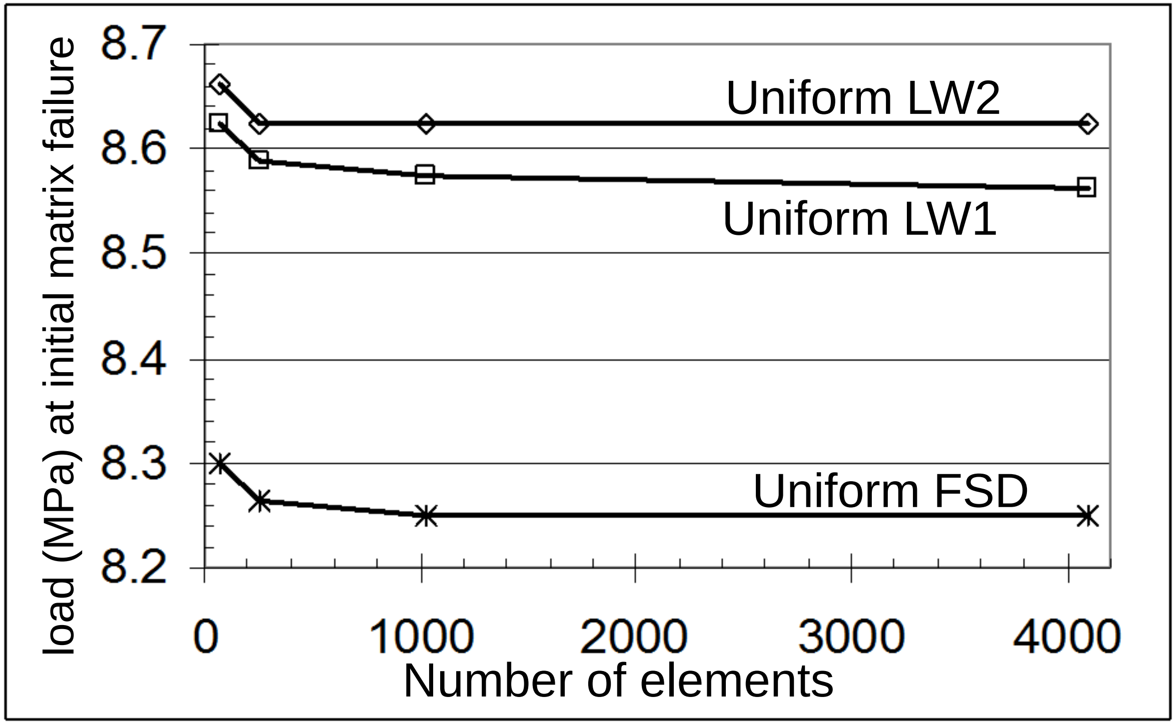
Model Type	uniform 8x8, 64 elements	uniform 16x16, 256 elements	uniform 32x32, 1024 elements	uniform 64x64, 4096 elements
FSD	322 d.o.f.	**1,282** d.o.f.	**5,122** d.o.f.	**20,482** d.o.f.
LW1	**1,218** d.o.f.	**4,866** d.o.f.	**19,458** d.o.f.	**77,826** d.o.f.
LW2	**1,730** d.o.f.	**6,914** d.o.f.	**27,650** d.o.f.	**110,594** d.o.f.



Solutions based on Uniform 2-D Mesh Density and Uniform Mathematical Model Type

Predicted Ultimate Load, and (*Load at Initial Matrix Constituent Failure*)

Model Type	uniform 8x8, 64 elements	uniform 16x16, 256 elements	uniform 32x32, 1024 elements	uniform 64x64, 4096 elements
FSD	**11.525**(*8.3*)	**11.154**(*8.263*)	**10.973**(*8.25*)	**10.887**(*8.25*)
LW1	**10.438**(*8.625*)	**10.120**(*8.588*)	**9.965**(*8.575*)	**9.838**(*8.563*)
LW2	**10.425**(*8.663*)	**10.130**(*8.625*)	**10.027**(*8.625*)	**9.938**(*8.625*)



