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, Eric Cregger, Marc Piehl, 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**

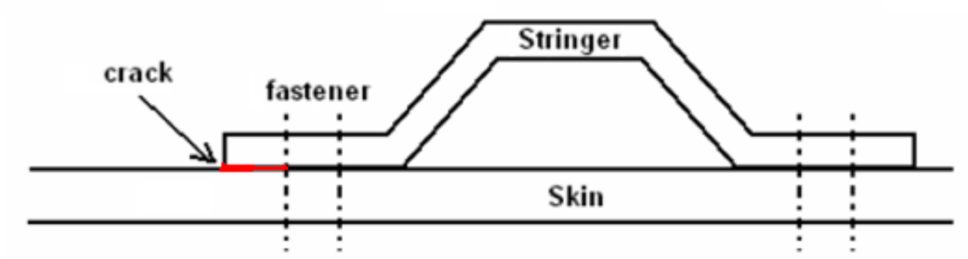
  1). Establish FE models in ABAQUS

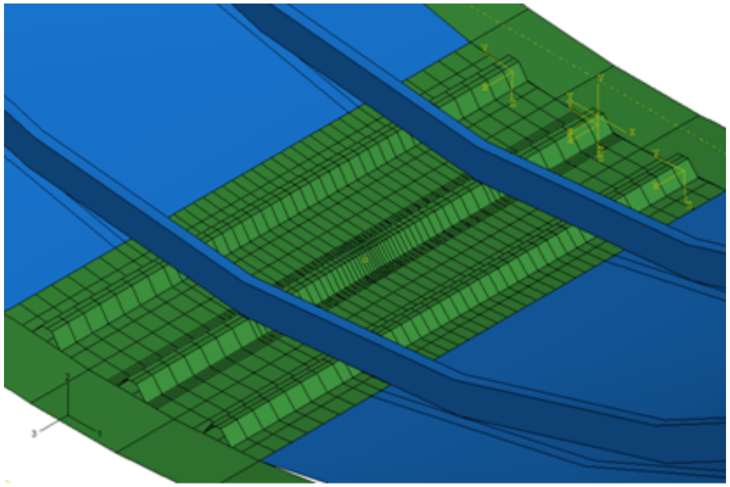
  2). Develop 1-D (beam) and 2D (plate) analytical capabilities

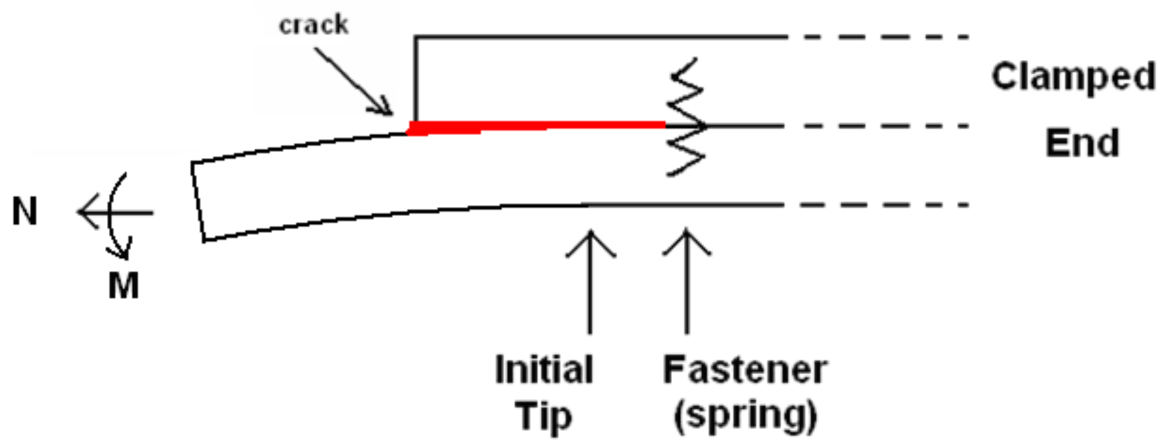
  3). Implement reliability analysis capability

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

Bonded Skin/Stiffener with Fasteners







Laminate Configuration (16 plies)

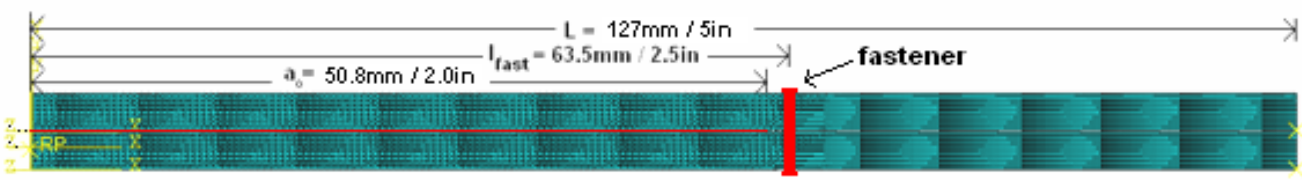
0-ply	Lay-up	E_x	C (in/lb) (joint compliance)
25.0%	$(45/0/-45/90/45/0/-45/90)_s$	7.42×10^{6}	7.73×10^{-6}
37.5%	$(45/0/-45/0/45/0/-45/90)_s$	9.29×10^{6}	6.57×10^{-6}
50.0%	$(45/0_2/-45/0_2/90_2)_s$	1.10×10^{7}	5.85×10^{-6}
62.5%	$(45/0_3/-45/0_2/90)_s$	1.30×10^{7}	5.25×10^{-6}

