Development of Reliability-Based Damage Tolerant Structural Design Methodology

Kuen Y. Lin, Chi Ho Cheung, and Andrey Styuart
Department of Aeronautics and Astronautics
University of Washington

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The Joint Advanced Materials and Structures Center of Excellence

FAA Sponsored Project Information

- **Principal Investigator:**
  - Dr. Kuen Y. Lin, Aeronautics and Astronautics, UW
- **Research Scientist:** Dr. Andrey Styuart, UW
- **Pre-Doctoral Research Assistant:** Chi Ho “Eric” Cheung, UW
- **FAA Technical Monitor:** Curtis Davies
- **Other FAA Personnel:** Larry Ilcewicz, Peter Shyprykevich (retired)
- **Industry Participants:** Marc Piehl, Gerald Mabson, Eric Cregger, Cliff Chen, Lyle Deobald, Steve Precup, Alan Miller (All from Boeing)
- **Industry Sponsors:** Boeing

Reliability-Based Damage Tolerant Structural Design Methodology

- ***Motivation and Key Issues:*** Composite materials are being used in aircraft primary structures such as 787 wings and fuselage. In these applications, stringent requirements on weight, damage tolerance, reliability and cost must be satisfied. Although currently there are MSG-3 guidelines for general aircraft maintenance, an urgent need exists to develop a standardized methodology specifically for composite structures to establish an optimal inspection schedule that provides minimum maintenance cost and maximum structural reliability.
- ***Objective:*** Develop a probabilistic method for estimating structural component reliabilities suitable for aircraft design, inspection, and regulatory compliance.

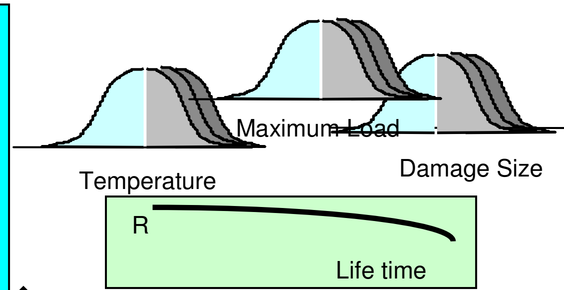
Technical Approach

- The approach is based on a probabilistic failure analysis with the consideration of parameters such as inspection intervals, statistical data on damages, loads, temperatures, damage detection capability, residual strength of the new, damaged and repaired structures.
- The inspection intervals are formulated based on the probability of failure of a structure containing damage and the quality of a repair.
- The approach combines the “Level of Safety” method proposed by Lin, et al. and “Probabilistic Design of Composite Structures” method by Styuart, at al.

RELACS – Reliability Life-Cycle Analysis of Composite Structures

Environmental Physics:

1. External Loads
2. Temperatures
3. Damage Source



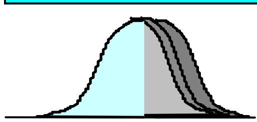
Damage Physics:

1. Damage size and Occurrence
2. Residual Strength
3. Damage Growth or Fatigue after Damage

RELACS

Operations:

1. Detection Probability
2. Repair Quality

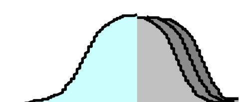


- Quantified Safety
- Better Design
- Optimized Maintenance

Experiments

FEA

(CAI, progressive damage model, VCCT, etc)



Program Capabilities: Various Failure Modes

- "Static" failure: load exceeds the strength of damaged structures
- Deformation exceeds acceptable level
- Flutter: airspeed exceeds the flutter speed of damaged or repaired structure*
- High amplitude limit cycle oscillations: the acceptable level of vibrations is exceeded*

**See the FAA Grant "Combined Local-Global Variability and Uncertainty in the Aeroservoelasticity of Composite Aircraft"*

Accomplishments

Work Accomplished: Phase 1

- 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**

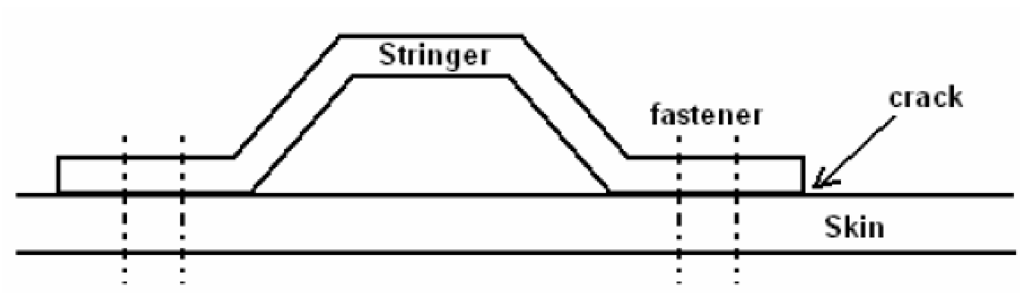
  1). Establish FE models in ABAQUS

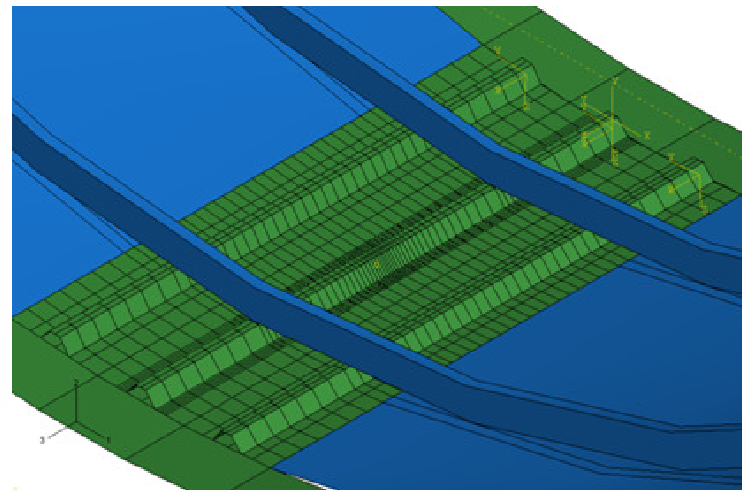
  2). Develop 1-D(beam) and 2D (plate) analytical capabilities

