Analysis of Fastener Disbond Arrest Mechanism for Laminated Composite Structures

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The Joint Advanced Materials and Structures Center of Excellence

FAA Sponsored Project Information

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- **Other FAA Personnel:** Larry Ilcewicz, Peter Shyprykevich (Ret.)
- **Industry Participants:** Gerald Mabson, Marc Pieh, Eric Cregger, Cliff Chen, Lyle Deobald, Alan Miller, Steve Precup (All from Boeing)
- **Industry Sponsors:** Boeing

Accomplishments

Work Accomplished: Phase 1

("Development of Reliability-Based Damage Tolerant Structural Design Methodology")

- Developed the methodology to determine the reliability and maintenance planning of damage tolerant structures.
- Developed a user-friendly software (RELACS) for calculating POF and inspection intervals.
- Developed software interface (VSTM) with Nastran to facilitate stochastic FEA.
- Implemented stochastic FEA to obtain initial/damaged residual strength variance.

Current Research

- Develop analytical methods to analyze disbond and delamination arrest mechanisms in bonded structures under mixed mode loading.
- To apply probabilistic methods to assess reliability of bonded structures with fasteners.

Analysis of Disbond/Delamination Arrest Mechanisms

- **Objectives**

  - To understand the effectiveness of delamination/disbond arrest mechanisms

  - To develop analysis tools for design and optimization

- **Tasks**

  1) Establish FE models in ABAQUS

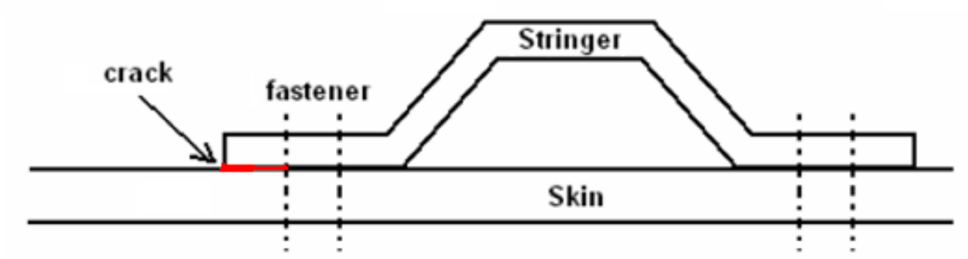
  2) Develop 1-D (beam) and 2D (plate) analytical capabilities

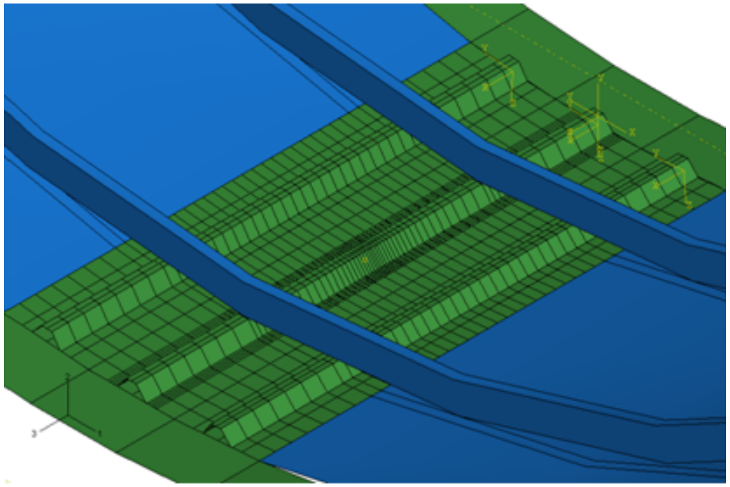
  3) Conduct validation experiments

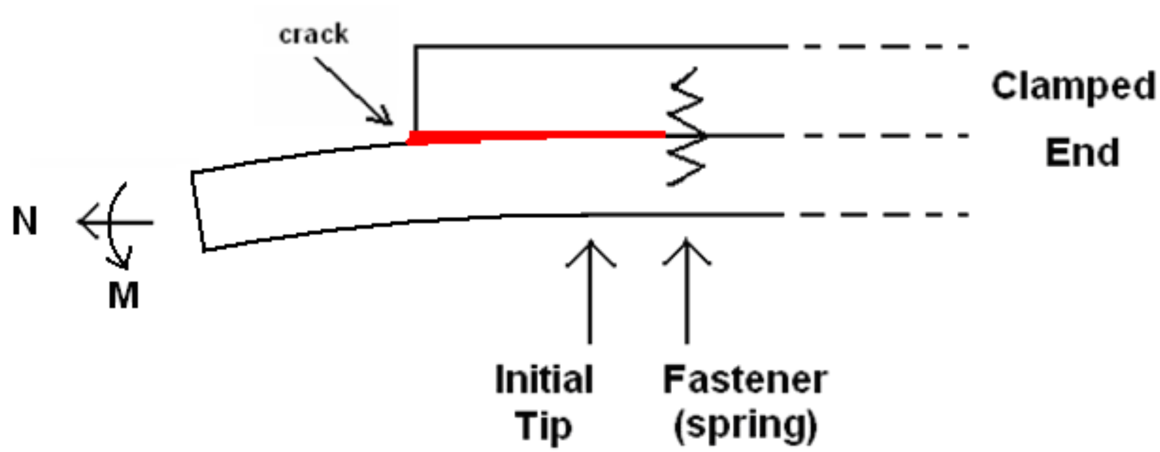
  3) Implement reliability analysis capability

  4) Conduct sensitivity studies on fastener effectiveness and stacking sequence effects