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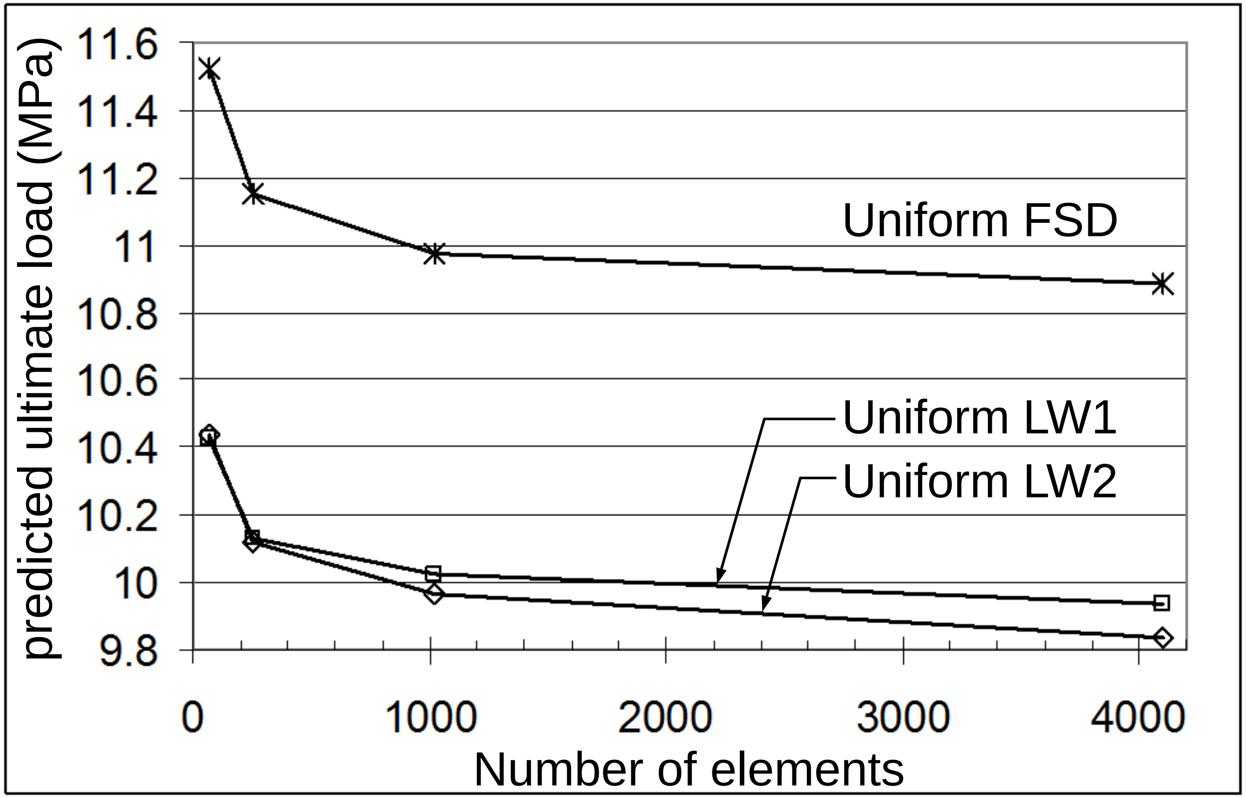