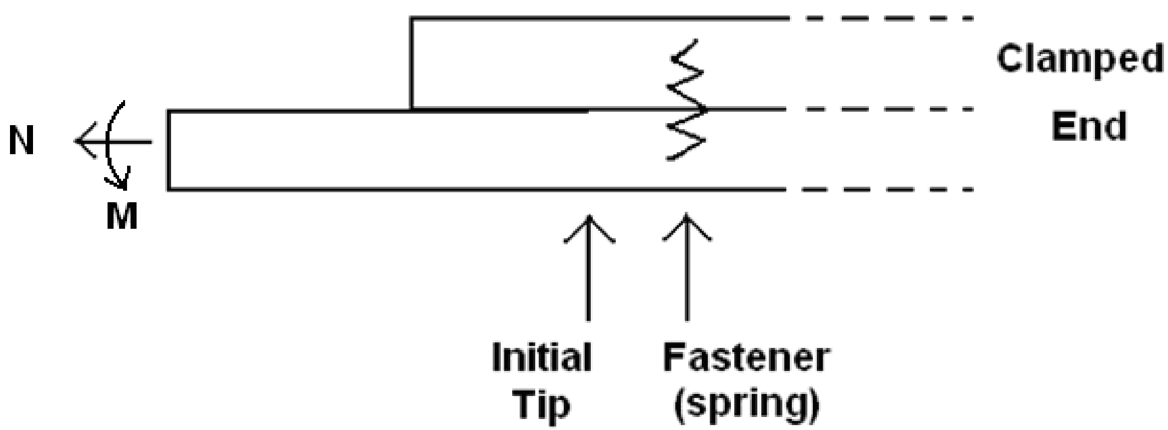
  3). Implement reliability analysis capability

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

Bonded Skin/Stiffener with Fasteners







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)

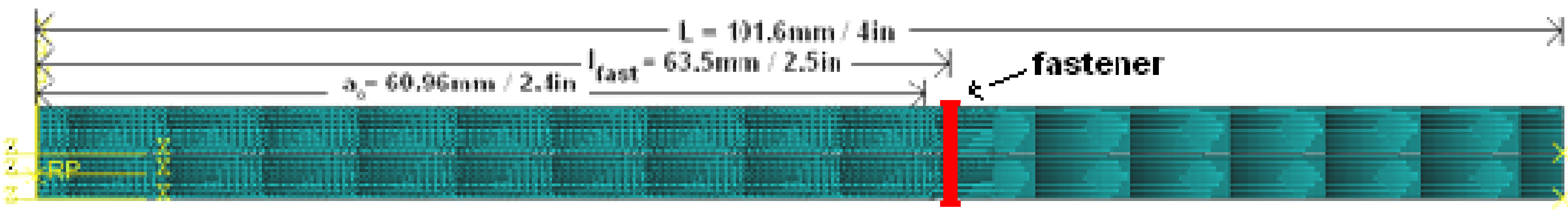
$$C = \left(\frac{t_1 + t_2}{2d}\right)^a \frac{b}{n}\left(\frac{1}{t_1 E_1} + \frac{1}{n t_2 E_2} + \frac{1}{n t_1 E_3} + \frac{1}{2 n t_2 E_3}\right)$$

Model Description

- B-K law for mixed-mode VCCT criteria

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

- Fastener failure not considered
- Fastener pull-through not considered



Material Properties (AS4/3501-6)

- E_1=127.5GPa
- E_2=11.3GPa
- G_{12}=6.0GPa
- v=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

- 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

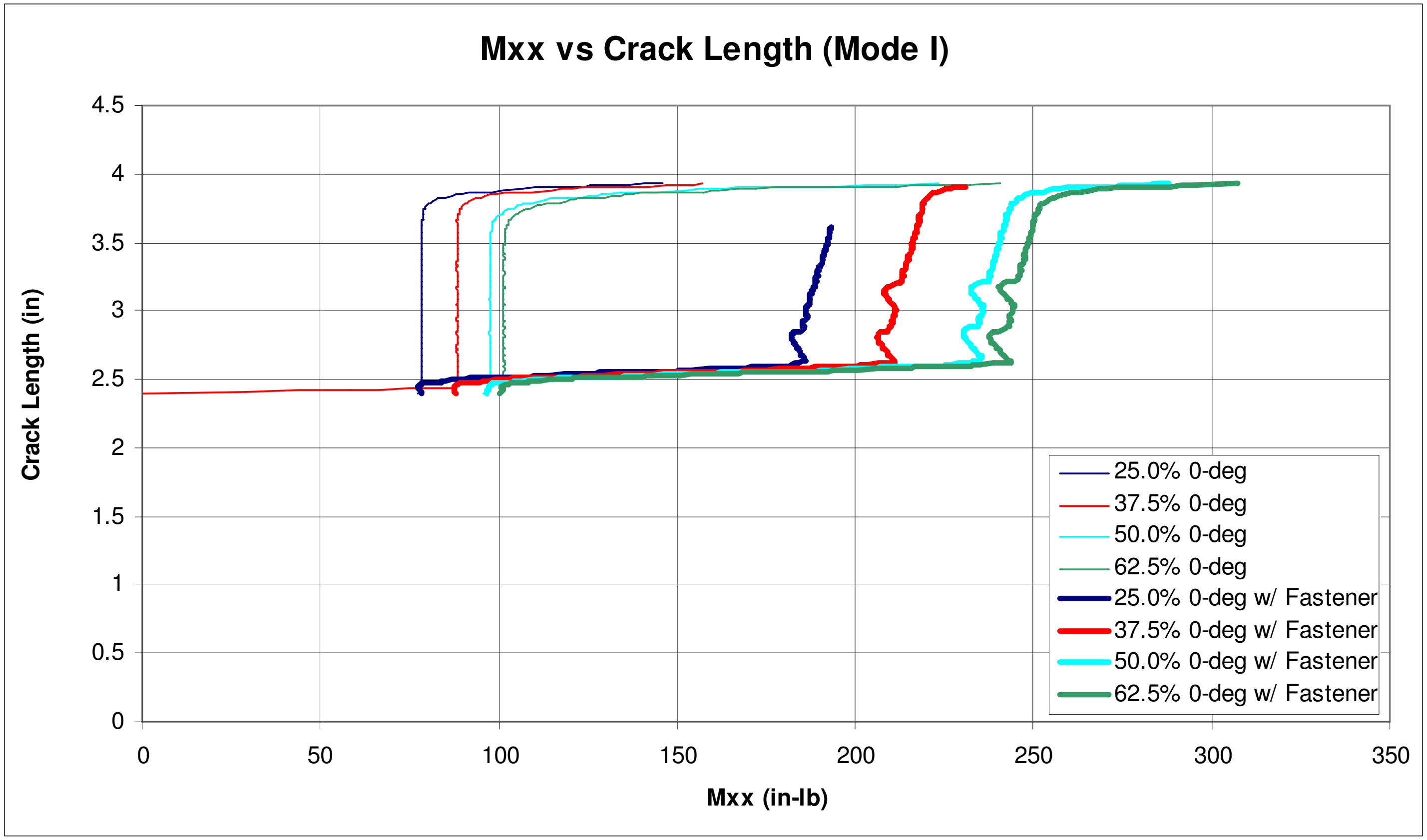
Laminate Configuration (16 plies)