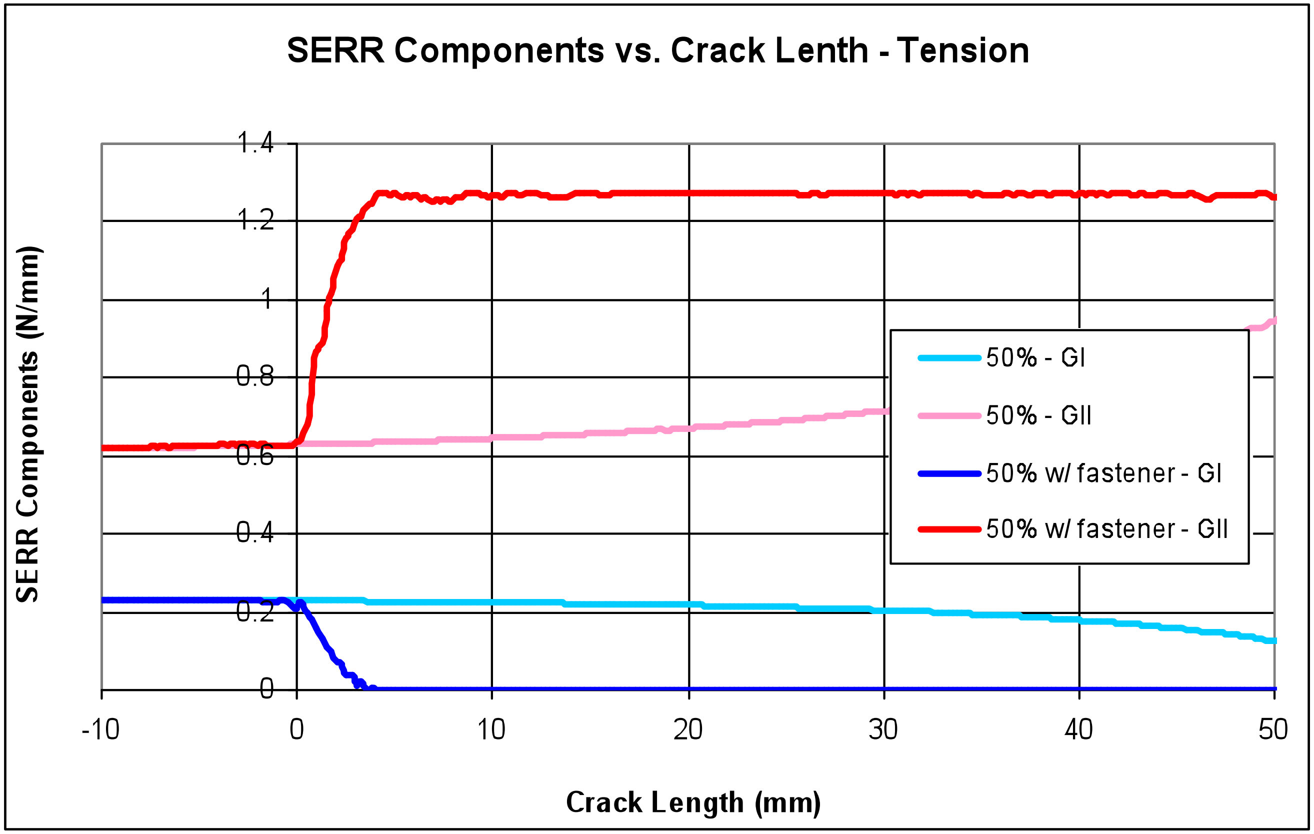
JAMS Bonded Skin/Stiffener with Fasteners

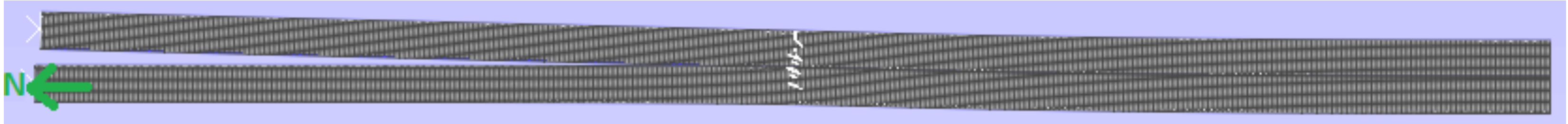






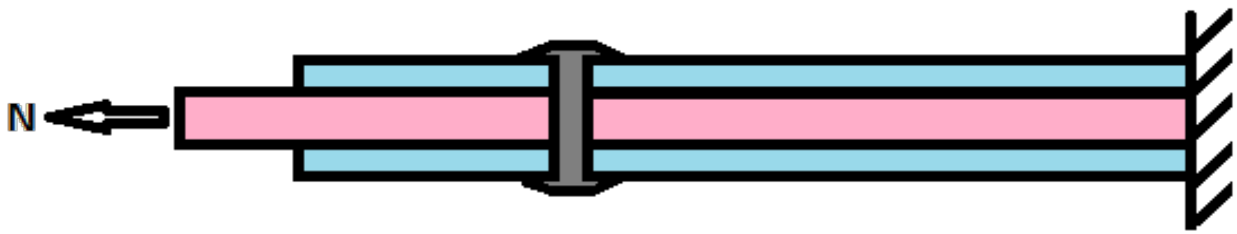
Mode Decomposition: Applied Tension Only

