Optimal Design of a Composite Scarf Repair Patch under Uniaxial Tension Load

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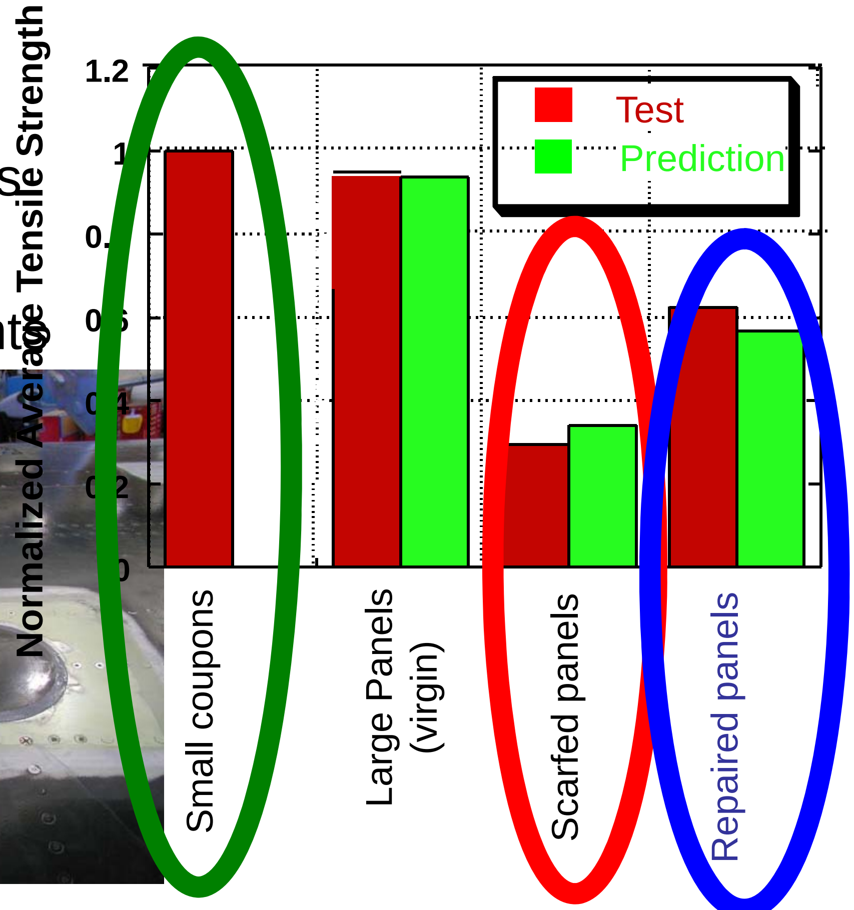
Composites Testing & Model Identification
Dayton, OH, US
20-22 October, 2008

Motivation

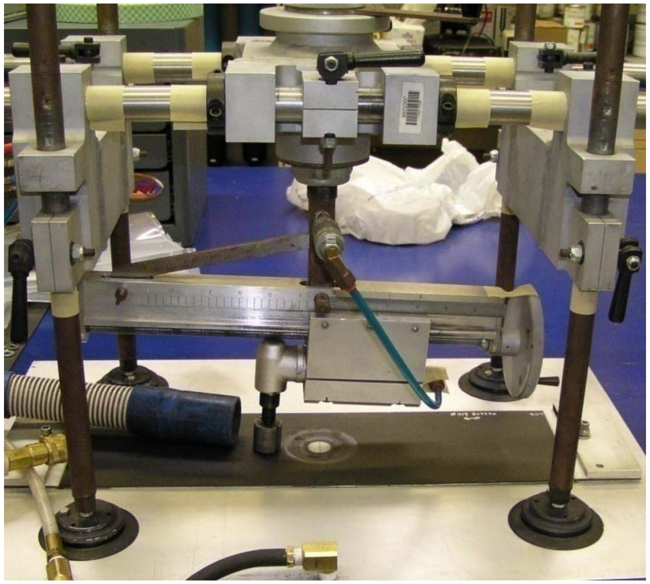
- Composite Repair Needs are Increasing
- Scarf Repair
  - repair technology
  - adhesive properties
  - patch geometry
  - special requirements

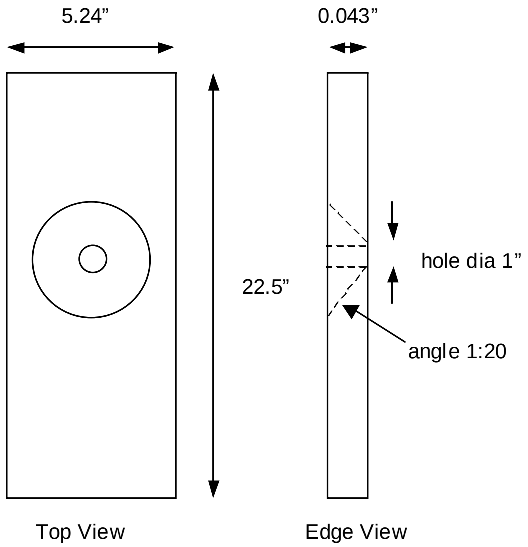


Outline

- Specimen preparation
- Basic material properties
- Experimental results
- Modeling approach
- Optimization
- Conclusion

Large Tensile Panels – Manufacture





- **Cut coupons from panels**
  - Bond tabs (EPON 828)
  - Drill holes for grip interface
- **Scarf portion of coupons**
  - Scarfomatic
  - Manufacture vacuum table jig
  - Fairly repeatable

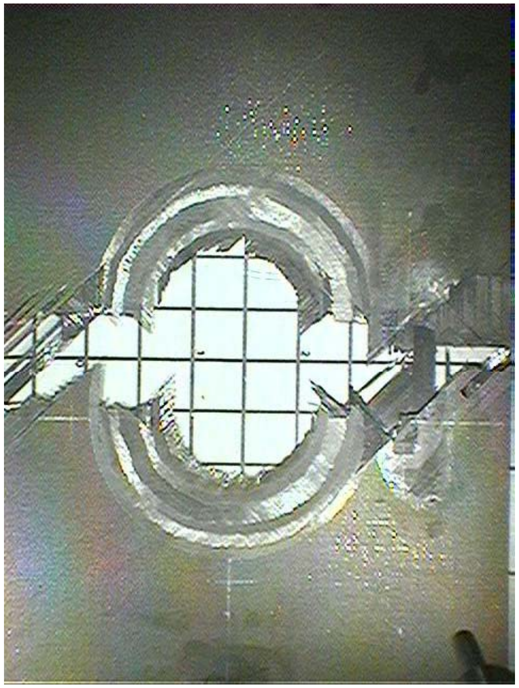
Panel	Outside Dia (in)	Inside Dia (in)
419T	2.74 to 2.83	1.10 to 1.12
420B	2.68 to 2.75	1.06 to 1.08
423T	2.60 to 2.69	0.98 to 1.00
419T	2.74 to 2.83	1.10 to 1.12
420B	2.68 to 2.75	1.06 to 1.08
423T	2.60 to 2.69	0.98 to 1.00
418T	2.69 to 2.79	0.94 to 0.96
419B	2.67 to 2.78	0.85 to 0.87
422B	2.8	1.1
423B	2.62 to 2.74	1.00 to 1.05