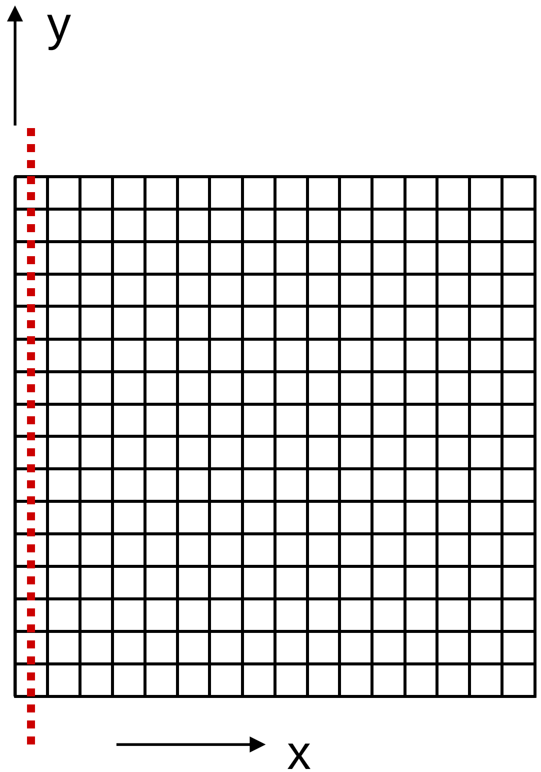
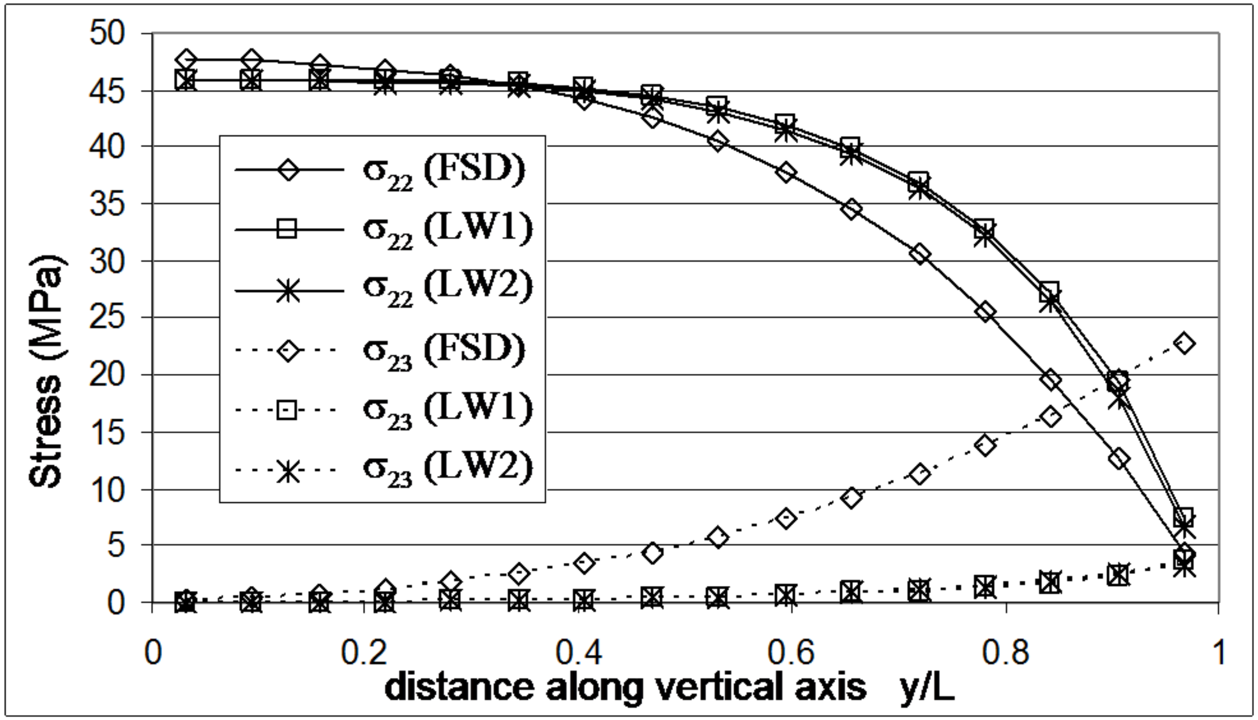