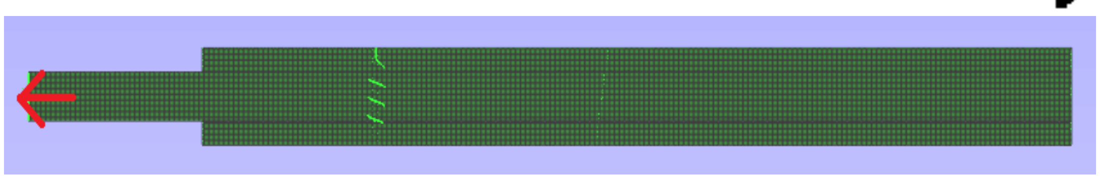




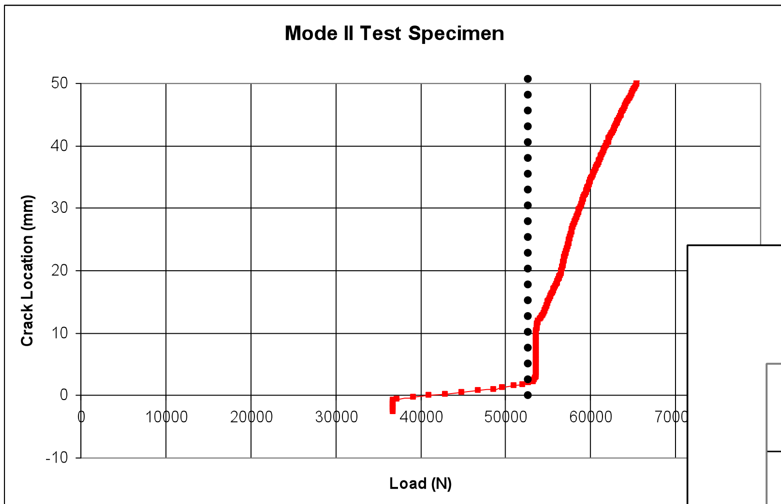
Mode II Test Specimen

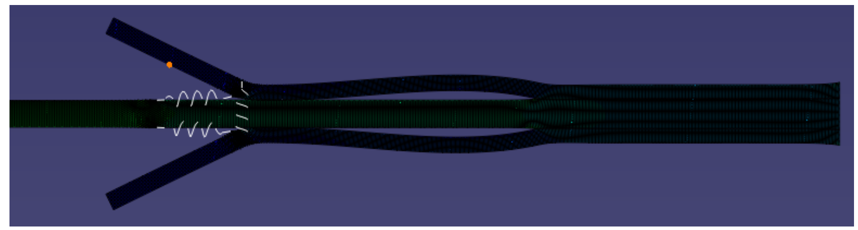
- Classical “bending type” specimen not suitable, e.g. SLB, ENF
  - Relatively thick compared to specimen length; specimen dimension coupling
  - Limited space for crack to propagate
- We want “axial type” specimen to test crack arrest behavior
  - Symmetric, 3-beam model, load applied to the center beam