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

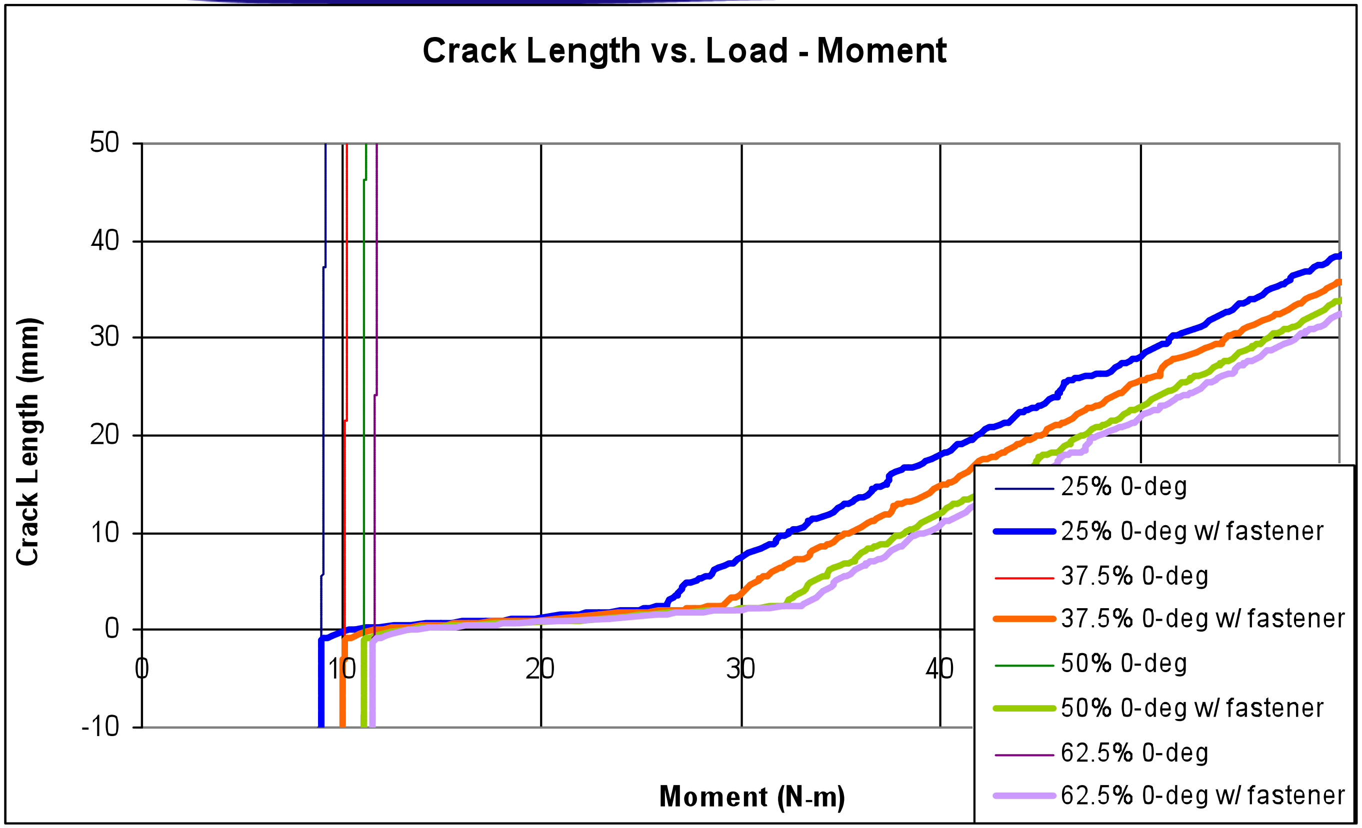
$$a=2/3,\ b=4.2,\ n=1$$

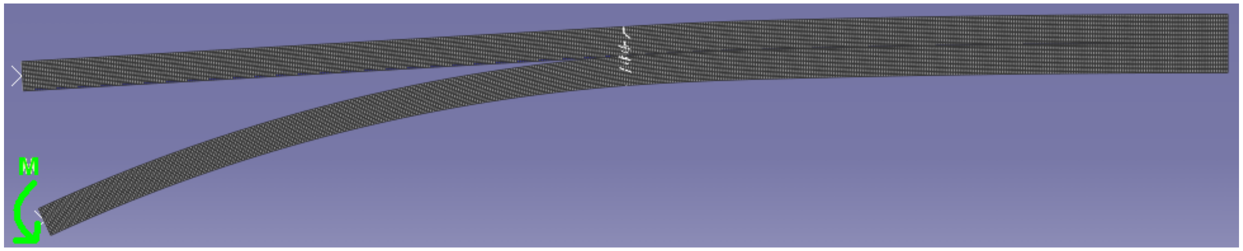
$$k_{clamp}=\frac{AE}{(t_1+t_2)}=3.37\times10^{6}$$