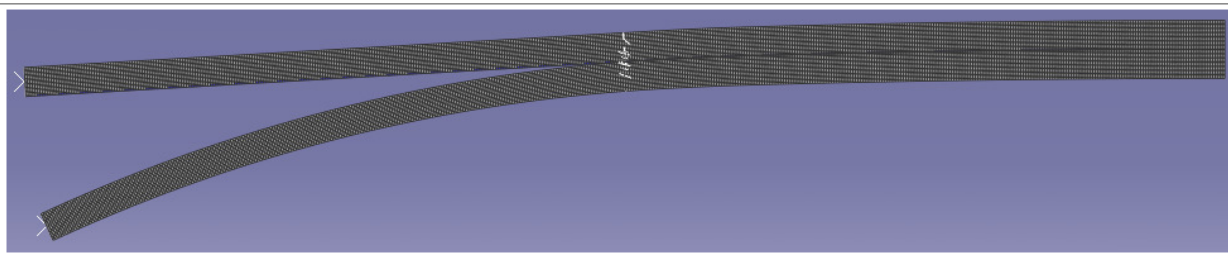
0-ply	Lay-up	E_x	C (in/lb) (fastener compliance)
25.0%	$(45/0/-45/90/45/0/-45/90)_s$	7.42×10^6	7.73×10^{-6}
37.5%	$(45/0/-45/0/45/0/-45/90)_s$	9.29×10^6	6.57×10^{-6}
50.0%	$(45/0_2/-45/0_2/90_2)_s$	1.10×10^7	5.85×10^{-6}
62.5%	$(45/0_3/-45/0_2/90)_s$	1.30×10^7	5.25×10^{-6}