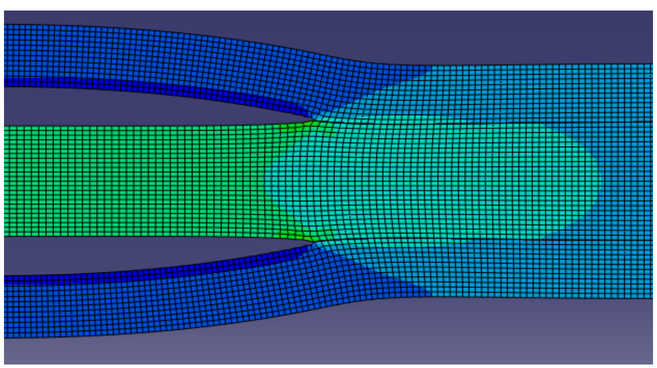


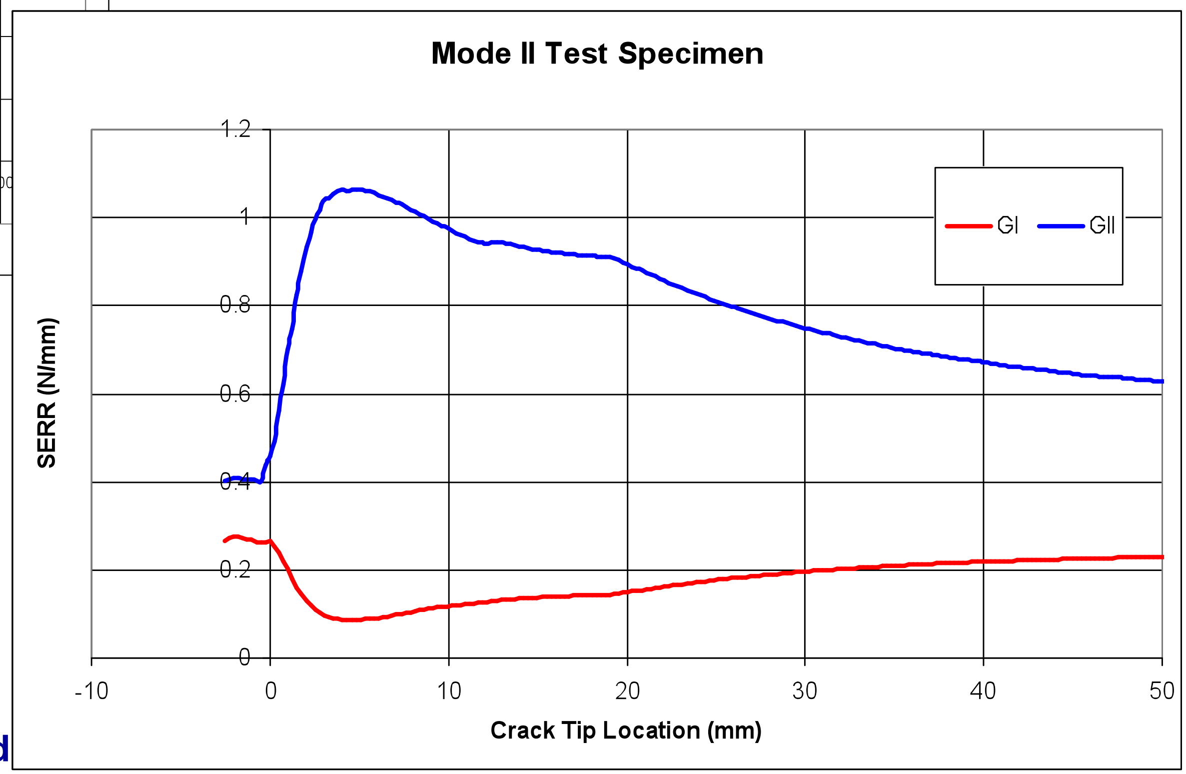


Mode II Test Specimen
Preliminary Findings



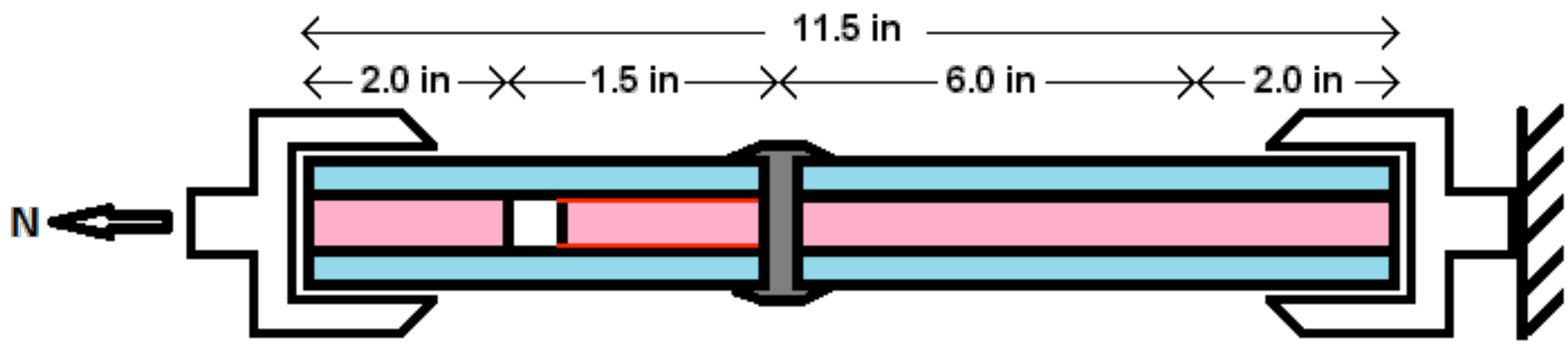


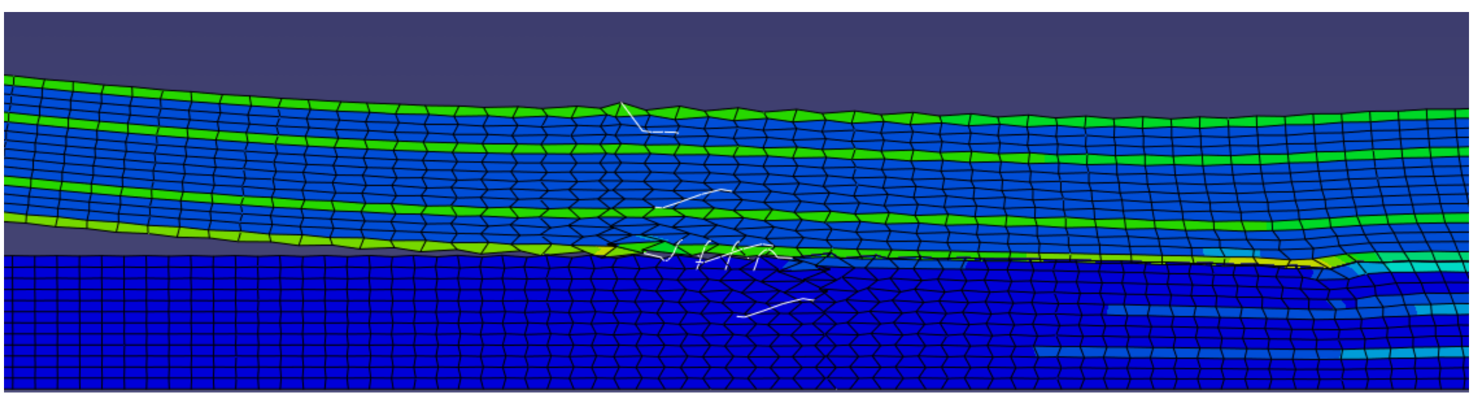