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

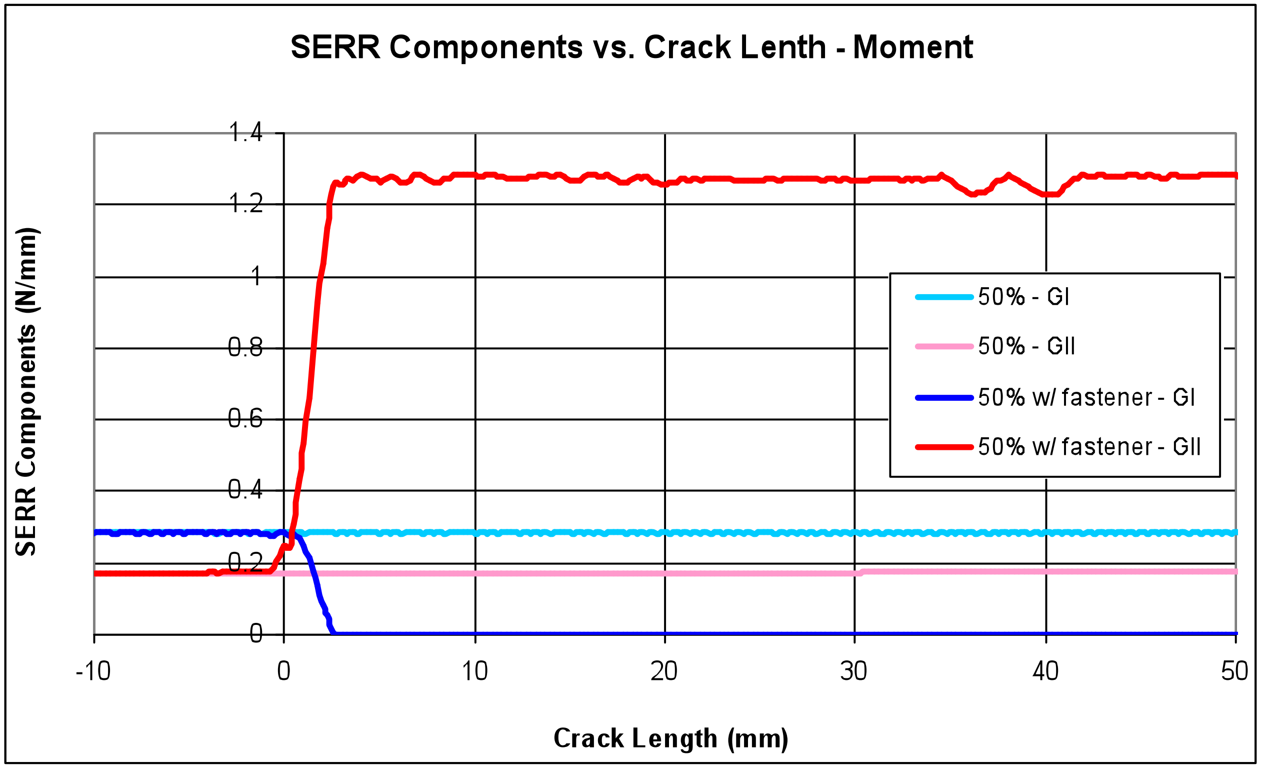


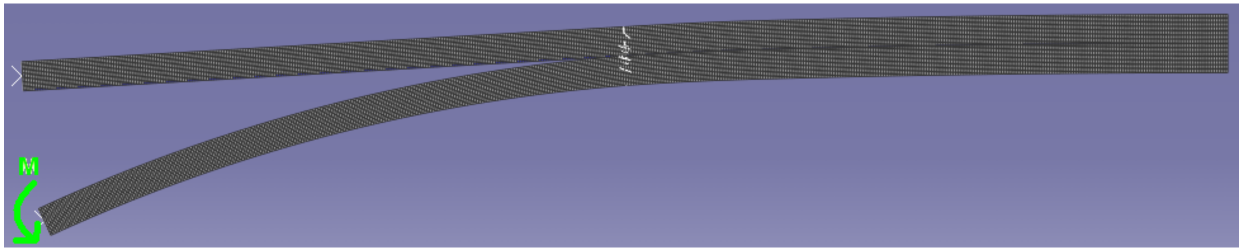
Results: Applied Moment Only



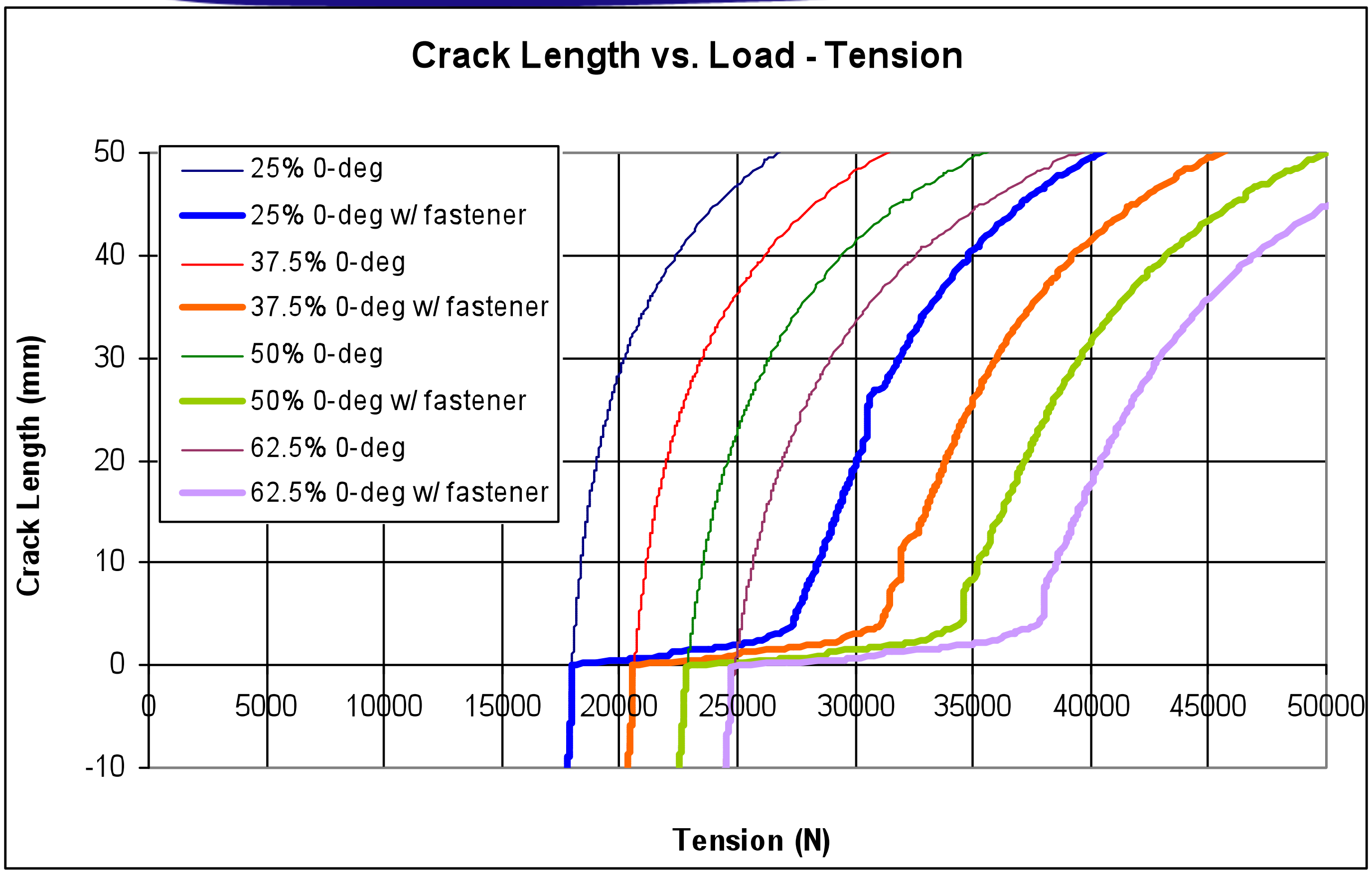


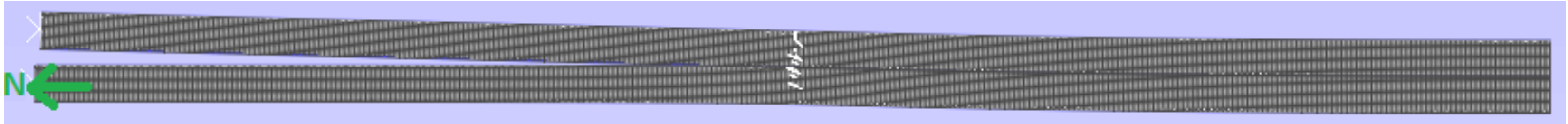
Mode Decomposition with Fastener: Applied Moment Only