Stress Distributions based on Uniform Mesh Density and Uniform Mathematical Model Type



Damaging stress components in the lower 0° ply

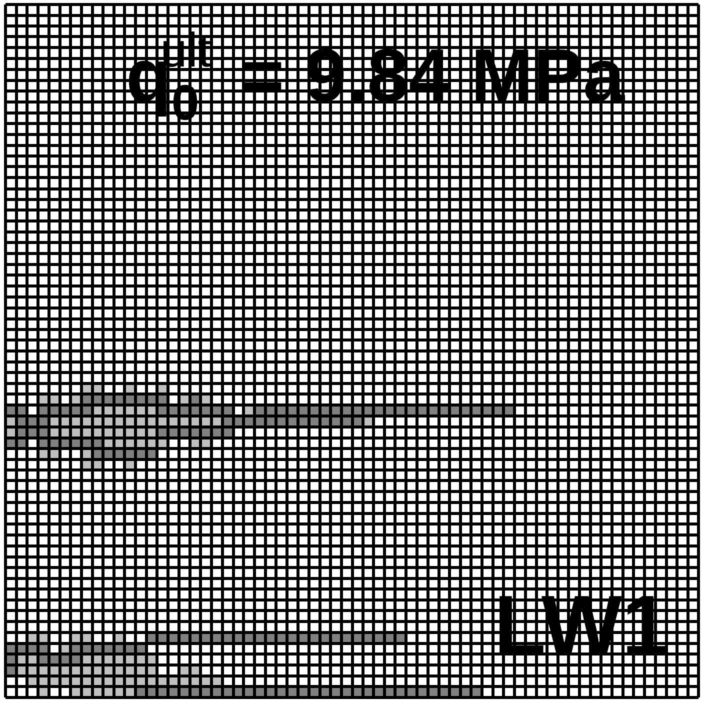


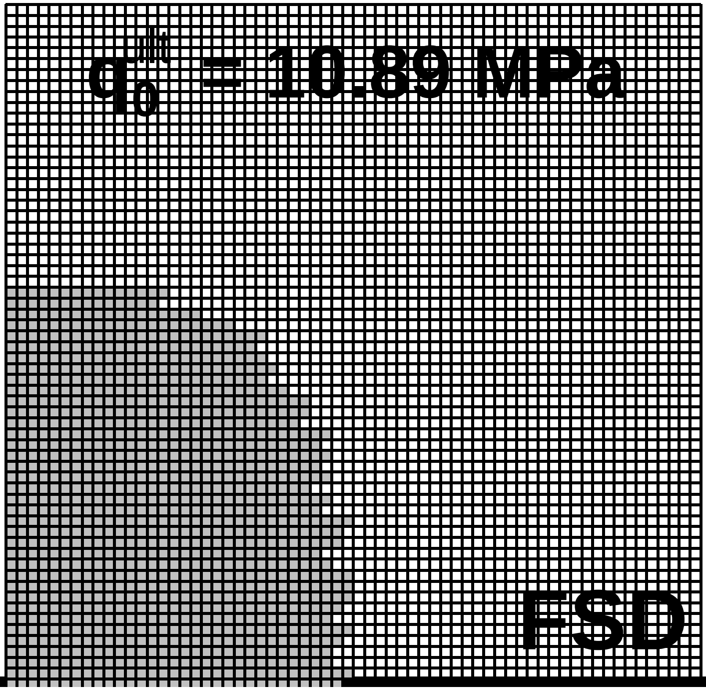
FSD model predicts higher peak value of σ_{22}

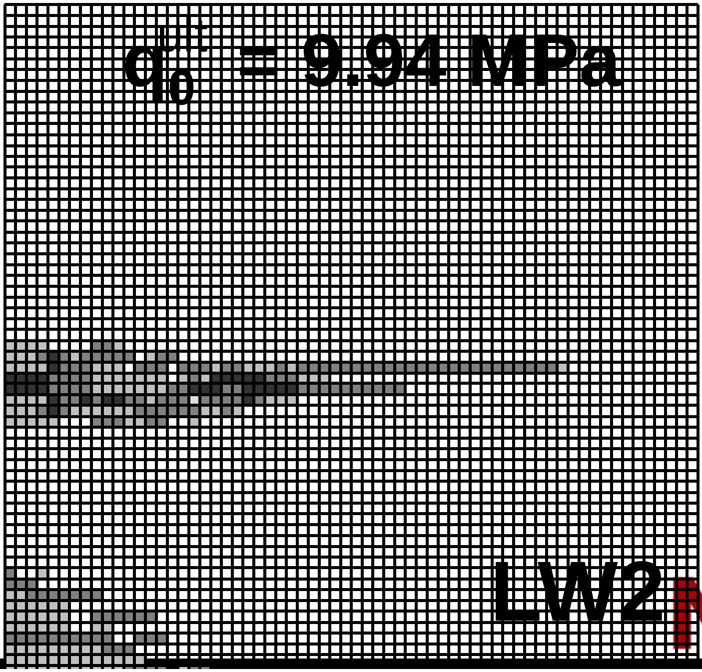
LW1 and LW2 models predict that σ_{22} maintains a relatively high value over a larger region than the FSD model.