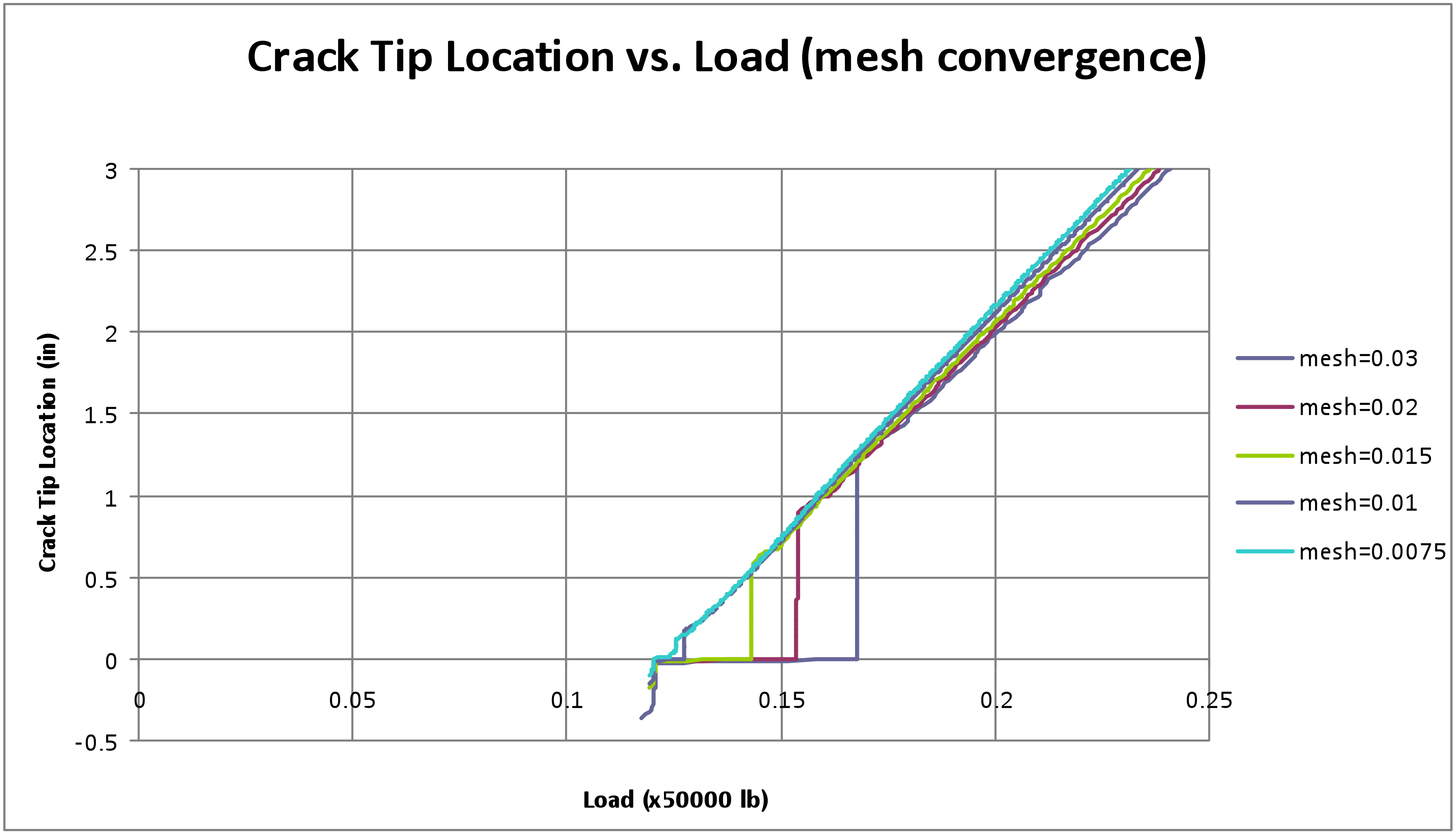
Mode II Test Specimen Mk.II

- Reversed Loading elements, i.e. apply tension to the outer two beams
- Closing moment exists at the crack tip