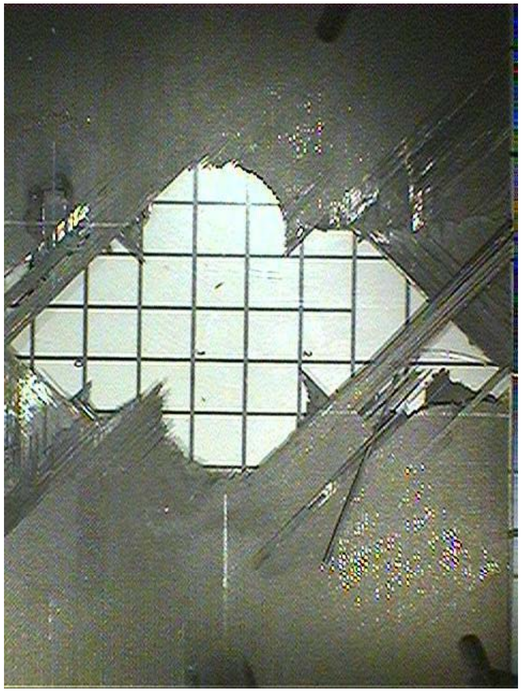
Half scarf angle = $87^0 \pm 0.26$ (87^0-nominal)
(pool of 40 angle data points)

Tensile Testing – Scarfed Laminate

IM6/3501-6

$[45/0/-45/90]_s$



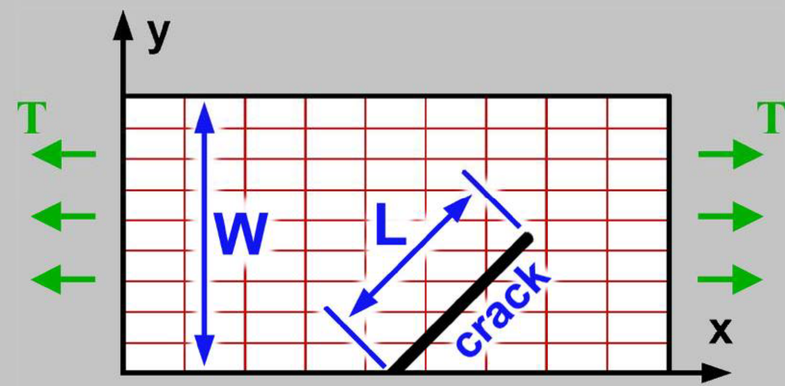


Tool Box

<u>B-Spline Analysis Method</u>

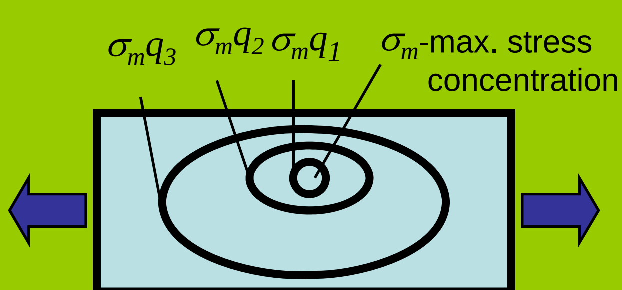
- **Variable defect B-spline approximation in 3-D, (*p*-element– particular case.**
- **Multibasis global-local approximations for laminated structures**
- **General anisotropy, including continuous point-wise variability**
- ***Cluster – BSAM "solid element"***
- **Cluster geometries are restricted to being parametric**

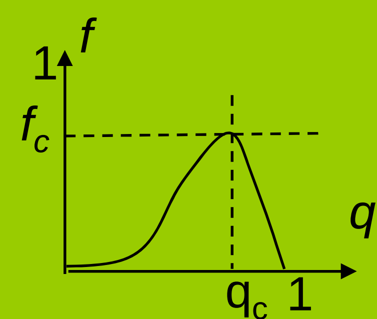
Mesh Independent Damage Model



Fiber Failure

<u>Critical Failure Volume (CFV)</u>

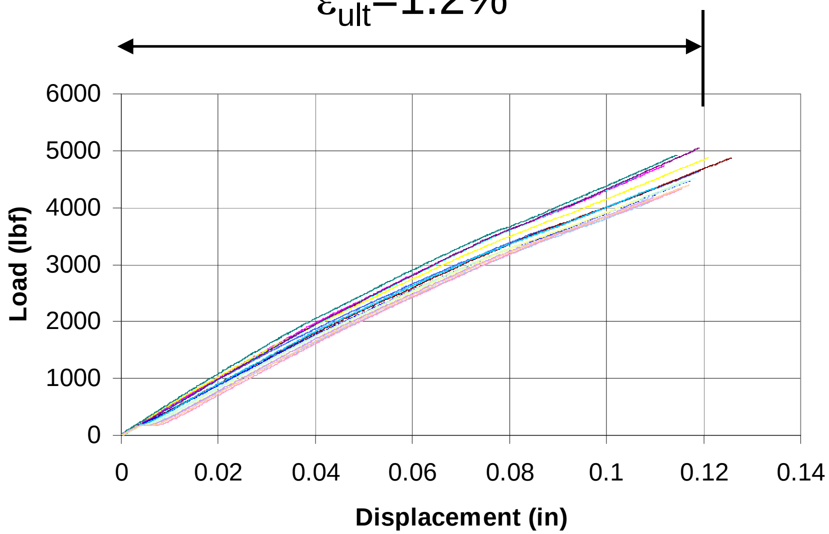




Basic material properties

composite

ε_{ult}=1.2%



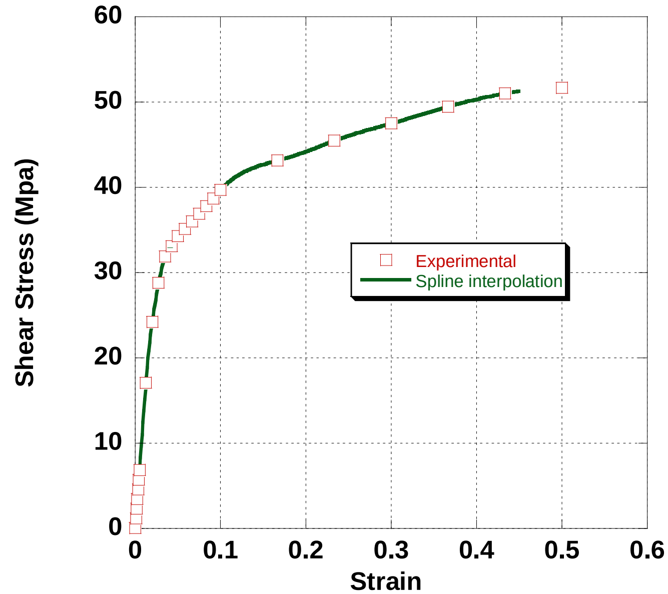
Stiffness properties

Fiber direction strength

$X_t=\varepsilon_{ult}E_{11}$= 1.82Gpa
V_0=0.78mm^3
Weibull modulus
α=40 (Wisnom (2005))