Damaged State at Impending Global Failure

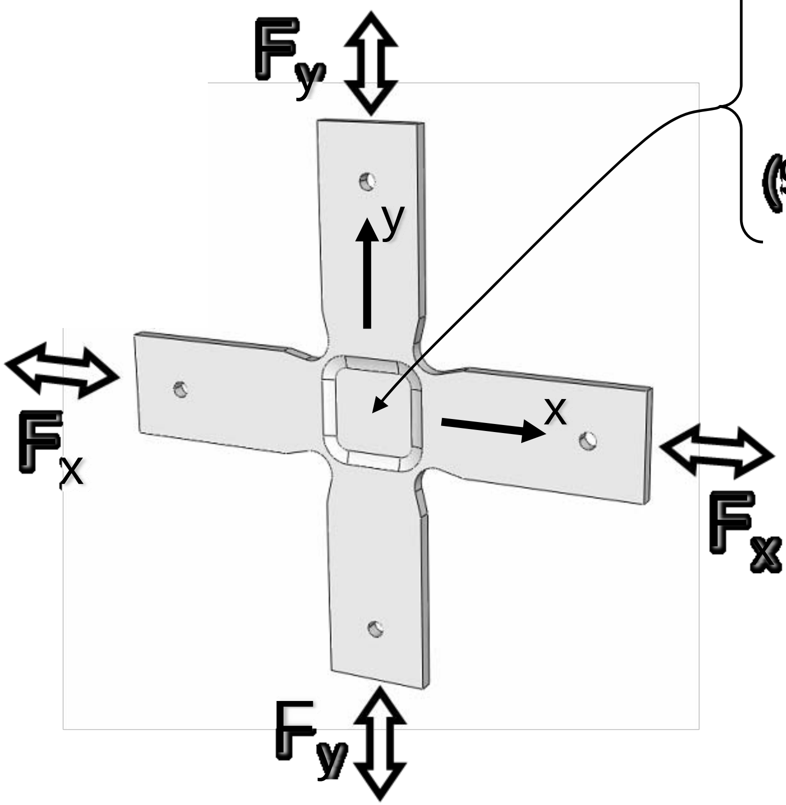
- ☐ No failed material layers
- ☐ One failed material layer
- ☐ Two failed material layers
- ☐ Three failed material layers



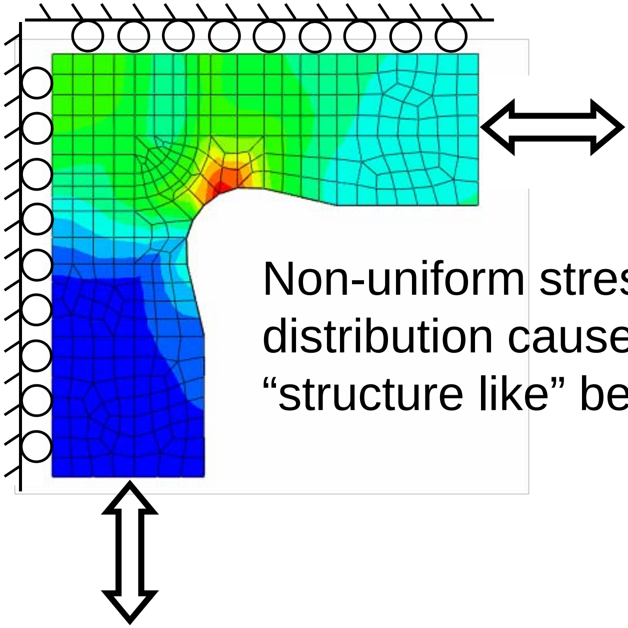




Quasi-Isotropic Cruciform Specimen (Laminate Strength under Biaxial Loading)



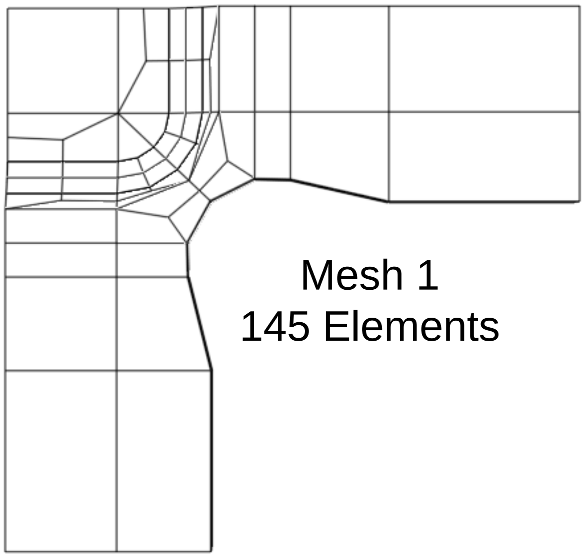
gauge section
quasi-isotropic layup
(90/+45/-45/0/0/-45/+45/90)



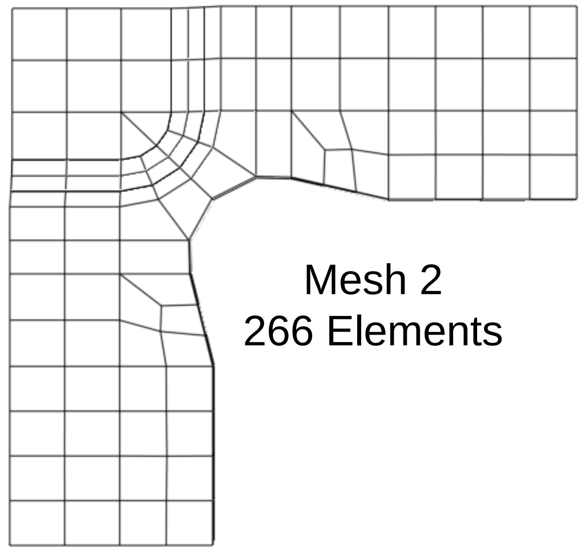
Non-uniform stress distribution causes "structure like" behavior

For various fixed ratios of F_x/F_y, incrementally increase the applied loads until structural failure occurs.