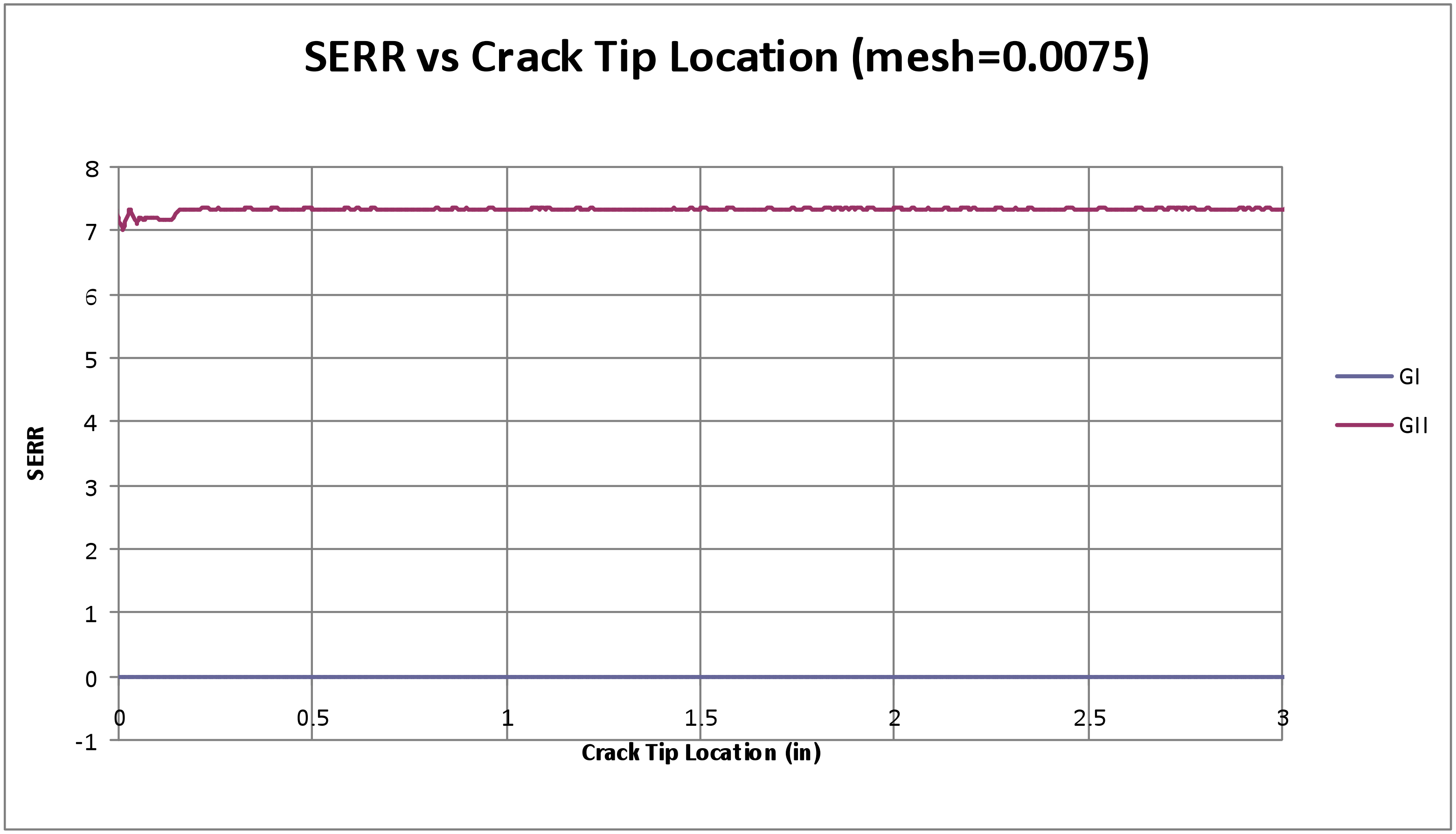




Mode II Test Specimen Mk.II Preliminary Findings



Mode II Test Specimen Mk.II
Preliminary Findings



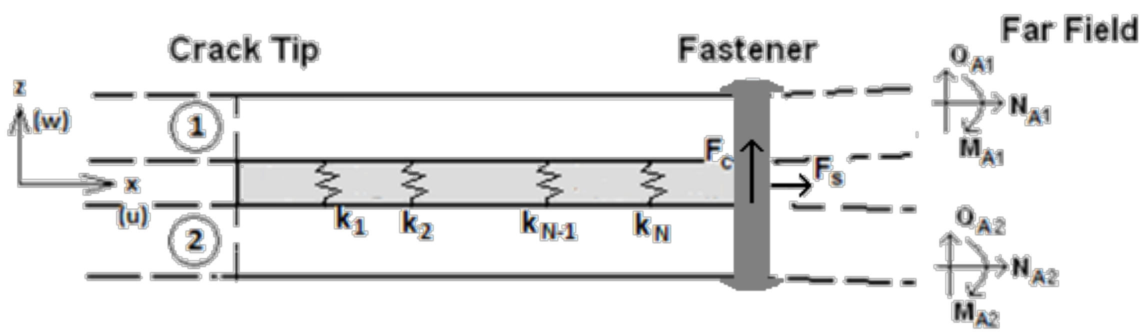
Sample Test Matrix

Layup (Top and bottom)	Layup (Center)	Fastener Diameter (in)	Width (in)	Number of Specimens
$[(0/45/-45/90)_2]_S$	$[(0/45/-45/90)_3]_S$	0.125	0.625	5
$[(0/45/-45/90)_2]_S$	$[(0/45/-45/90)_3]_S$	0.25	1.250	5
$[(0/45/-45/90)_2]_S$	$[(0/45/-45/90)_3]_S$	0.375	1.875	5
$[(0/45/-45/90)_3]_S$	$[(0/45/-45/90)_3]_S$	0.25	1.250	5
$[(0/45/-45/90)_3]_S$	$[(0/45/-45/90)_3]_S$	0.375	1.875	5

- Specimens to be manufactured by Boeing
- Testing to be conducted at University of Washington

Analytical Approach

- Uses Rayleigh-Ritz method and the energy principle.
- Two beams, fastener (two springs), and an elastic foundation layer between beams.
- Elastic layer is composed of *N* individual springs where *k* is very large in compression and zero in tension, for contact and separation.
- Solve system for the state of minimum potential energy iteratively.
- SERR mode decomposition by VCCT.



Rayleigh-Ritz Method (PMPE)

$$\delta\Pi = 0; \quad where\ \Pi = U_{total} - W_{total}$$

Beam Energy Terms

$$U_b = \frac{1}{2}EI\int_0^L \left(\frac{d^2w}{dx^2}\right)^2 dx$$

$$U_s = 1.2\frac{EI^2}{A}(1+\nu)\int_0^L \left(\frac{d^3w}{dx^3}\right)^2 dx$$

$$U_{ba} = \frac{1}{2}N\int_0^L \left(\frac{dw}{dx}\right)^2 dx$$

Elastic Layer Energy

$$U_{EL} = \sum_{n=1}^{N} \frac{1}{2} k_n (w_2 - w_1)^2 |_{x=L\left(\frac{n}{N}\right)}$$

Fastener/Spring Energy

$$U_{kc} = \frac{1}{2}k_c(w_2 - w_1)^2|_{x=L}$$

$$U_{ks} = \frac{1}{2}k_s(u_2 - u_1)^2|_{x=L}$$

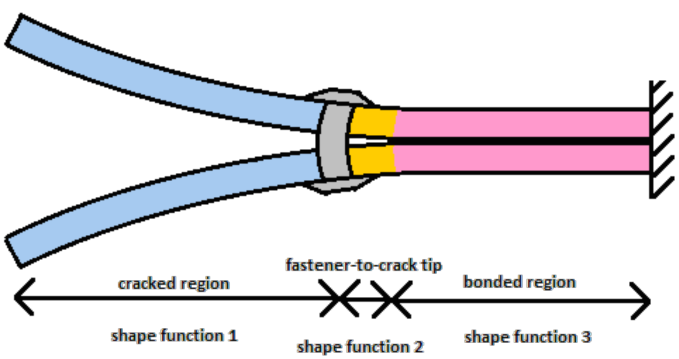
Work Terms

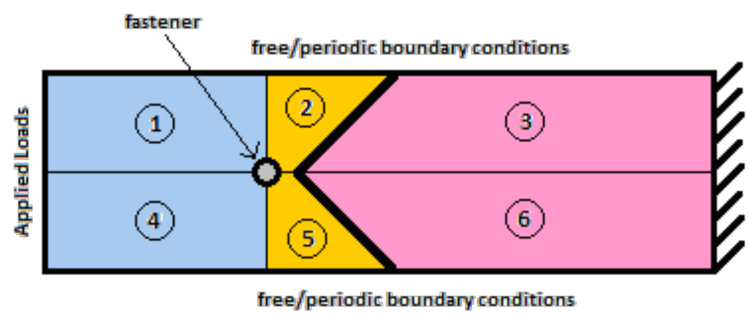
$$W_Q = Qw|_{x=L}$$

$$W_M = M\left(\frac{dw}{dx}\right)|_{x=L}$$

Piecewise Adaptive Shape Function

- Discontinuities require piecewise treatment of the model
- The set of shape functions have to adapt to new geometry after crack growth
- Shape functions must satisfy geometric boundary conditions
- Why is it important?