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

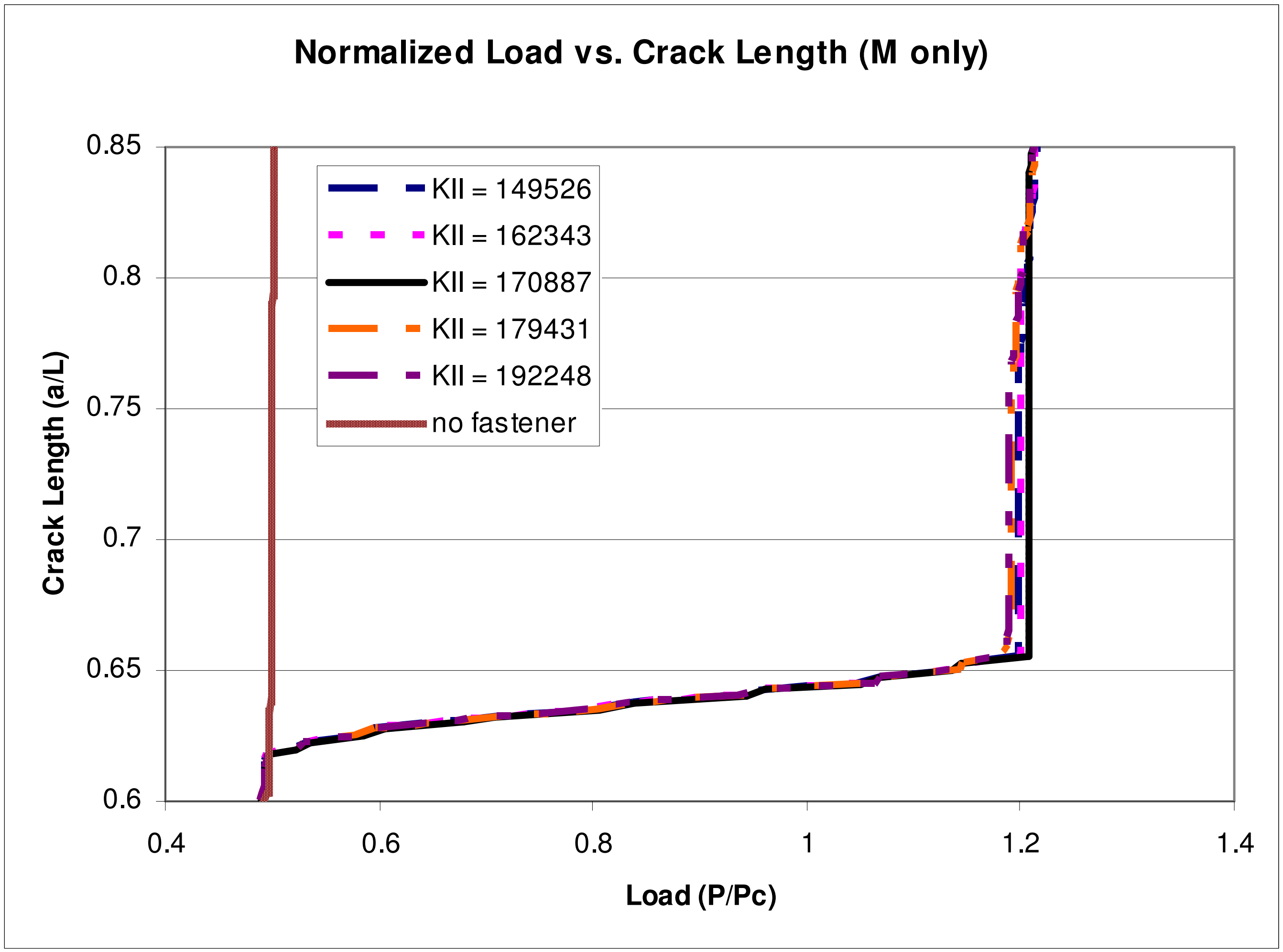
$$a=2/3,\ \ b=4.2,\ \ n=1$$

Results: Applied Moment M Only

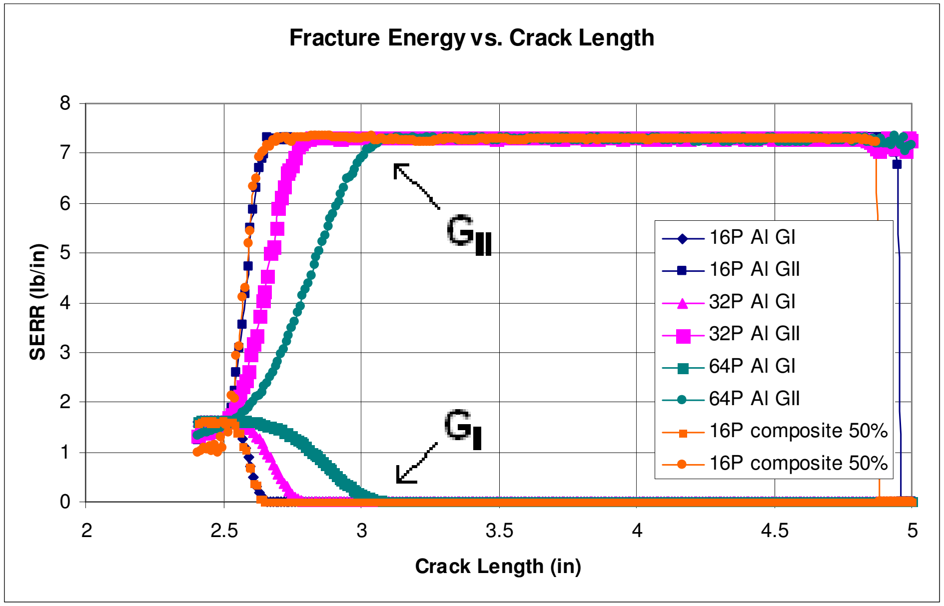


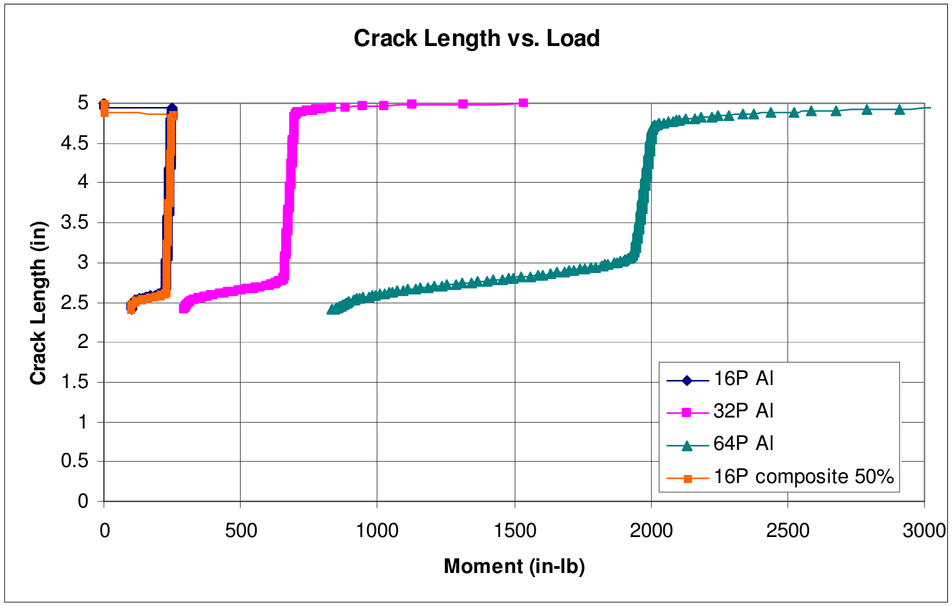


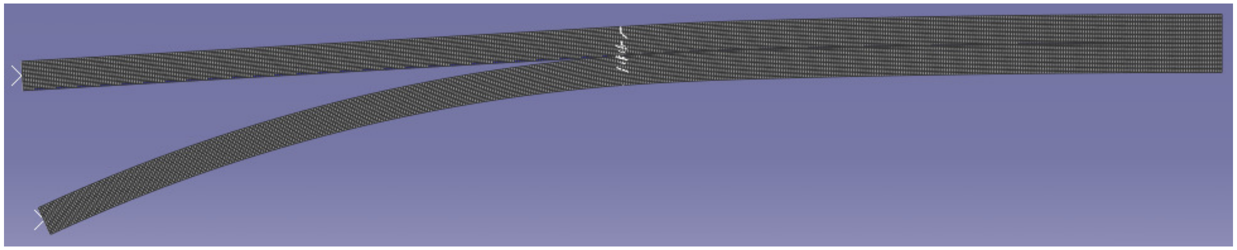
Growth of a Disbond Caused by Applied Moment M