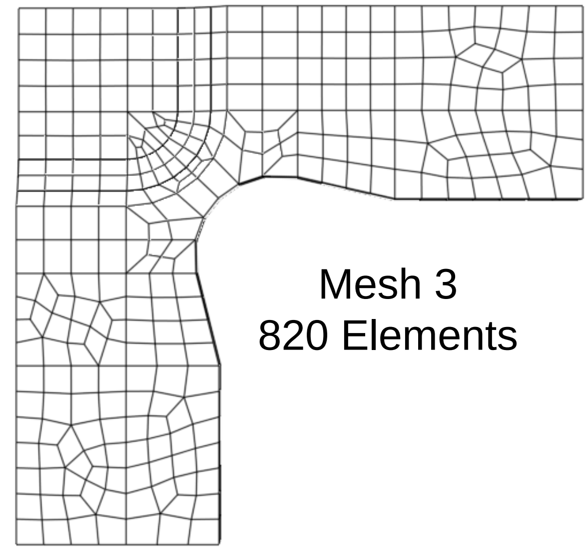
Five Levels of Mesh Density



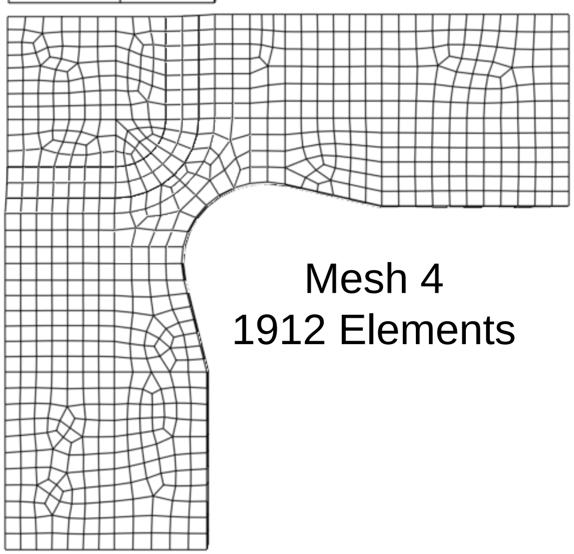
Mesh 1
145 Elements



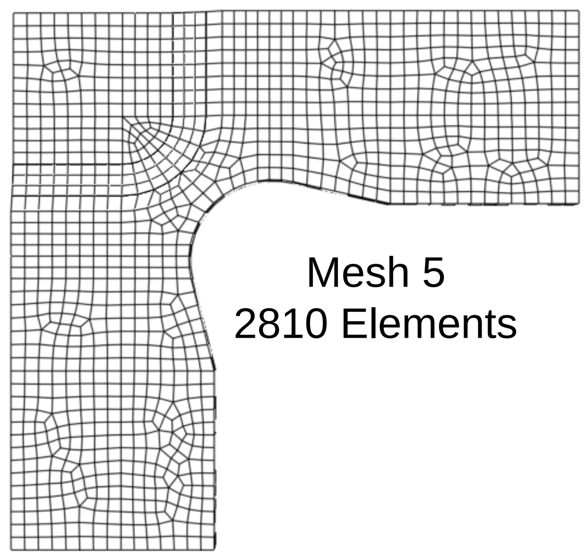
Mesh 2
266 Elements



Mesh 3
820 Elements



Mesh 4
1912 Elements

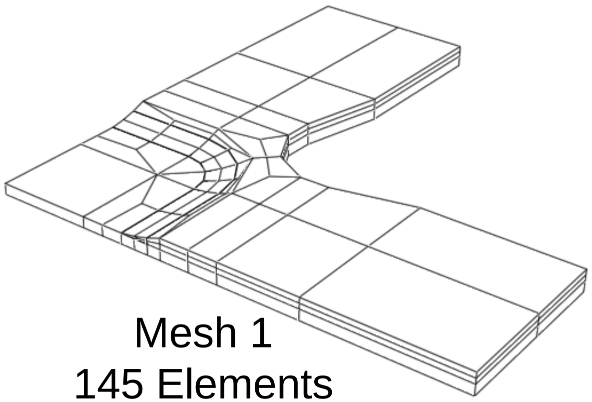


Mesh 5
2810 Elements

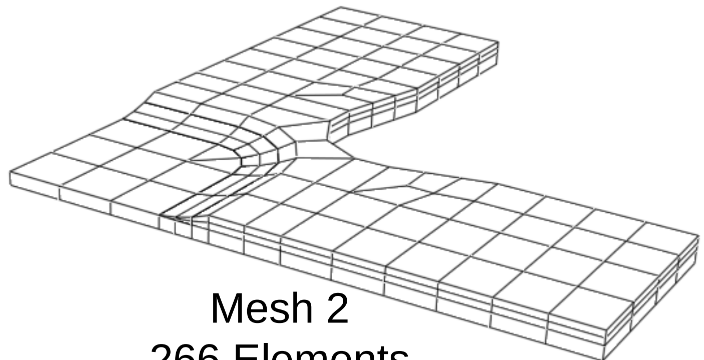
All elements are ABAQUS continuum shell elements (type SC8R)

Five Levels of Mesh Density

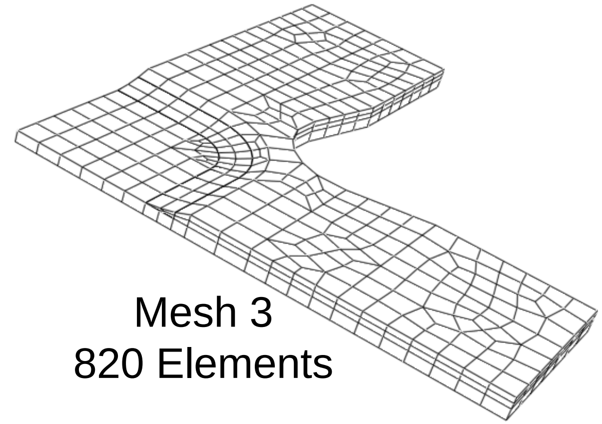
All elements are ABAQUS continuum shell elements (type SC8R)