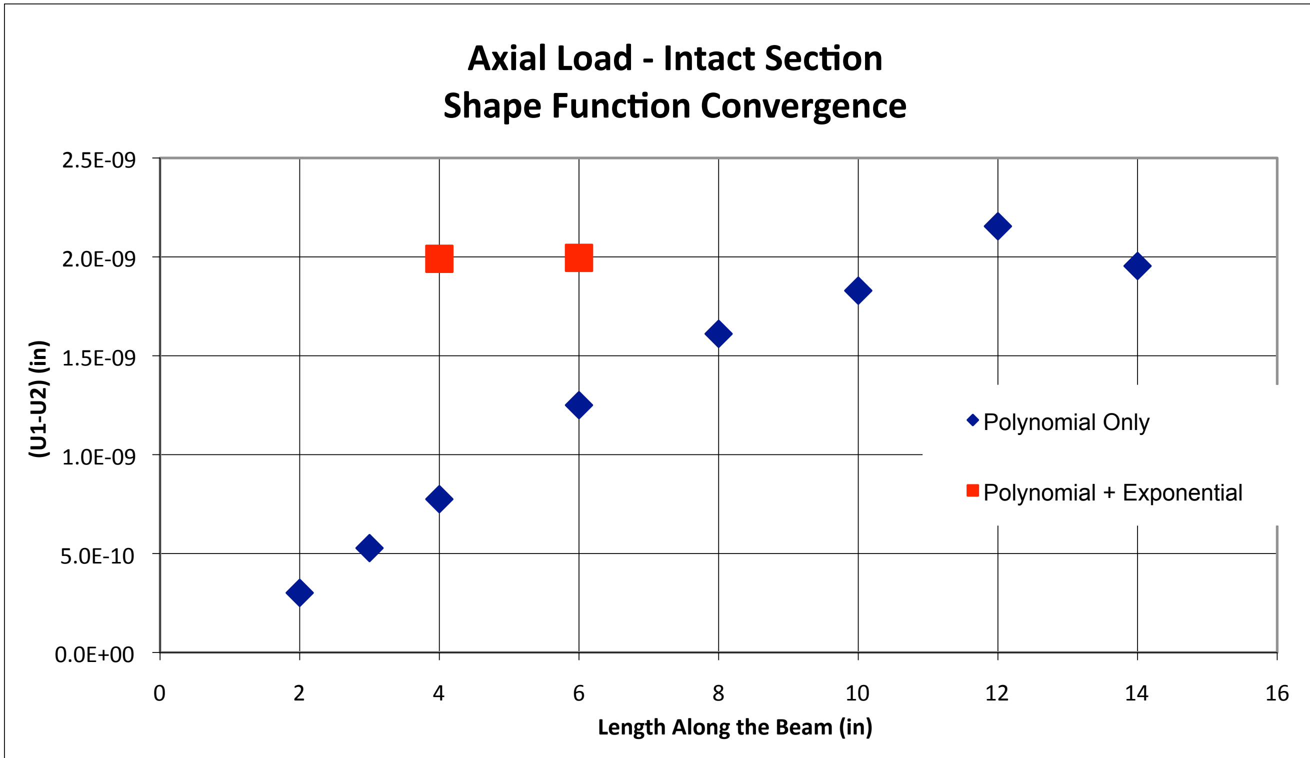
Example: Pure Axial Load Case

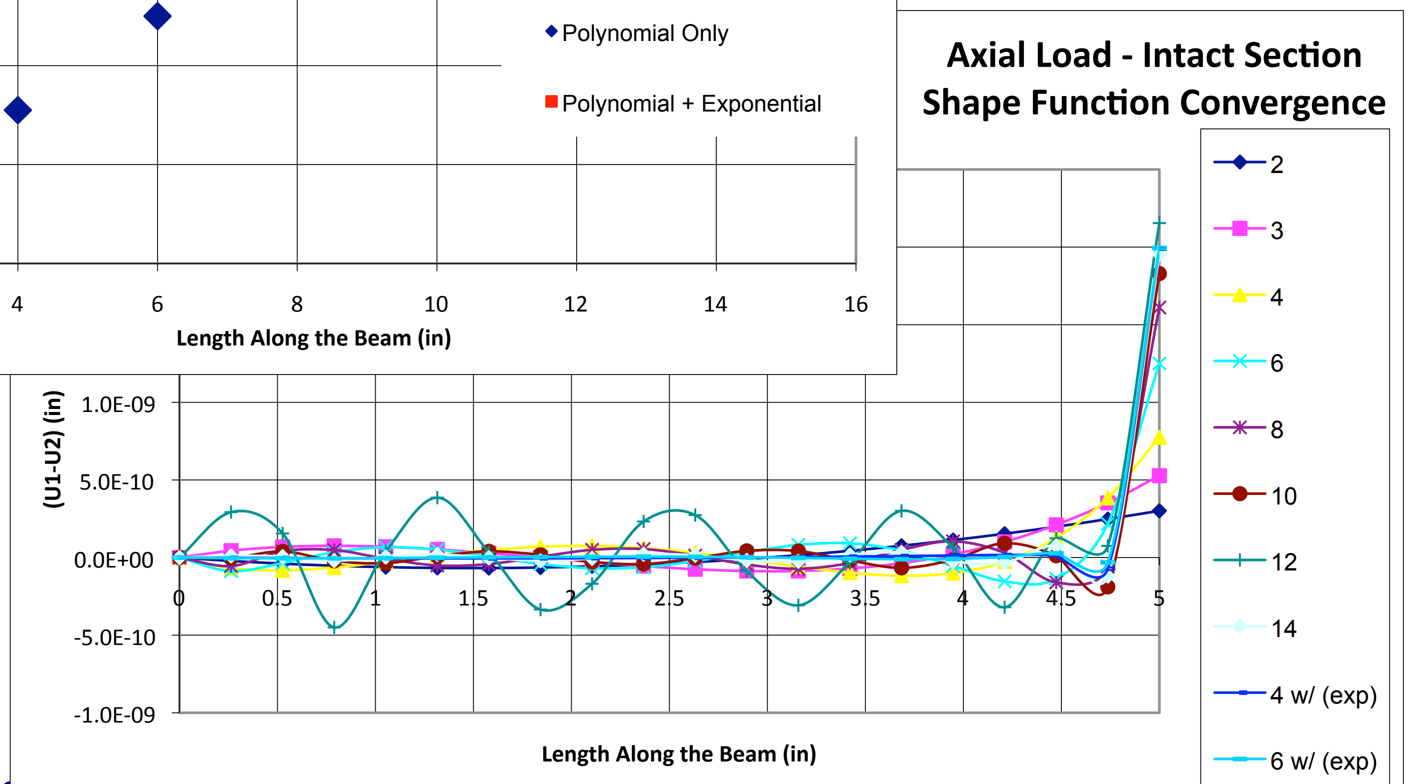
- Conventional vs. Composite shape functions
- The crack tip force can be used in VCCT
- Plots (u1-u2) – which gives the shear transfer between two beams