Mode Decomposition: Applied Moment M Only







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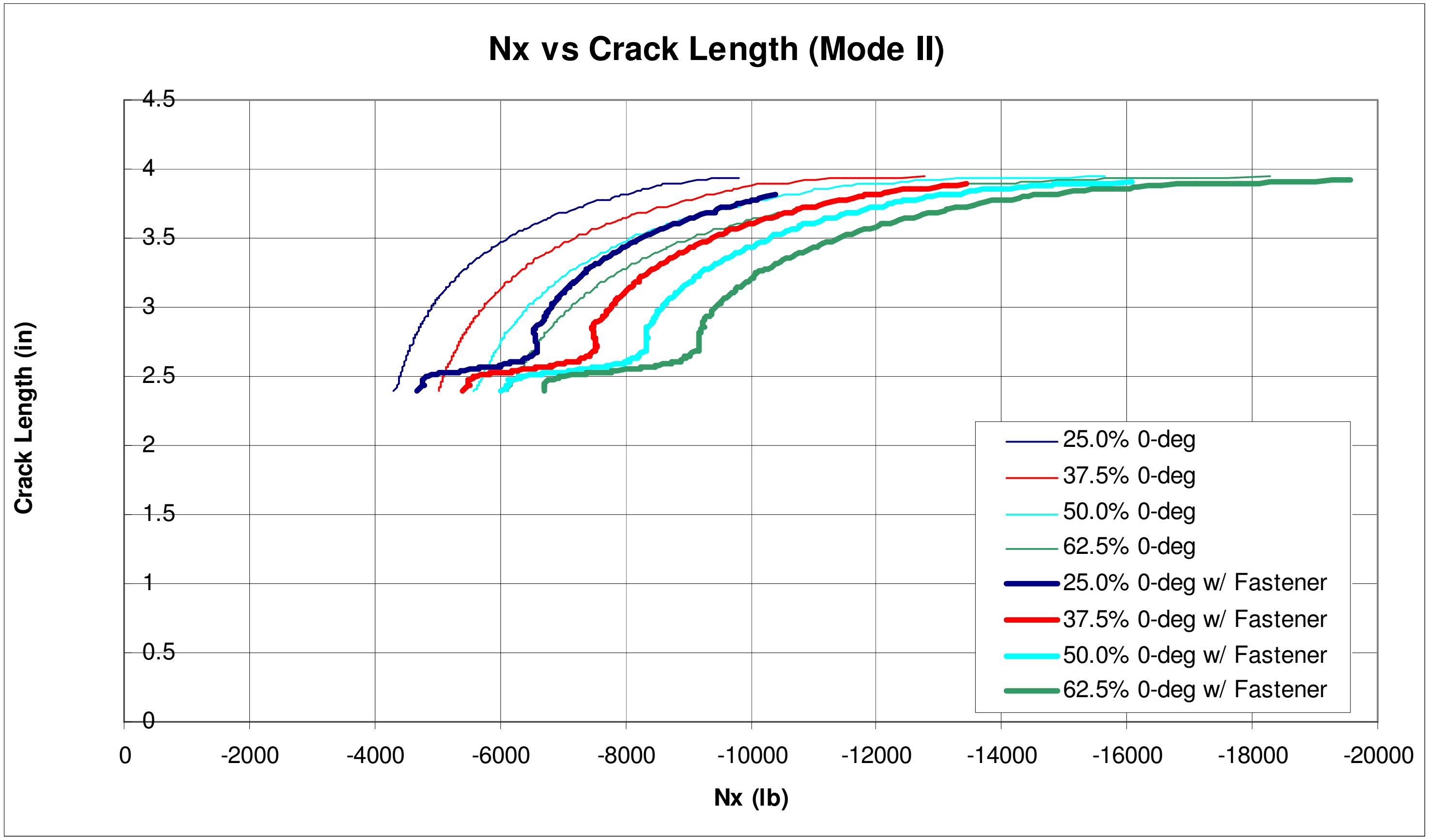
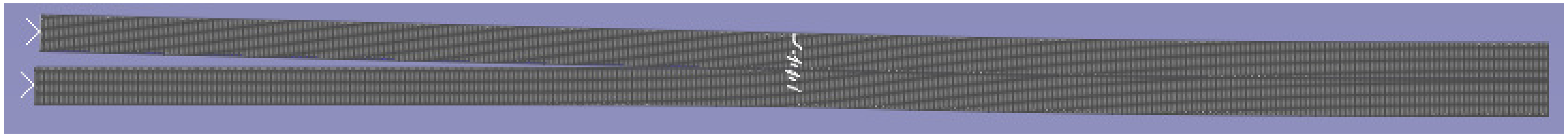
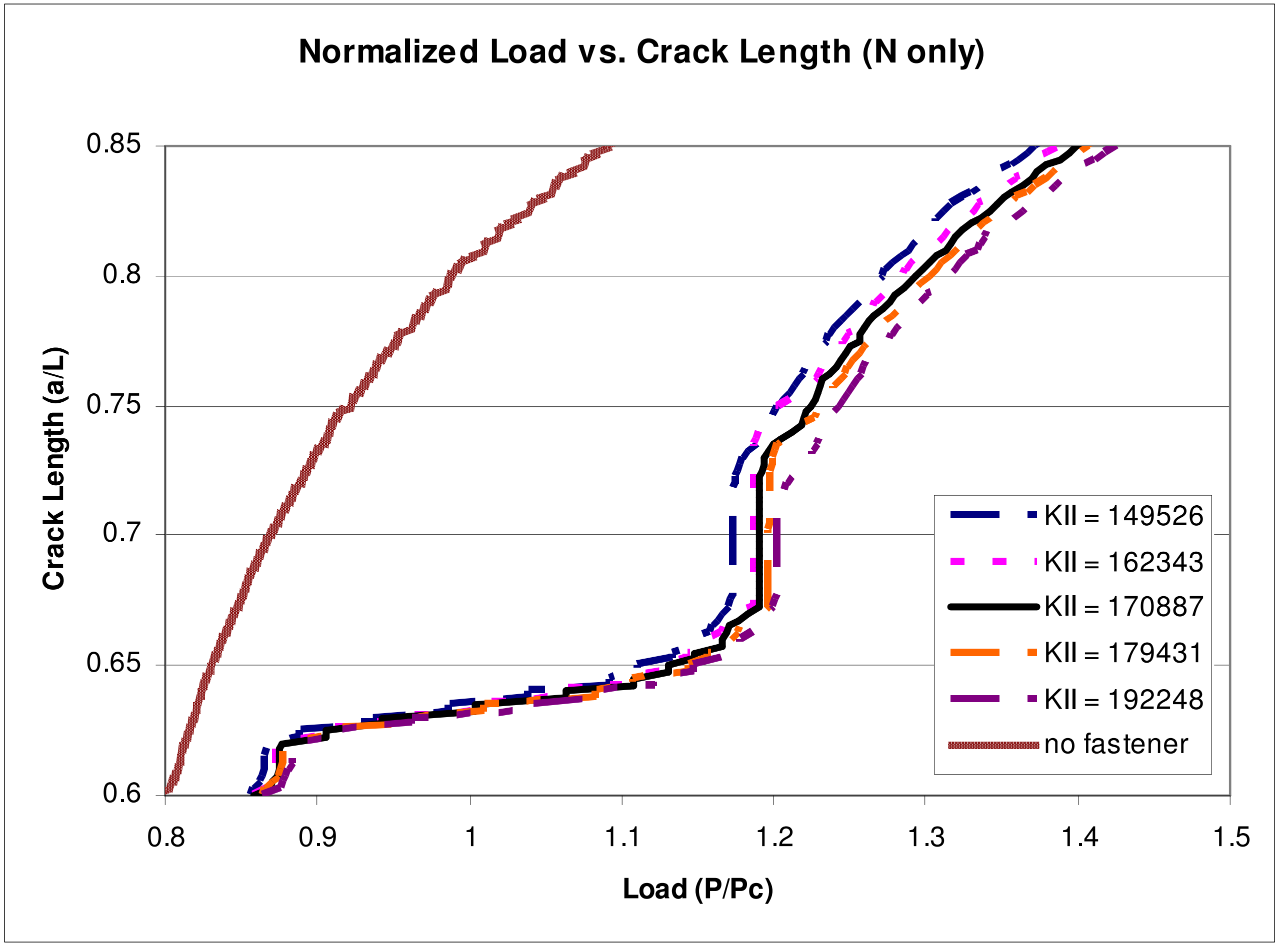
Results: Applied Tension N Only