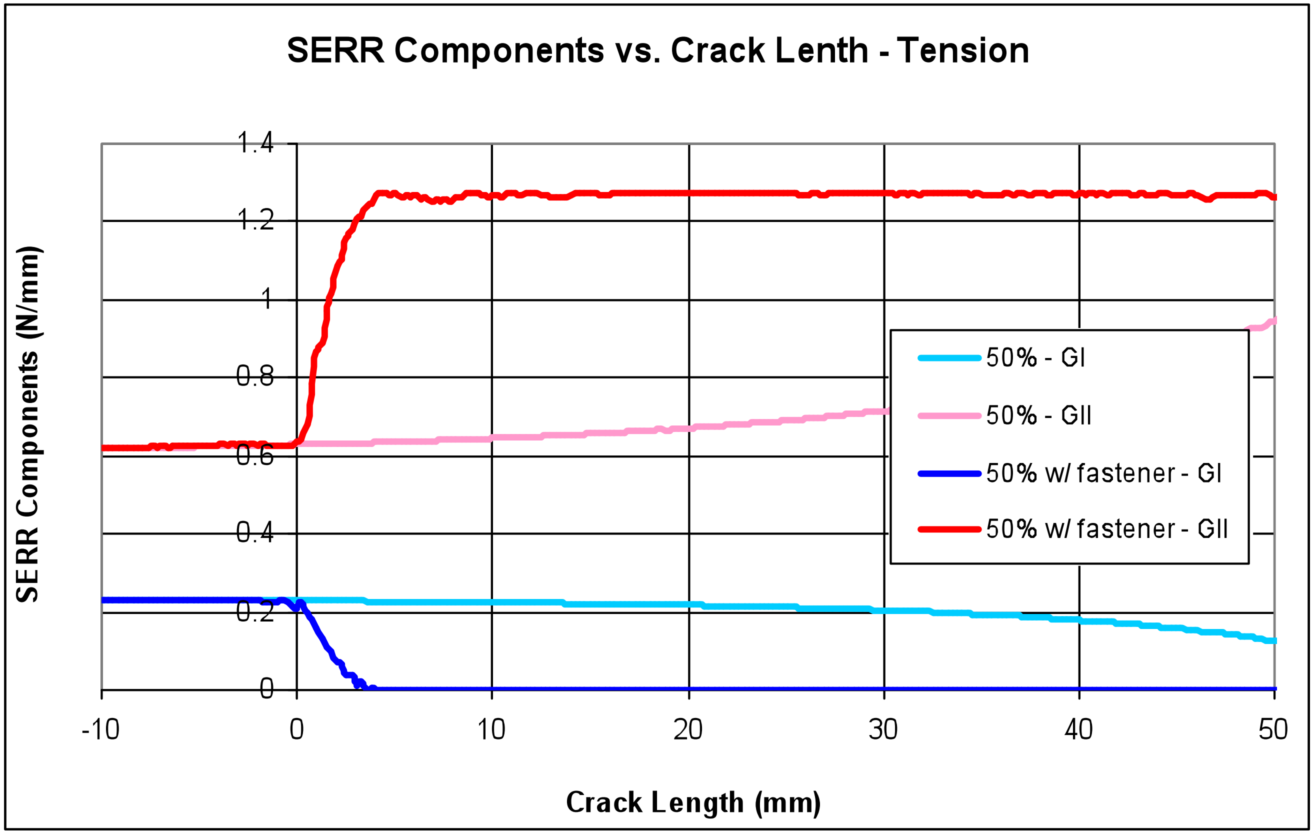


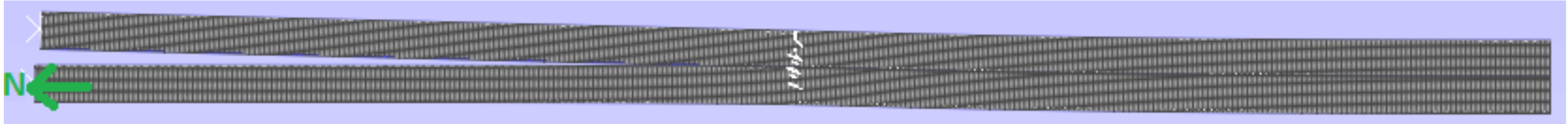
Results: Applied Tension Only



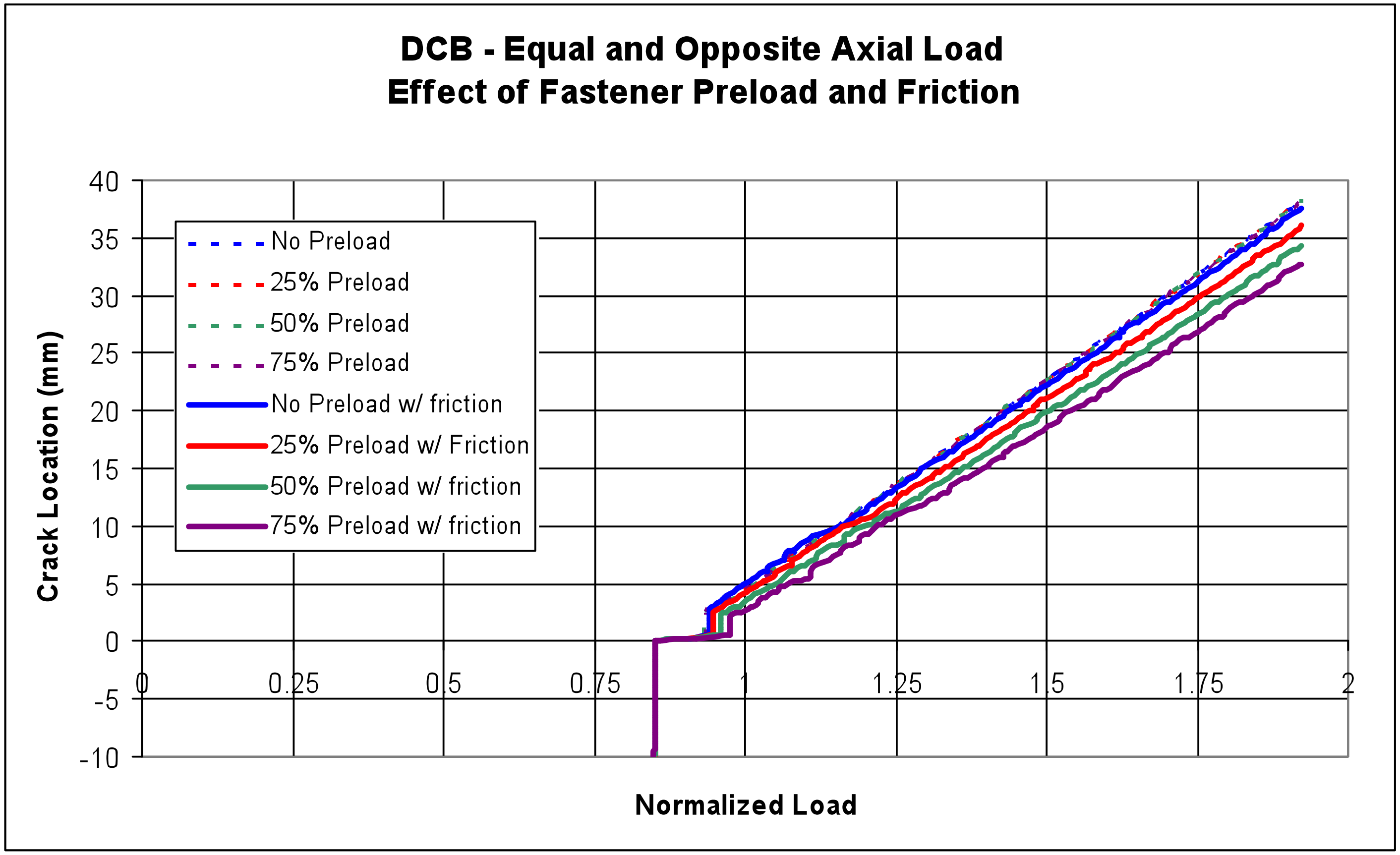


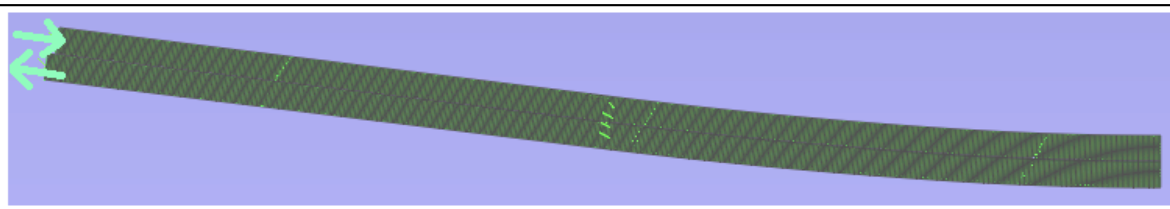
Mode Decomposition: Applied Tension Only





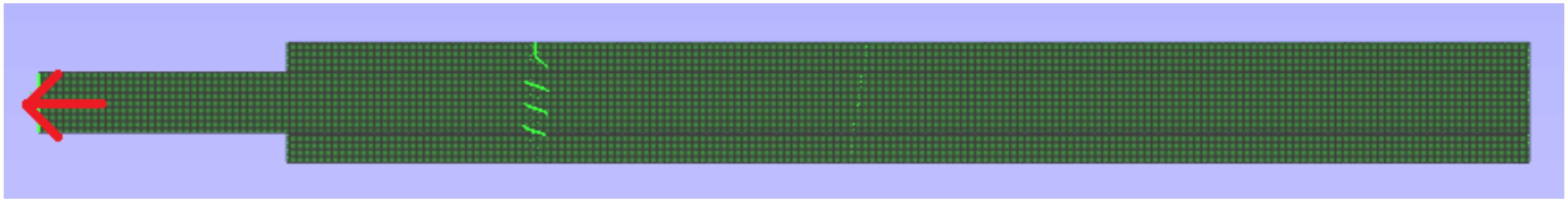
Friction and Fastener Preload



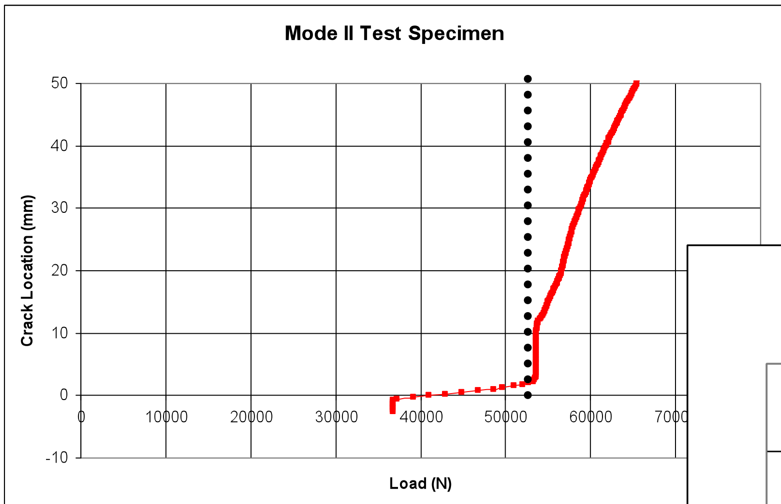


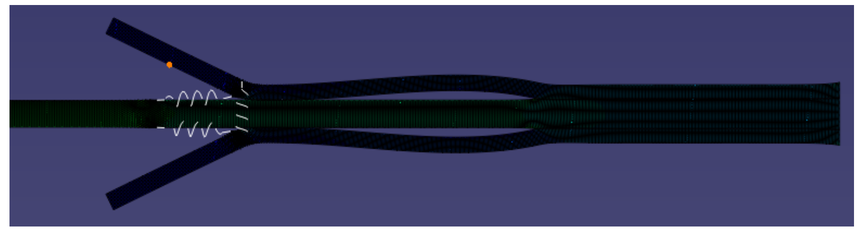
Mode II Test Specimen

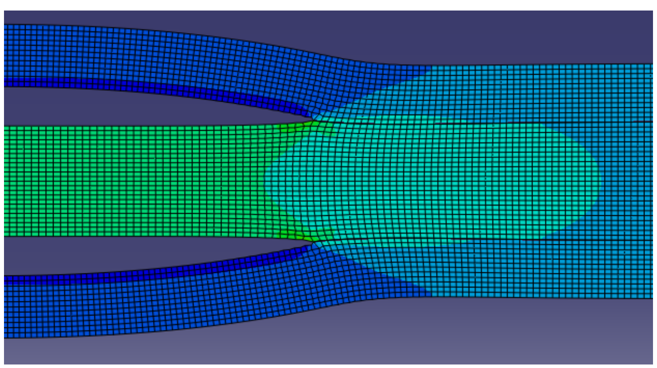
- Classical "bending type" specimen not suitable, e.g. SLB, ENF
  - Relatively thick compared to specimen length; specimen dimension coupling
  - Limited space for crack to propagate
- We want "axial type" specimen to test crack arrest behavior
  - Symmetric, 3-beam model, load applied to the center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