$$u_{1,2} = \sum\left(a_i x^i\right)$$

$$u_{1,2} = \sum\left(a_i x^i + b_j e^{\frac{t}{j^2}(x-L)}\right)$$

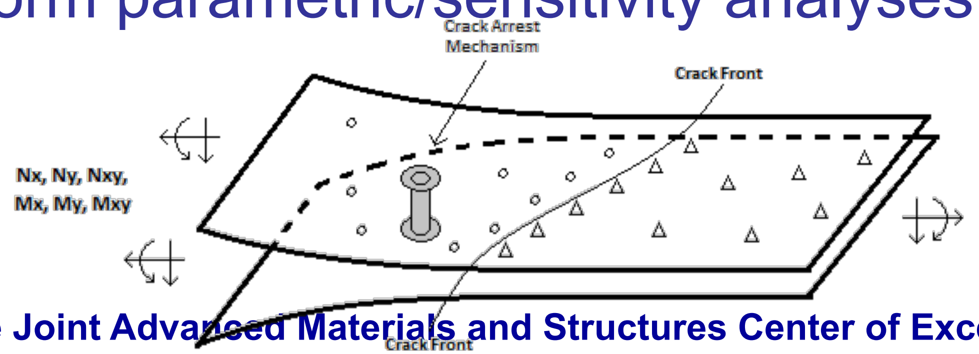
Example: Pure Axial Load Case





Work in Progress / Future Work

- Develop analytical solutions
- Consider all alternate failure modes
- Model crack propagation around the fastener in 3-D
- Consider multiple fasteners
- Design validation experiments
- Generate design curves
- Identify key variables for design and optimization
- Perform parametric/sensitivity analyses



A Look Forward

- **Benefit to Aviation**
  - Provide analysis tools for fastener arrest mechanism
  - Provide a fail-safe path to the design of integrated composite structures
  - Optimization can lead to weight savings while properly addressing safety issue
  - Integrating with probabilistic analysis method can properly address design uncertainties

[back up]
Laminate Configuration (16 plies)

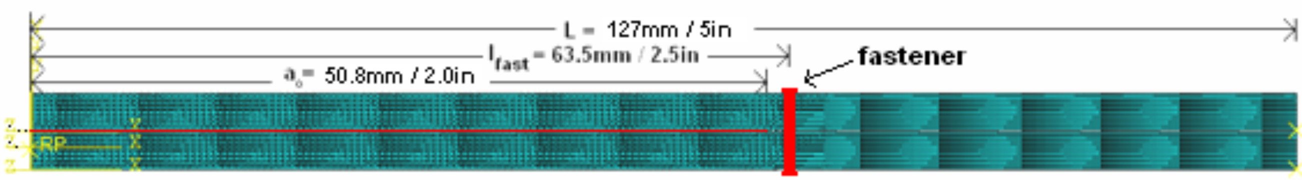
0-ply	Lay-up	E_x	C (in/lb) (joint compliance)
25.0%	$(45/0/-45/90/45/0/-45/90)_s$	7.42×10^6	7.73×10^{-6}
37.5%	$(45/0/-45/0/45/0/-45/90)_s$	9.29×10^6	6.57×10^{-6}
50.0%	$(45/0_2/-45/0_2/90_2)_s$	1.10×10^7	5.85×10^{-6}
62.5%	$(45/0_3/-45/0_2/90)_s$	1.30×10^7	5.25×10^{-6}

$$C=\left(\frac{t_1+t_2}{2d}\right)^a\frac{b}{n}\left(\frac{1}{t_1E_1}+\frac{1}{nt_2E_2}+\frac{1}{nt_1E_3}+\frac{1}{2nt_2E_3}\right)$$

$$a=2/3,\ \ b=4.2,\ \ n=1$$

$$k_{clamp}=\frac{AE}{(t_1+t_2)}=3.37\times10^6$$

$$G_{equivC}=G_{IC}+\left(G_{IIC}-G_{IC}\right)\left(\frac{G_{II}}{G_I+G_{II}}\right)^\eta$$



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Model Description

- 16-ply CFRP (t = 0.0075” x 16 = 0.12”)
- Lay-ups
  - Percentage of 0-deg: 25% / 37.5% / 50% / 62.5%
- Fastener
  - Ti-Al6-V4 (E = 16.5×10^6psi)
  - d = 0.25 in
- Fastener Flexibility (H. Huth, 1986)

$$C = \left(\frac{t_1 + t_2}{2d}\right)^a \frac{b}{n}\left(\frac{1}{t_1 E_1} + \frac{1}{n t_2 E_2} + \frac{1}{n t_1 E_3} + \frac{1}{2 n t_2 E_3}\right)$$

[back up]
Material Properties (AS4/3501-6)

- E_1=127.5GPa
- E_2=11.3GPa
- G_{12}=6.0GPa
- ν=0.3
- X_t=2282MPa
- X_c=1440MPa
- Y_t=57MPa
- Y_c=228MPa
- S_{xy}=71MPa
- G_{IC}=0.2627N/mm
- G_{IIC}=1.226N/mm
- η=1.75

- E_1=18.5Msi
- E_2=1.64Msi
- G_{12}=0.871Msi
- v=0.3
- X_t=331ksi
- X_c=208.9ksi
- Y_t=8.3ksi
- Y_c=33.1ksi
- S_{xy}=10.3ksi
- G_{IC}=1.5lb/in
- G_{IIC}=7.0lb/in
- η=1.75