adhesive

FM300M



Manufacturer data, KGR-1 instrumentation

Tensile testing

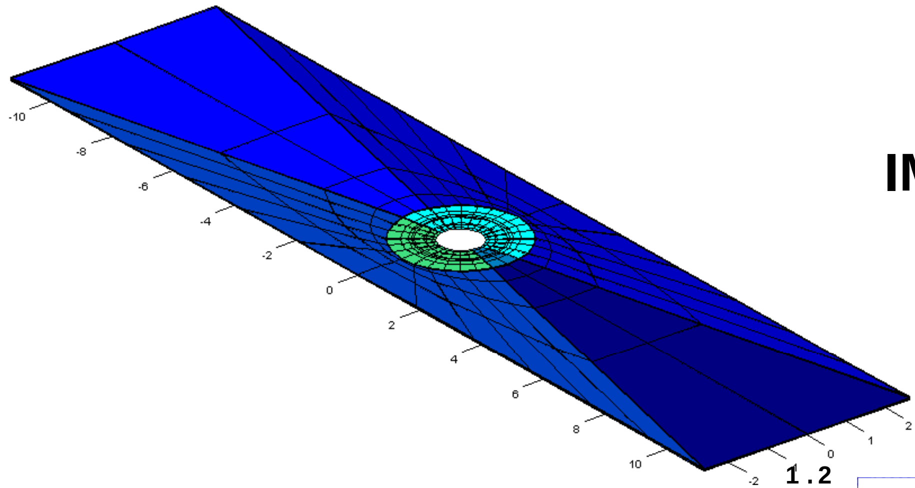
2 - ¾"x4" specimens with tabs

Poisson's ratio

Strain gage comparison of x to y

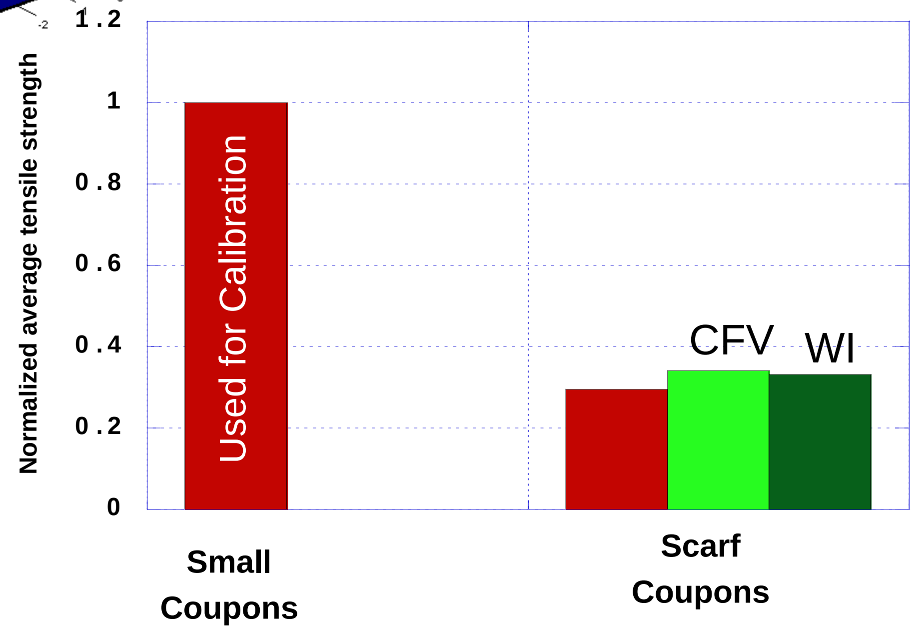
$$G = f(\varepsilon_{vm}),\ \nu = 0.38$$

Tensile Testing – Scarfed Laminate



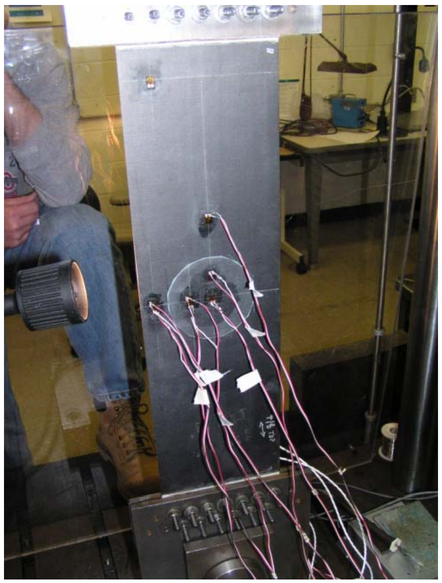
IM6/3501-6; $[45/0/-45/90]_s$

Ply-by-ply 3D analysis (BSAM)

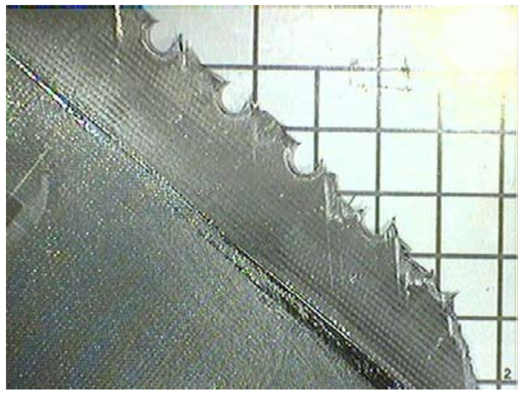


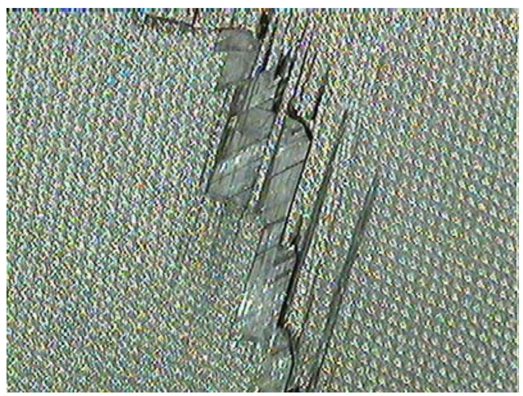
Repaired Specimen Testing

Instrumentation

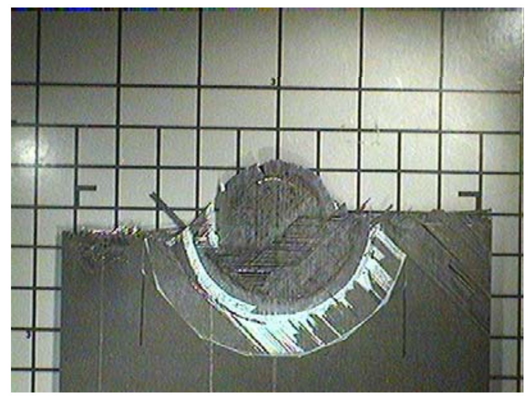


Large virgin panels
- Grip failures
- Some gage section failures
- Significant scatter of strength