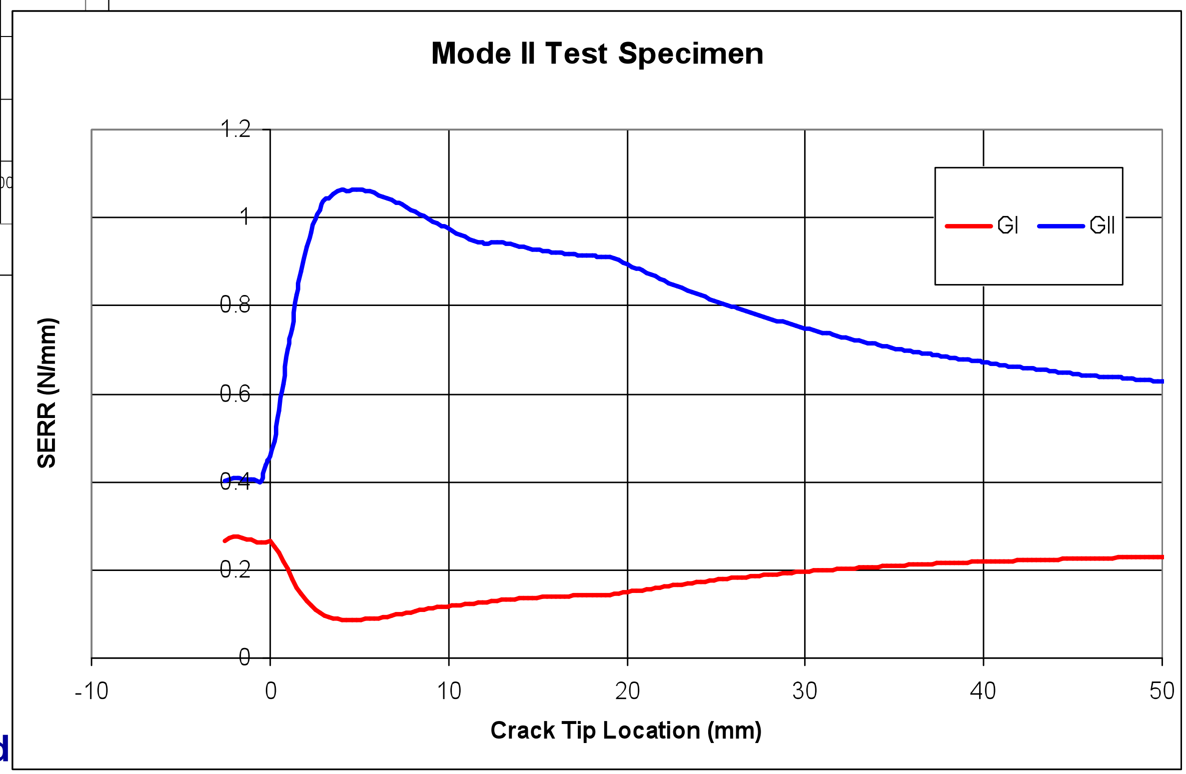


Mode II Test Specimen
Preliminary Findings

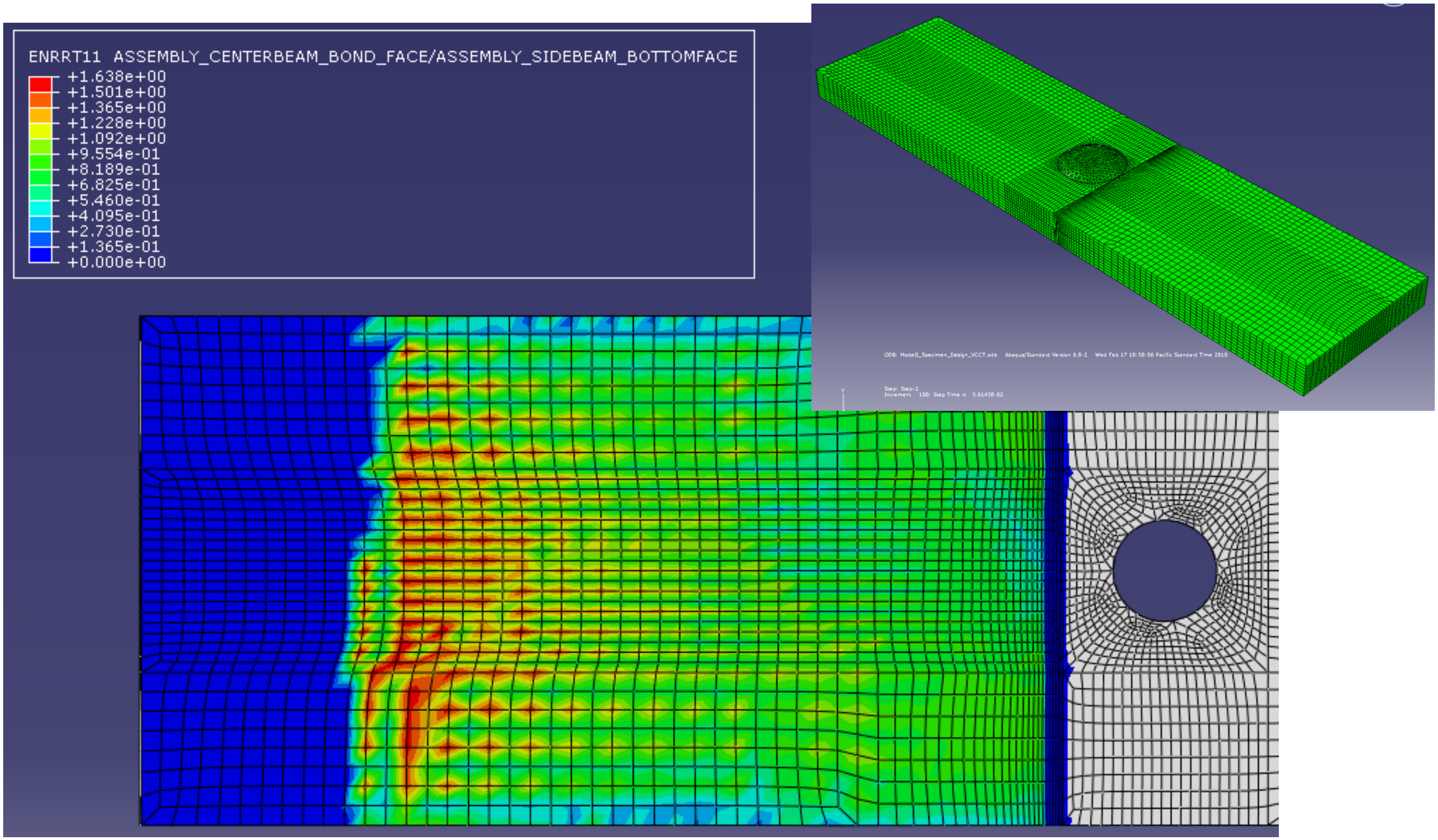






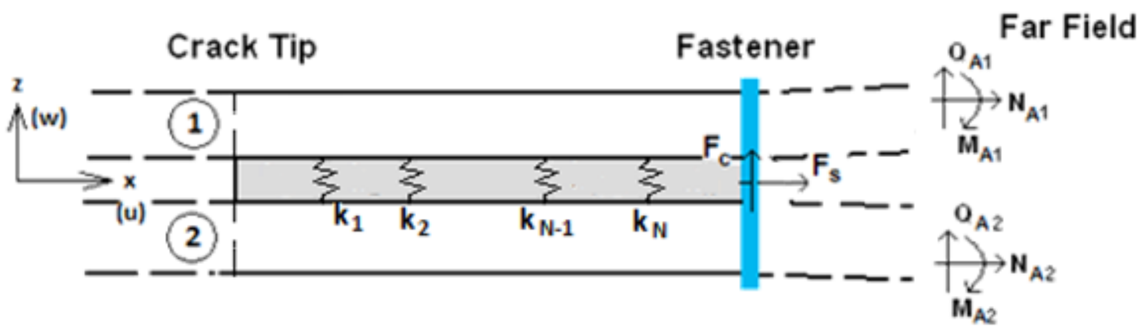


Mode II Test Specimen in 3-D



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 Wang/Qiao.



Rayleigh-Ritz Method (PMPE)

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

Beam Energy Terms

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

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

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

Elastic Layer Energy

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

Fastener/Spring Energy