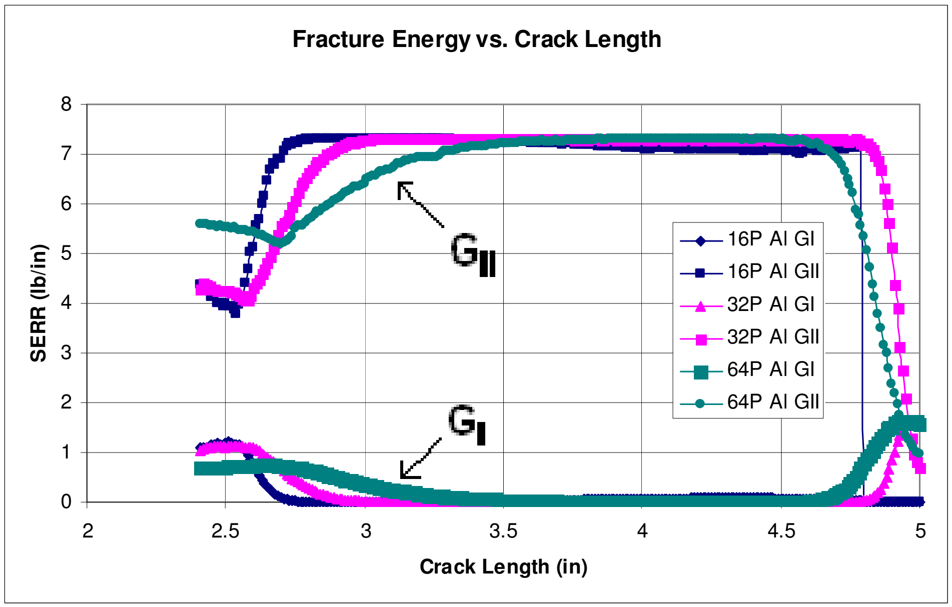


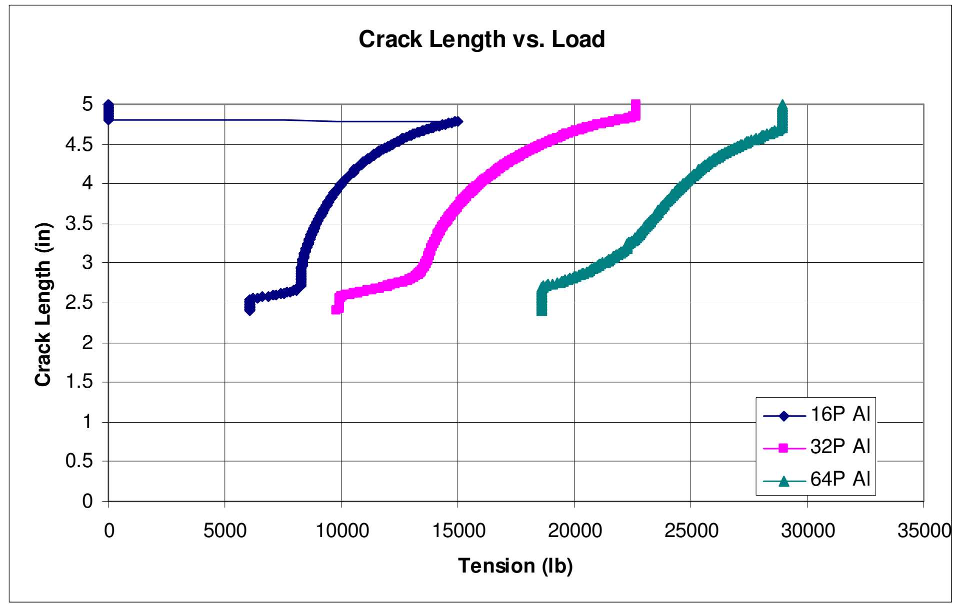


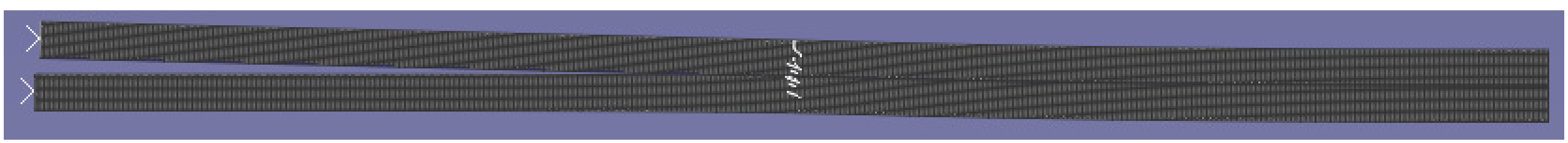
Growth of a Disbond due to Applied Tension N