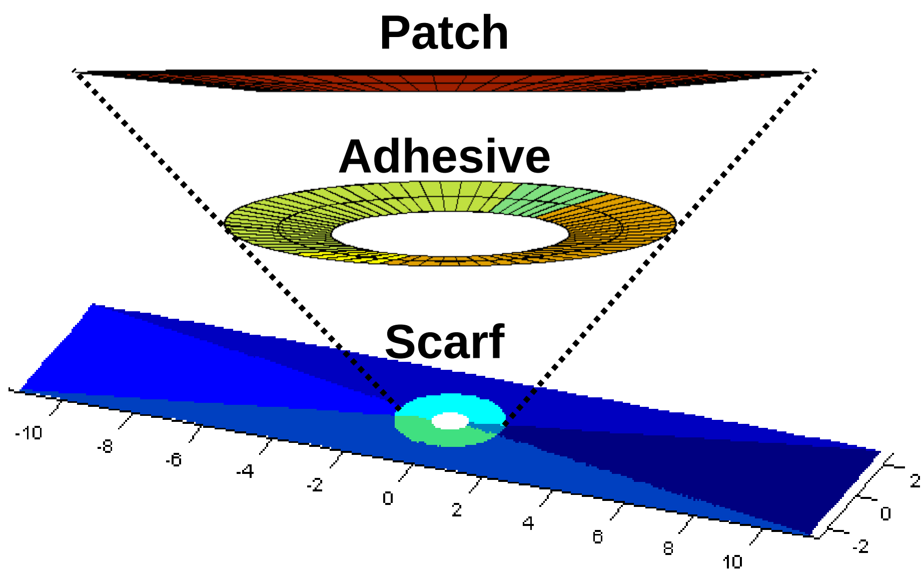




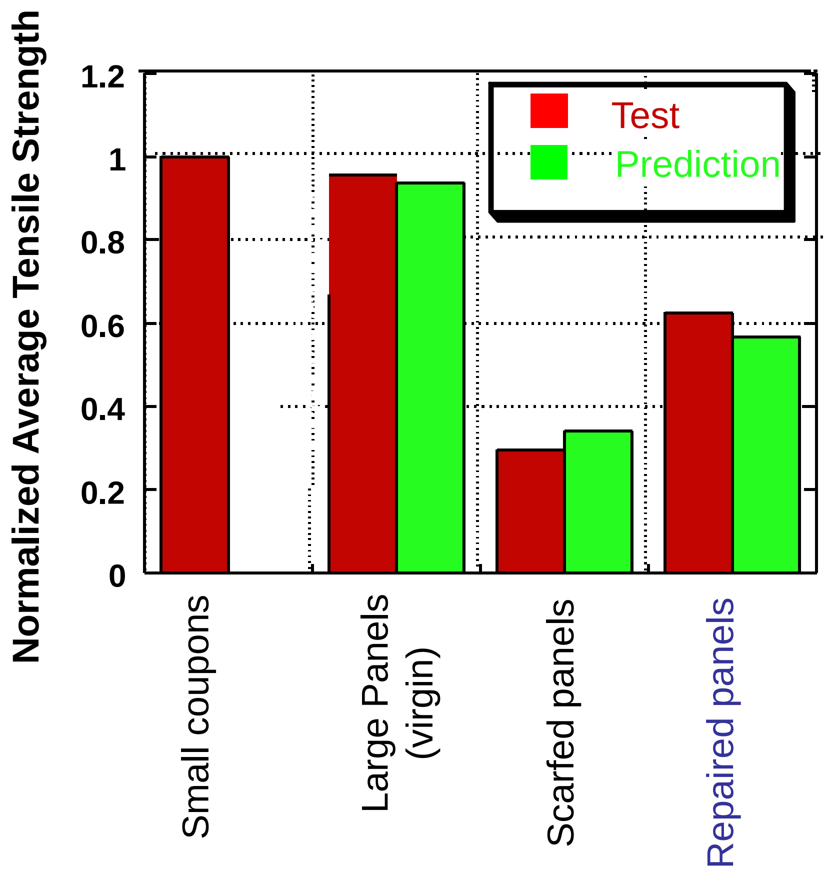
Repaired panels
- Apparent brittle failure
- The patch is mainly intact
- The overplay delaminates



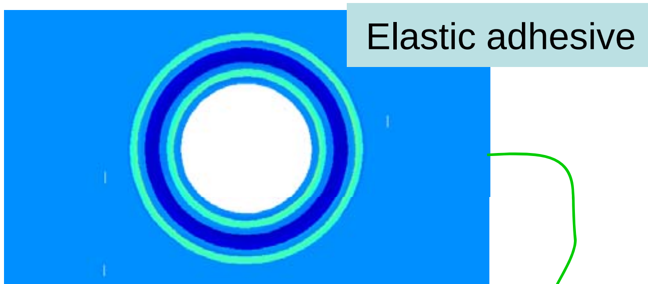
Flush Repair Analysis



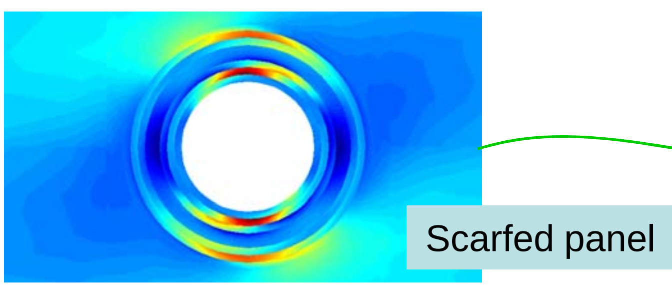
Strength Results



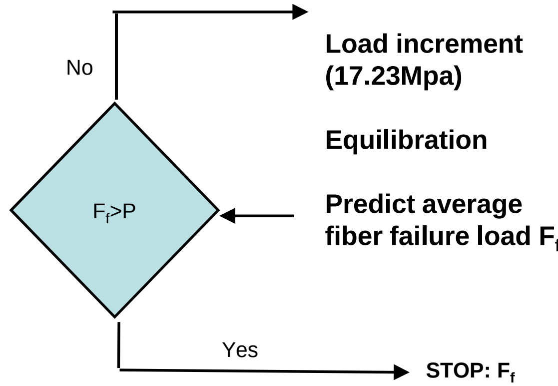
Nonlinear Strength Prediction



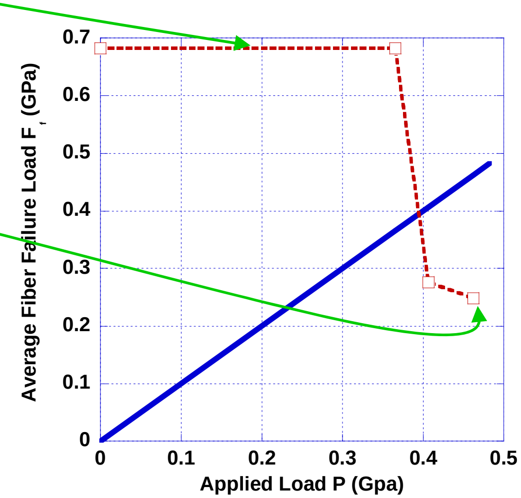
Stress in fiber direction



Incremental Nonlinear analysis

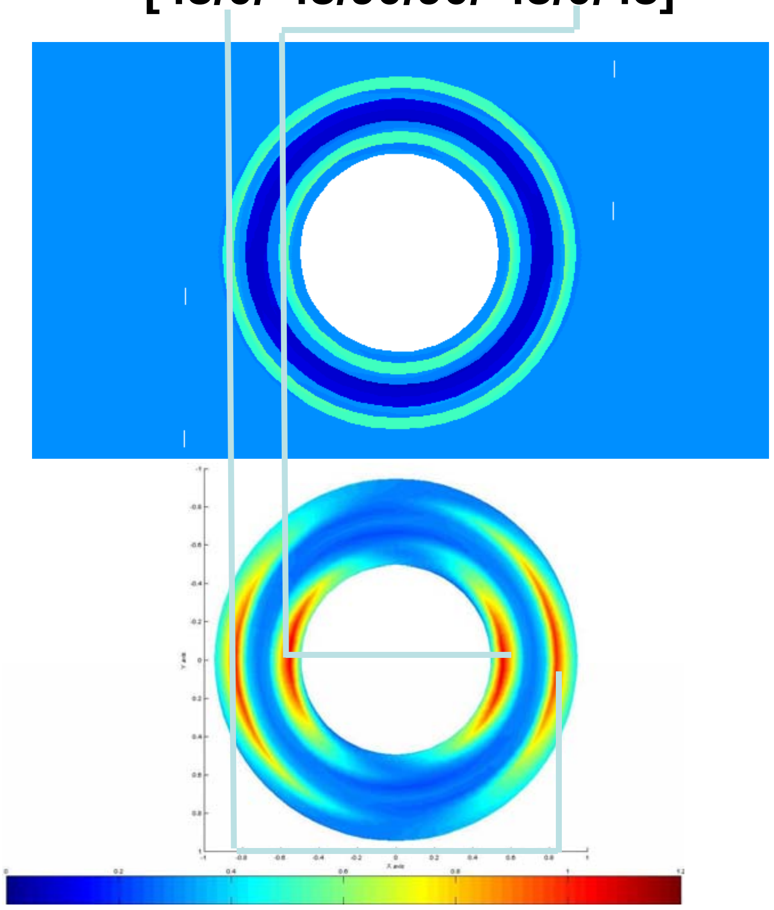


Adhesive failure appears sudden and determines the failure of the repair



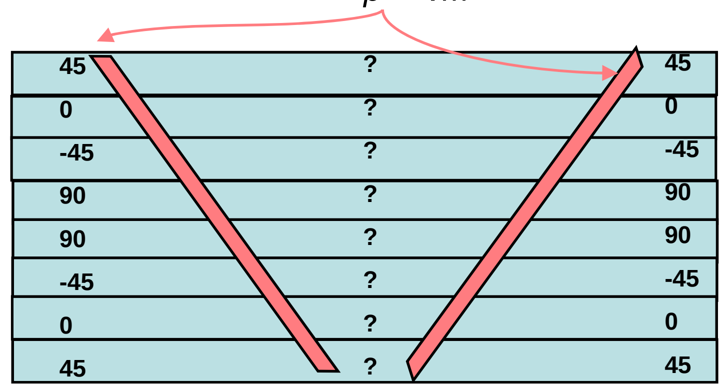
Adhesive Stress Concentration Motivation for Optimal Deisgn Problem