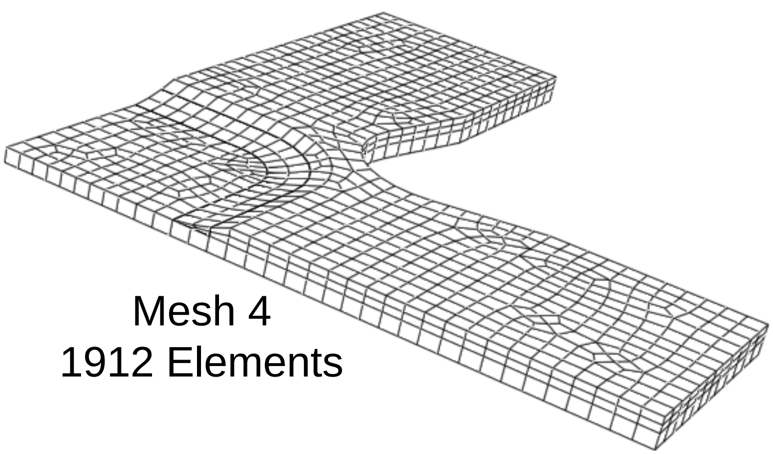
Mesh 1
145 Elements



Mesh 2
266 Elements



Mesh 3
820 Elements



Mesh 4
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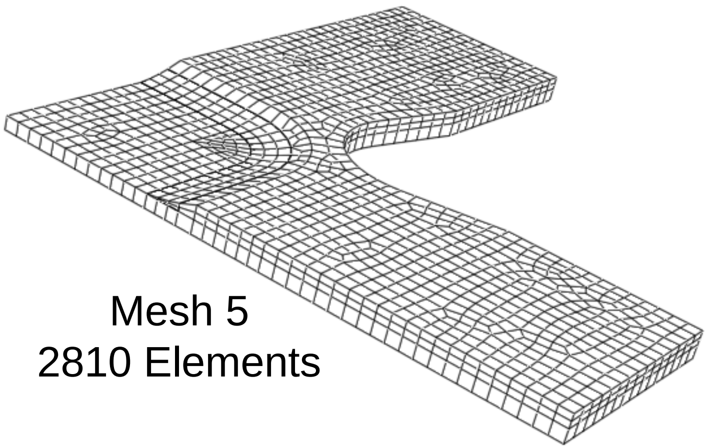
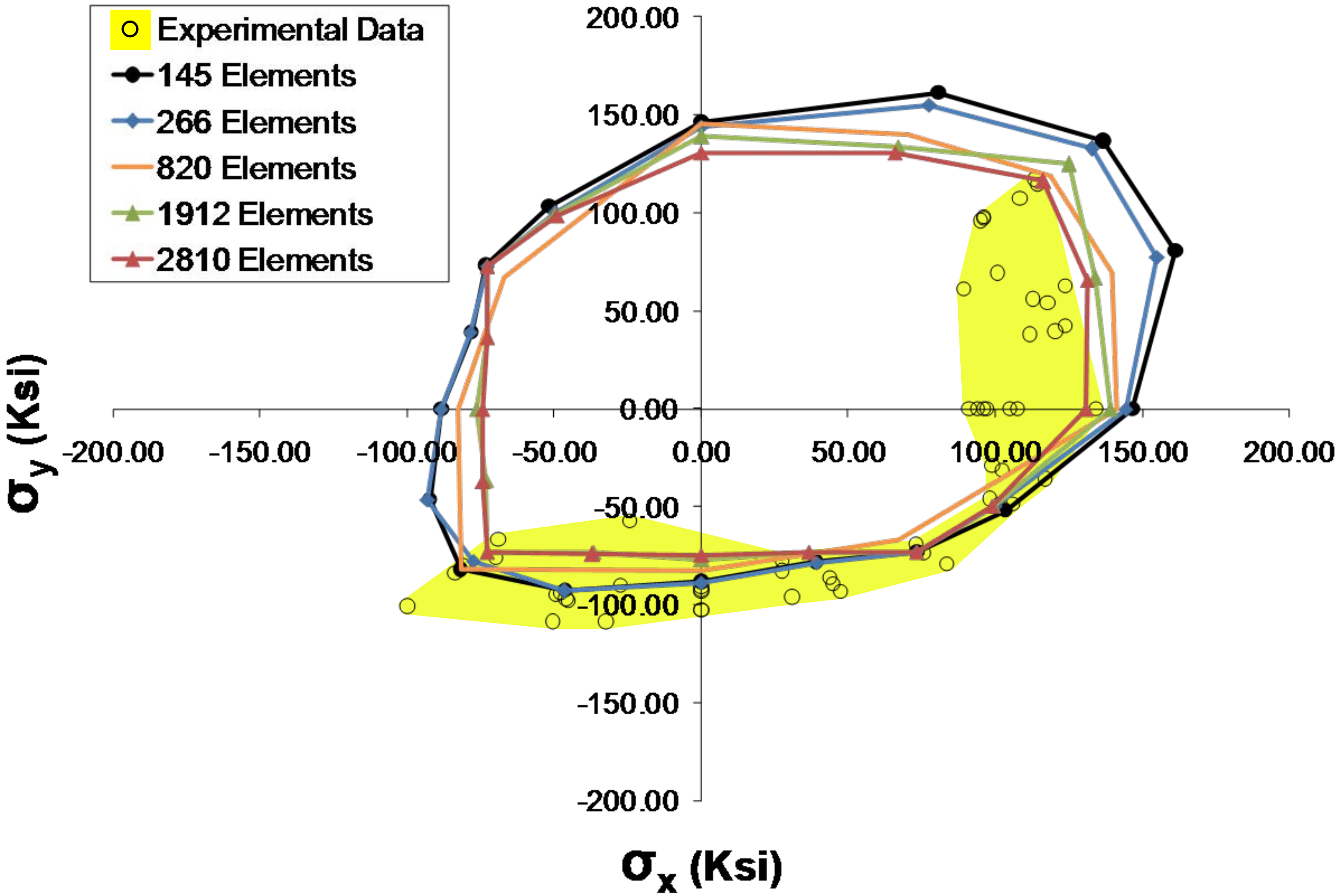


Mesh 5
2810 Elements

Failure Envelope (predicted vs. measured)



Recent Sucesses

<u>1.5 liter, linerless, filament-wound composite tank</u>
MCT-based progressive failure model predicted leak pressure to within 3% of the measured leak pressure.

Large composite space structure (conic adapter) <u>under combined compression, bending and shearing</u>
MCT-based progressive failure model predicted the ultimate load of the structure to within 2% of the measured ultimate load.

Software Availability

Firehole Technologies has encapsulated the MCT multiscale material model in an ABAQUS User-Defined Material Subroutine.

Beta version is scheduled for release next month.

First commercial version is scheduled for release in the first quarter of 2009.

The End

The Firehole River **(Yellowstone National Park, Wyoming)**