Mode Decomposition: Applied Tension N Only

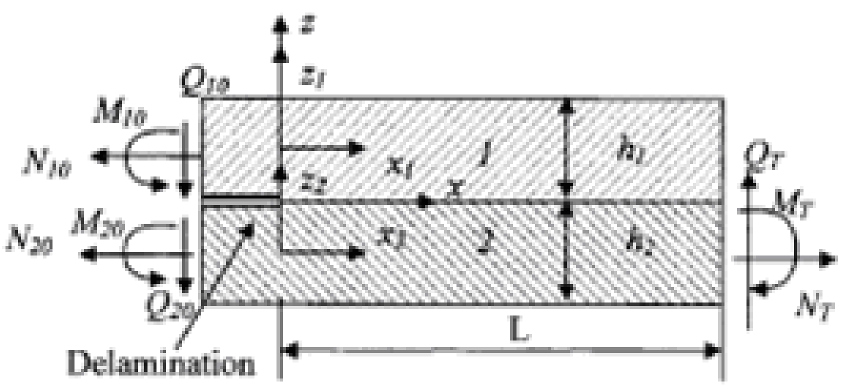




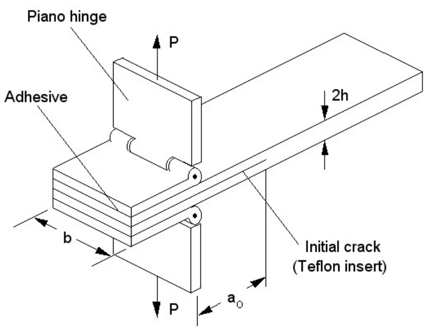


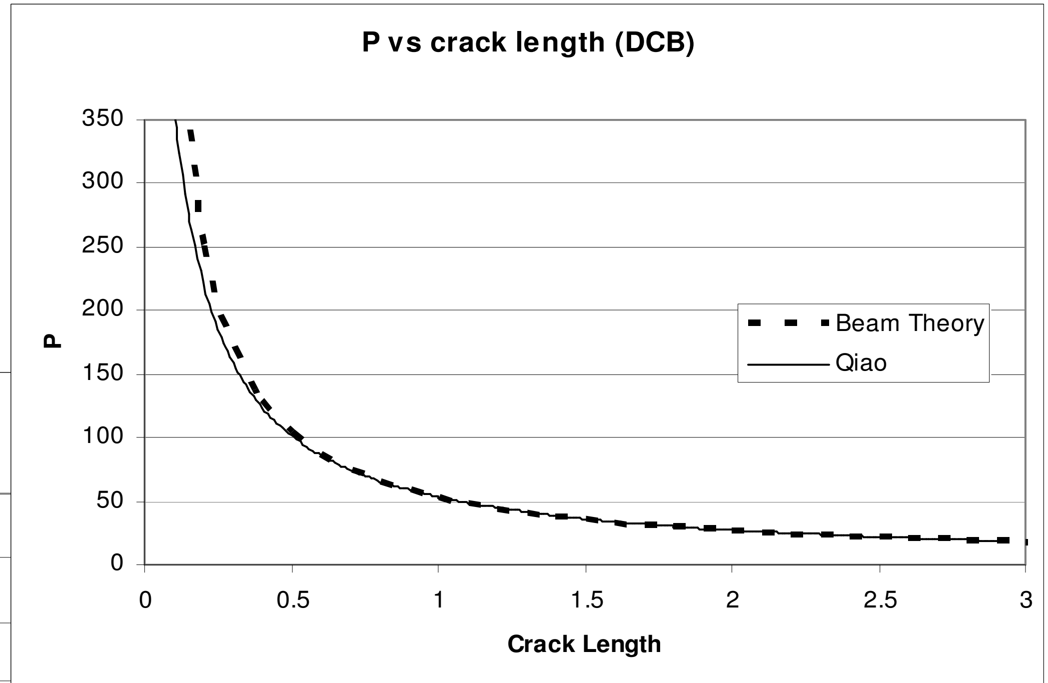
Crack-Tip Fracture Analysis

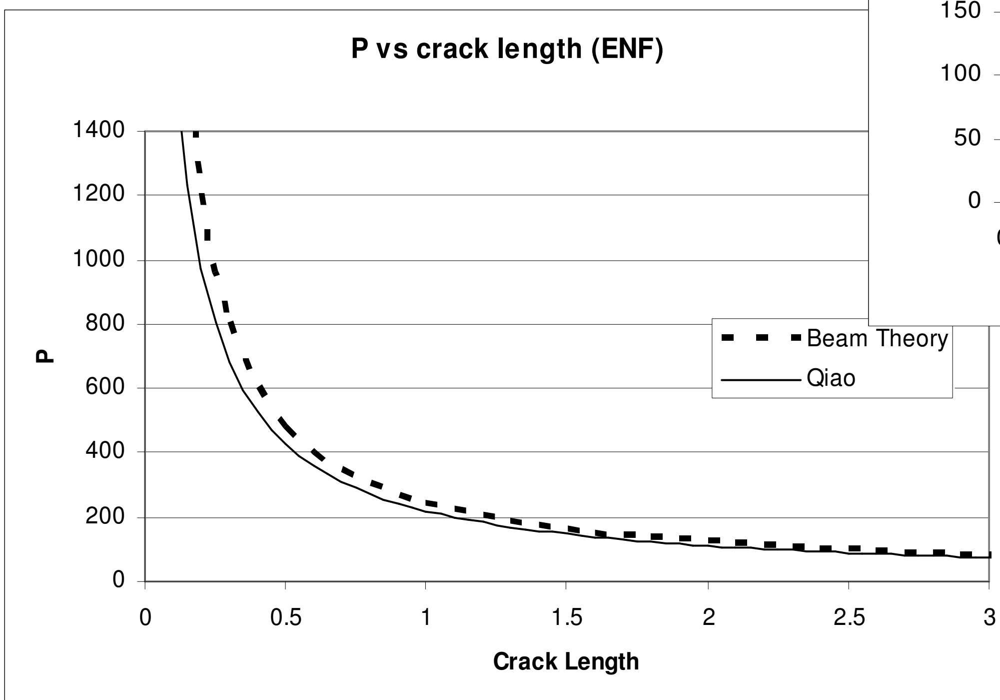
- Uses the closed-form solution obtained by Wang and Qiao ["Fracture Analysis of Shear Deformable Bi-Material Interface," Journal of Engineering Mechanics, pp. 306-316, March 2006.]
- Uses shear deformable beam theory