[45/0/-45/90/90/-45/0/45]



Optimal Design Problem

$F = L_p(\sigma_{vm})$



$$L_p(g(\mathbf{x})) = \left(\frac{1}{V} \int_V (g(\mathbf{x}))^p \, dv \right)^{1/p} \qquad p=15$$

Optimization solution minimizes ***elastic*** stress field in the adhesive

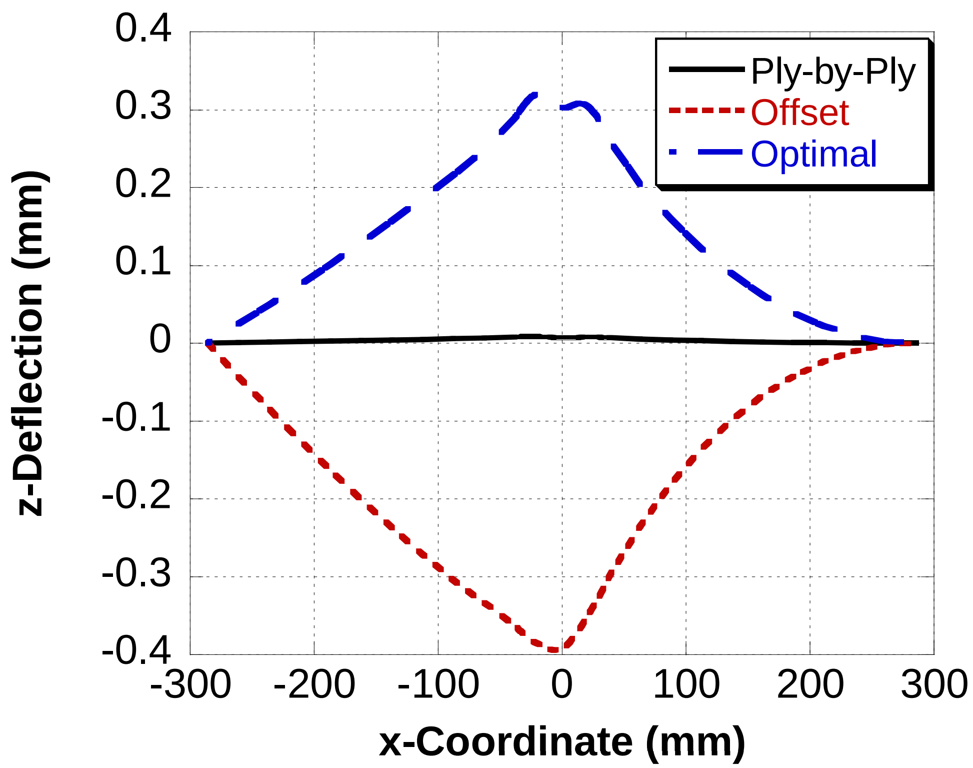
σ_{vm} – von Mises stress

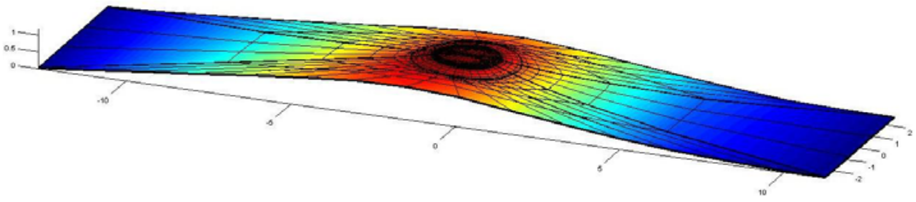
Simplex method used for optimization

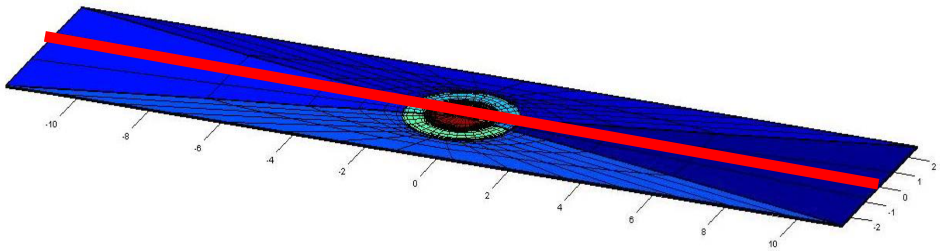
Optimization Results – No overply

PLY	Optimal
45	36
0	-36
-45	-72
90	106
90	68