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

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

Work Terms

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

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

Shape Functions

- Shape functions must satisfy geometric boundary conditions.
  - Shape functions considered for transverse displacement.

$$w_1 = \sum_{i=1}^{I} \alpha_i x^{i+1} \; ; i = 1,2 \ldots I$$

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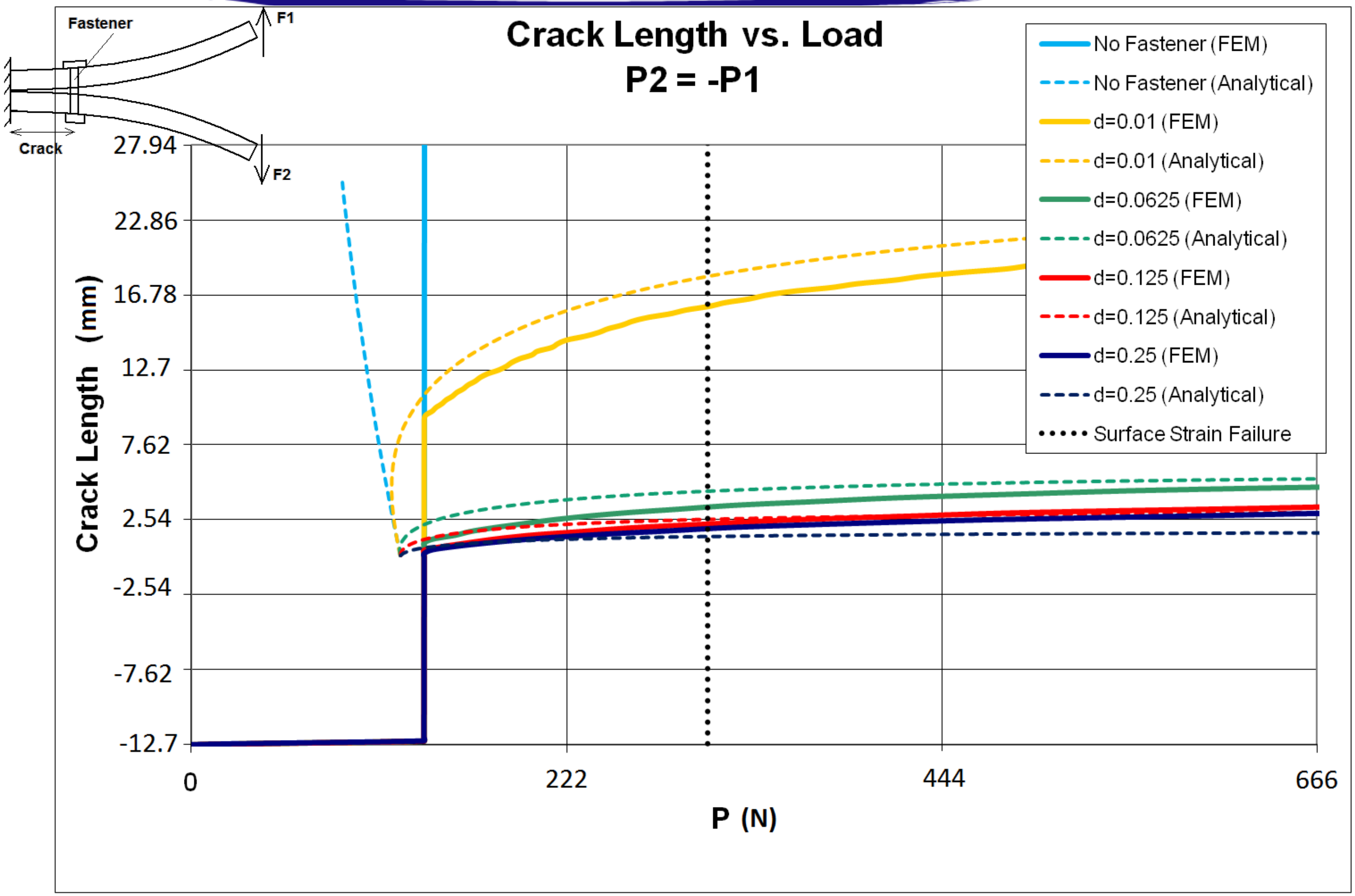
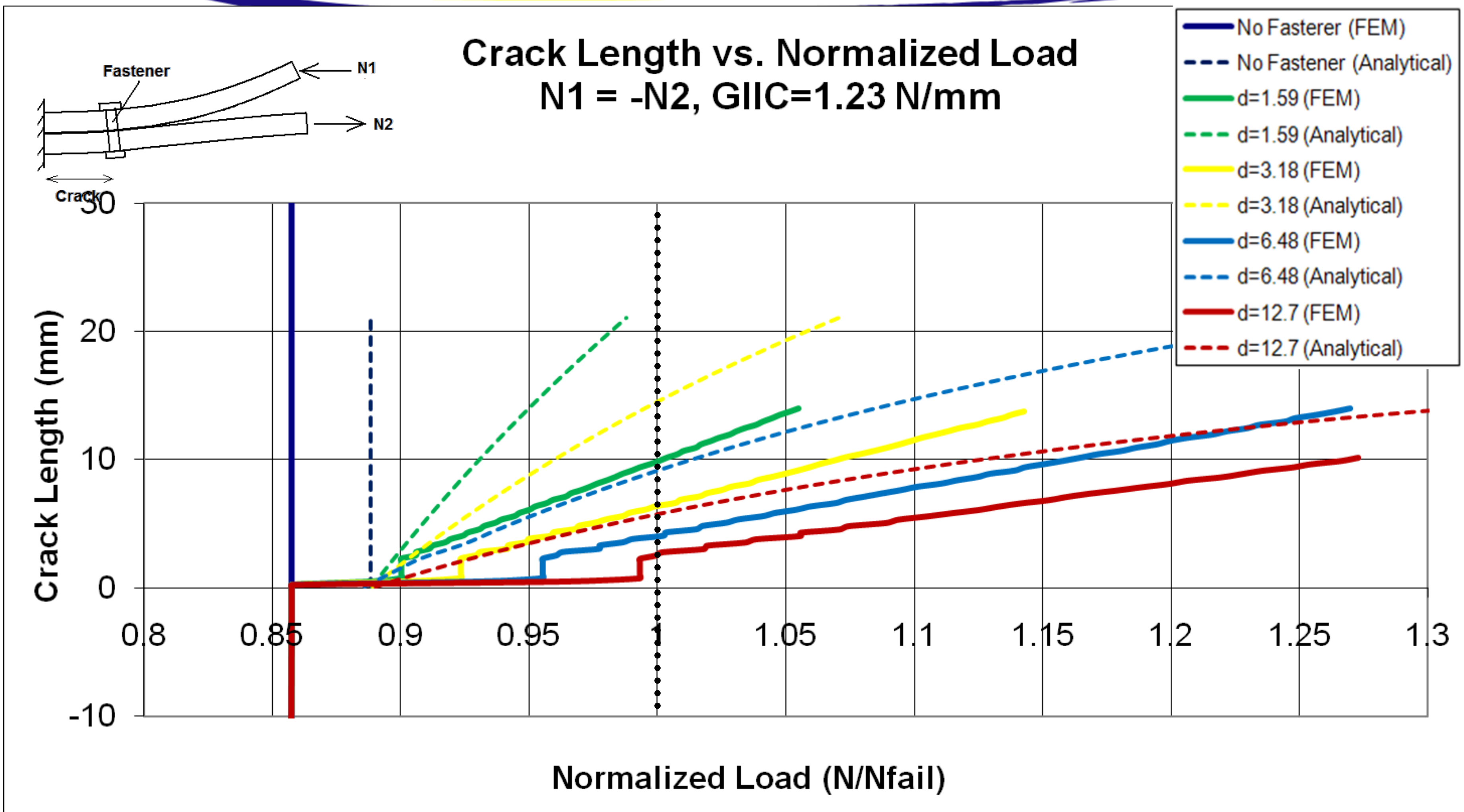
- Shape functions considered for axial displacement