-45	-31
0	47
45	50

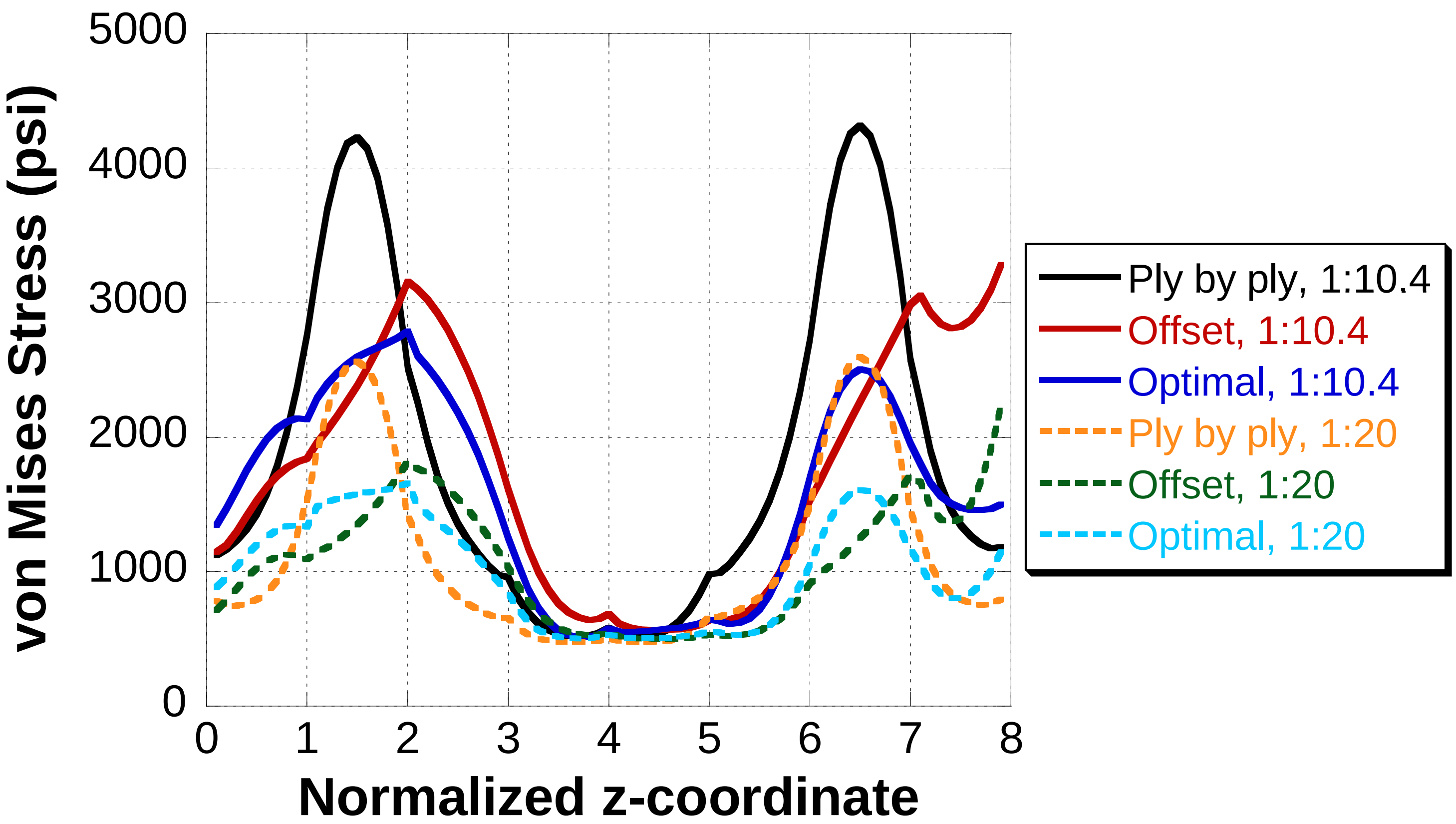
Case Study: Extension/Bending



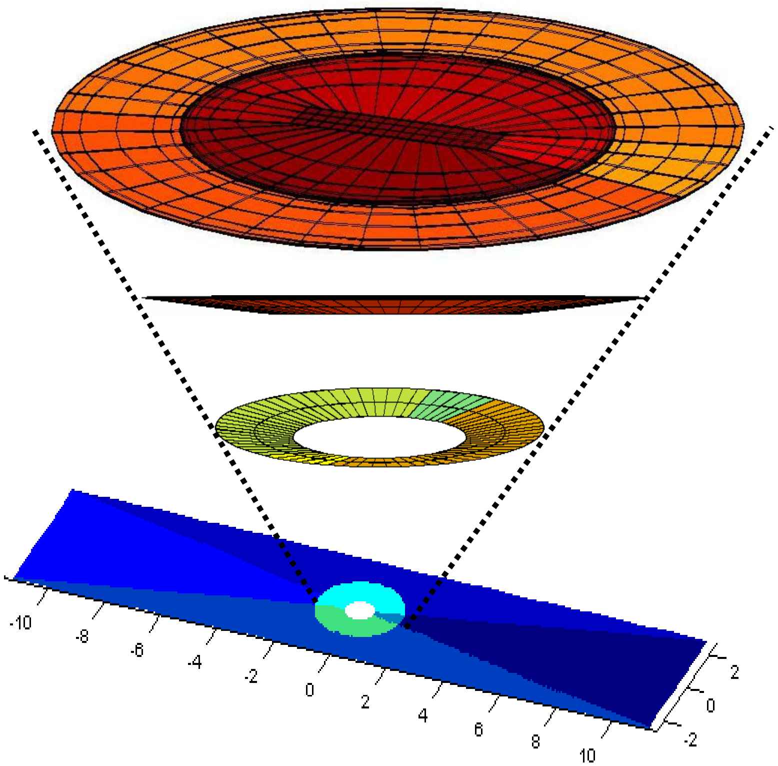




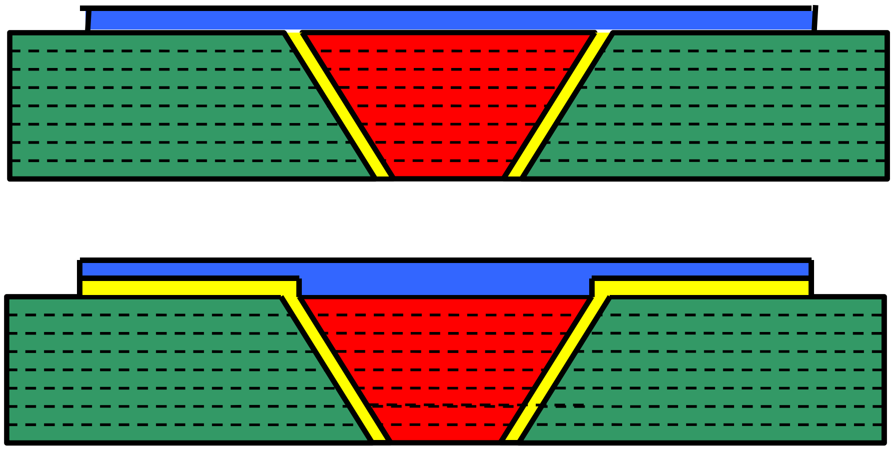
Case Study: Scarf Angle



Overply Repair Analysis



Scarf Geometry (2-D cut-away view)



Blue – Overply

Yellow – Adhesive

Red – Patch

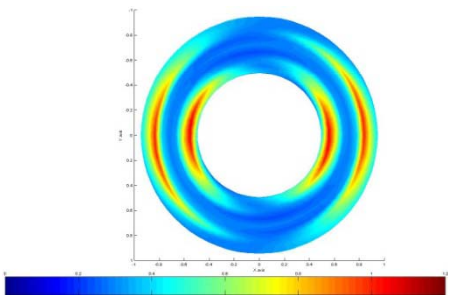
Green - Adherent

Case Study: Overply Thickness

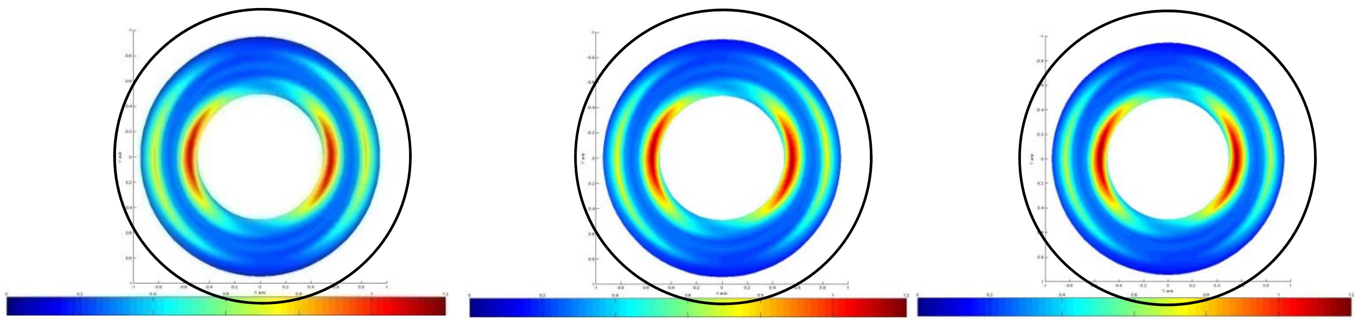
The overply is “attached” to the top of the adherend without adhesive

45° overply

No overply

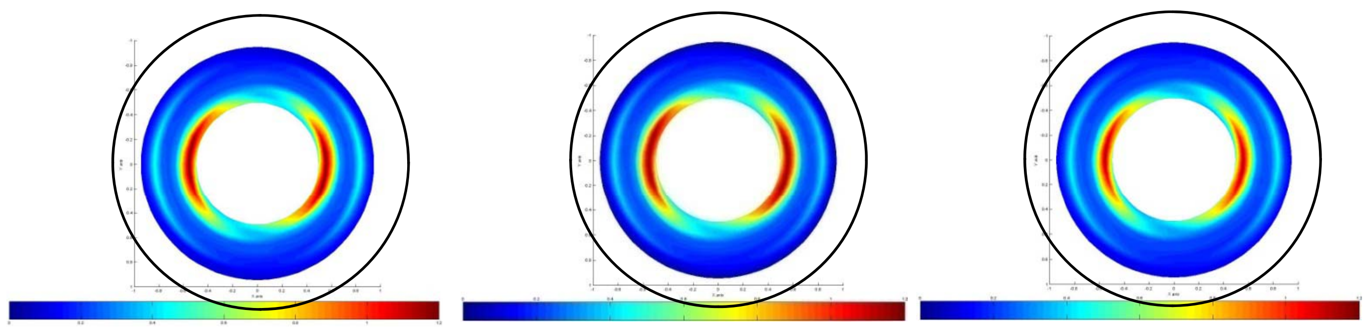


2t 4t 8t

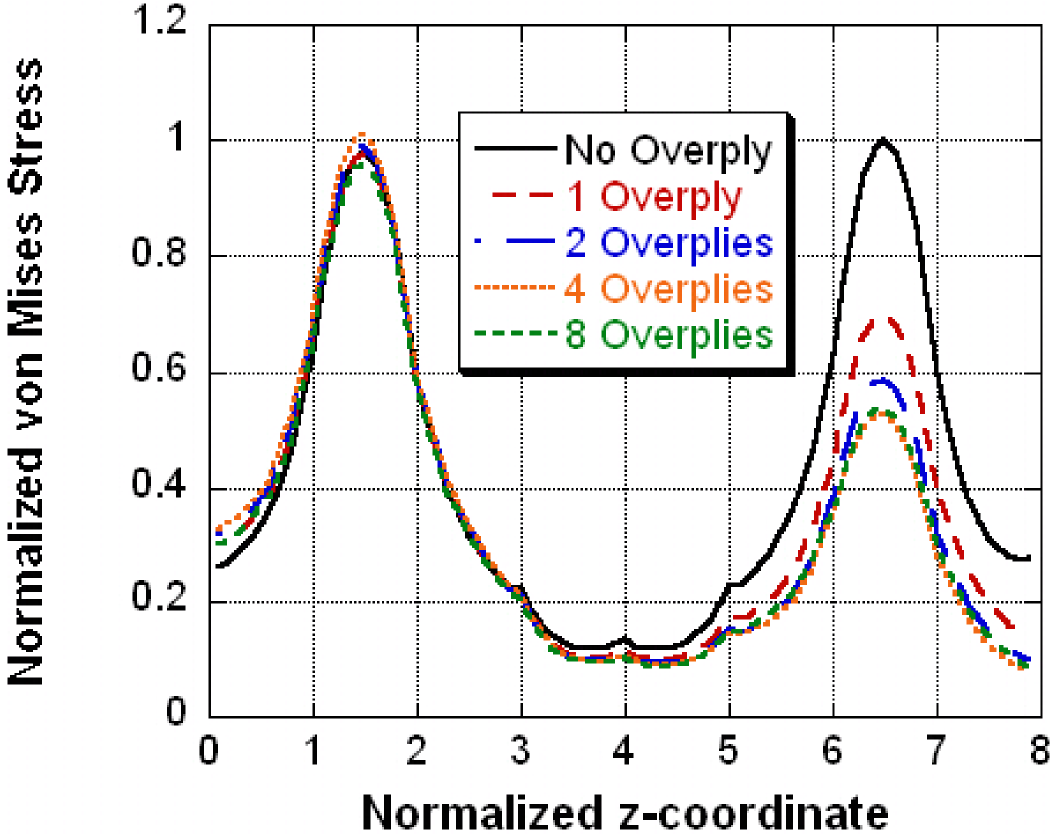


0° overply

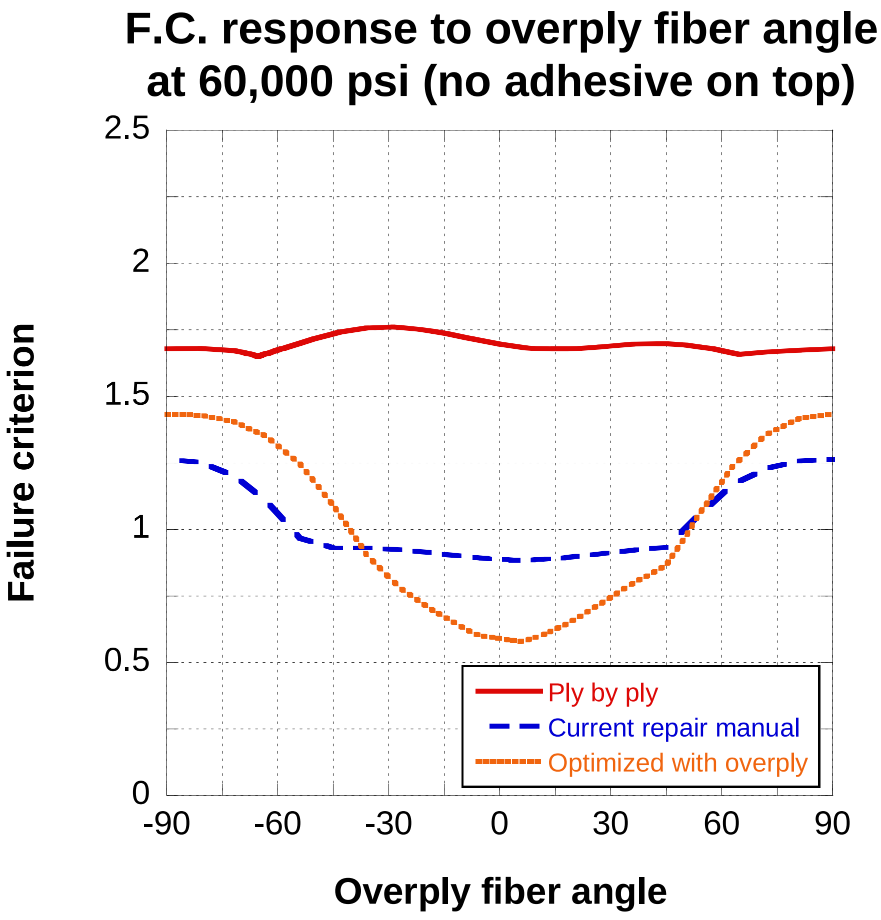
2t 4t 8t

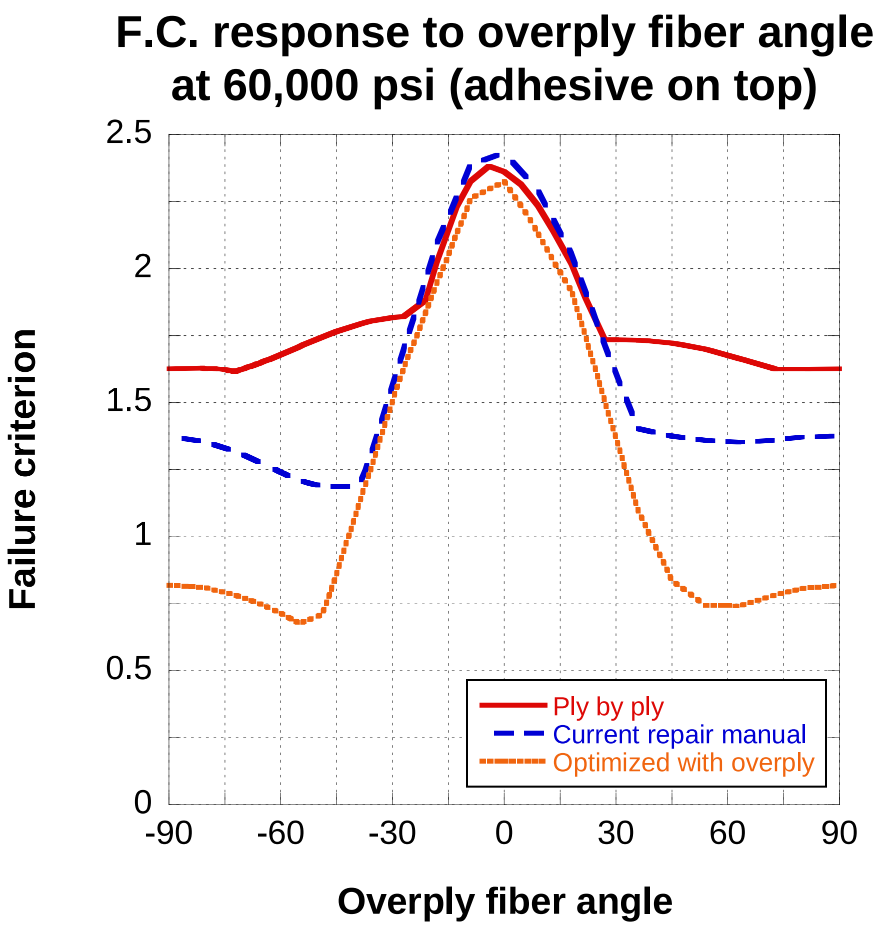


Case Study: Overply Thickness



Case Study: Overply angle





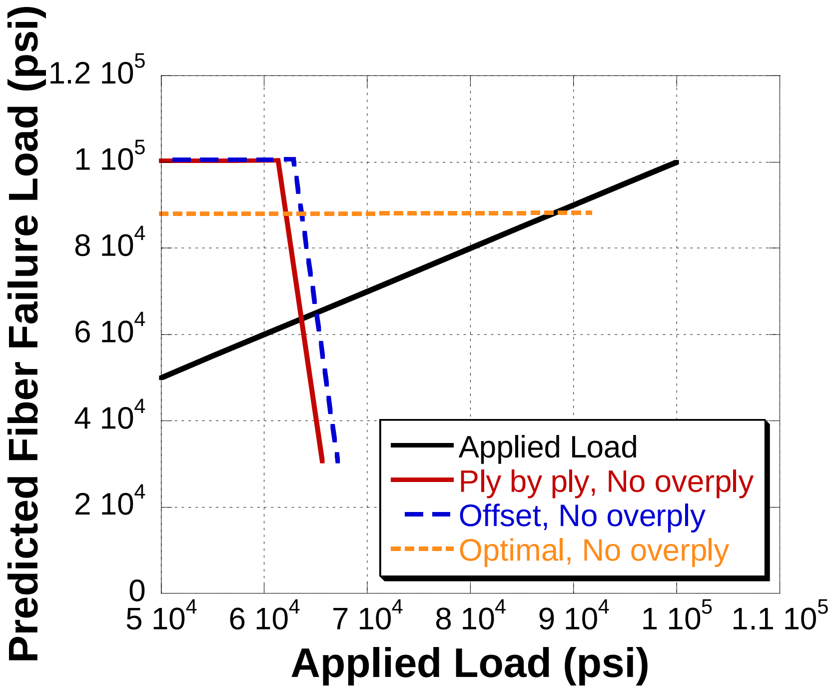
Overply angle is not aligned with loading direction due to peel stress in the adhesive on top

Optimized patch & overply angles

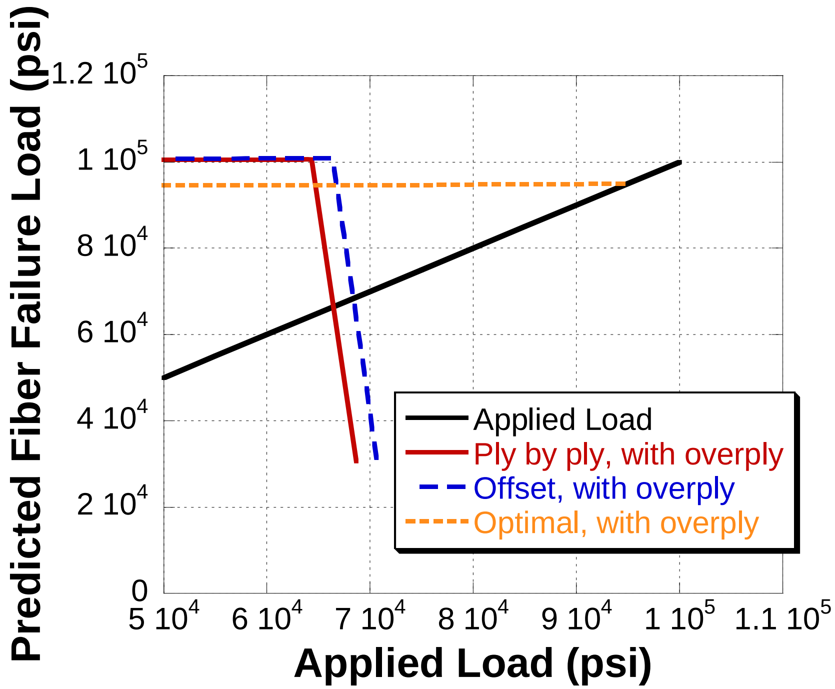
Parent	Ply by ply	Offset	Optimized with overply & <u>no</u> adhesive	Optimized with overply & adhesive
overply	**-72.**	**-45.1**	**5.26**	**-54.7**
45.000	45.000	0	11.746	43.809
0.0000	0.0000	-45	-45.282	-37.435
-45.000	-45.000	90	0.11019	-121.78
90.000	90.000	90	91.267	67.234
90.000	90.000	-45	-12.123	15.001
-45.000	-45.000	0	-25.158	-54.138
0.0000	0.0000	45	48.474	44.783
45.000	45.000	45	50.417	57.455

Strength Results

No Overply



With Overply



Conclusions

- Developed highly repetitive scarfing and repair procedures for IM6/3501-6 composites by using Scarfomatic device.

- Benchmarked strength prediction of scarfed and repaired panels based on small UNNOTCHED coupon tensile strength calibration
  - Good agreement with both scarfed and repair strength