$$u_1 = x\left(1 + \frac{N_1}{A_1 E_1}\right) \qquad u_2 = x\left(1 + \frac{N_2}{A_2 E_2}\right)$$

Mode I: FEM vs. Analytical Fracture Analysis

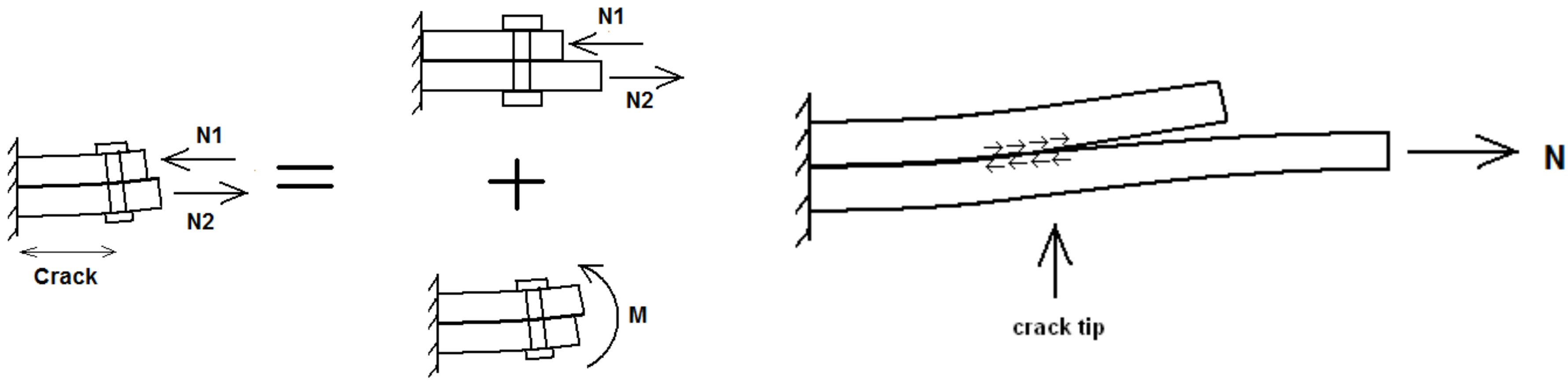


Mode II: FEM vs. Analytical Fracture Analysis



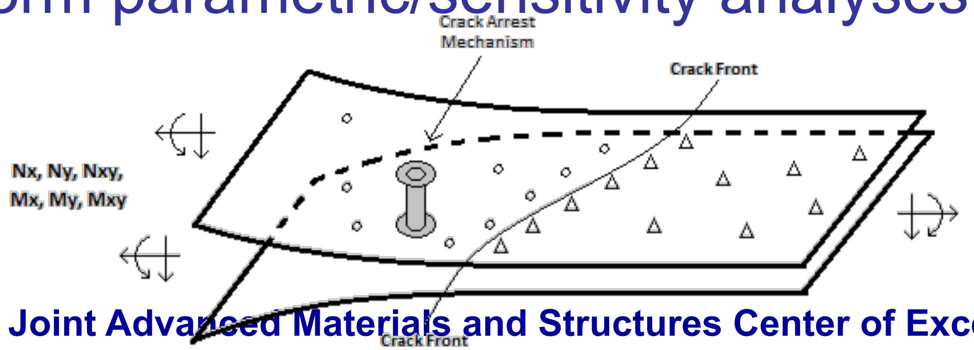
Analytical Model Enhancements

- Opposite axial forces causes a bending moment that counteracts the relative displacement of the beams at the location of the fastener.
- Traction acting on intact portion of the beams contributes to moment coupling through equilibrium requirements.
- Use piece-wise adaptive shape functions to model the entire beam



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]
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 = 16.5x10^{6}psi)
  - 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