  - Modeling of adhesive failure is critical for repair strength prediction

- Optimization of the patch composition to delay adhesive failure
  - Understood the stress transfer mechanisms with/- the overply
  - 20% or more effect on strength due to patch composition
    - Softening of the patch
      - Fabric patch makeup
      - Stress in the adherend

- Future work
  - Adhesive characterization
  - Multidirectional loading
  - Testing

B-spline Analysis Method

$$\mathbf{u}(x_1 x_2 x_3) = \sum_i \sum_j \sum_k X_i(x_1) Y_j(x_2) Z_k(x_3) \mathbf{U}_{ijk}$$

$\{X_i(x)\}, \{Y_j(y)\}, \{Z_k(z)\}$ – system of B-spline functions of given defect and power - n

$$\sigma_{ij} = C^p_{ijkl}(\varepsilon_{kl} - e^p_{kl}\Delta T)$$ $p=1,\ldots,N$, -ply number

Mechanical loading

$$\Delta T = 0$$

$$-u_x(0,y,z) = u_x(L,y,z) = \varepsilon_0 L/2$$

$$u_y(0,0,0) = u_z(x,y,0) = 0$$

Residual stress

$$\Delta T = -176^0 F$$

$$u_x(0,0,0) = u_y(0,L,0) = u_z(x,y,0) = 0$$

$$\sigma_{ij} = \sigma_0 \sigma^M_{ij} + \sigma^T_{ij}$$

Calculation of the overstresses volume function

$$\mathrm{v}(q_i) = \sum_{g_1} \sum_{g_2} \sum_{g_3} w_{g_1} w_{g_2} w_{g_3} \det \mathbf{J}(x_1^{g_1}, x_2^{g_2}, x_3^{g_3}) \eta(\sigma - q_i \sigma_m)$$

$$\eta(\sigma) = \begin{cases} 1, \sigma > 0 \\ 0, \sigma \le 0 \end{cases}$$