- Calculates mode-decomposed strain energy release rate components, G_I and G_{II}

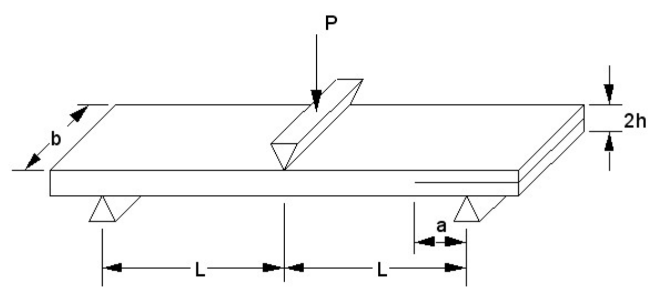


Comparison with Classical Beam Solutions

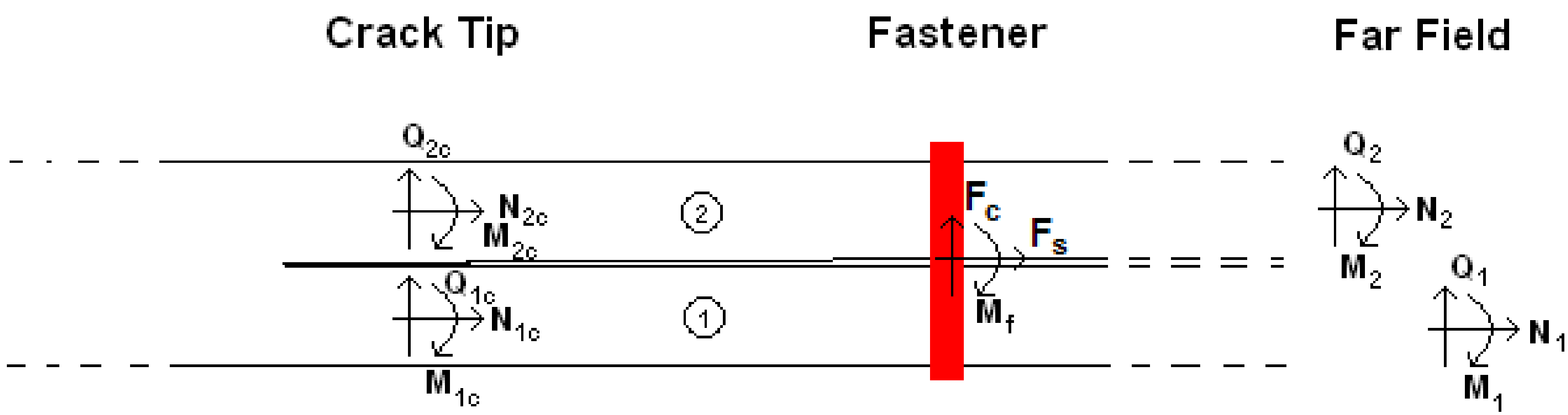






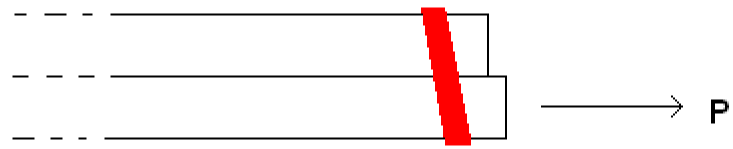


Local Crack-tip and Far-field Applied Forces and Moments



Linear Solutions for Fastener Force

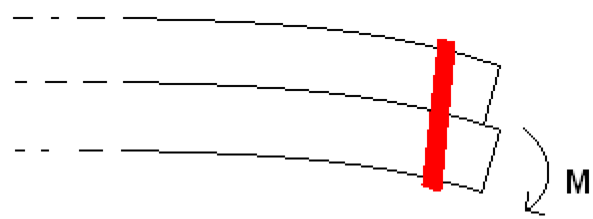
- Pure Tension



$$F_s = \frac{E_2 k_s L P t_2}{E_1 k_s L t_1 + E_2 k_s L t_2 + b E_1 E_2 t_1 t_2}$$

- Pure Moment

$$F_s = \frac{2 b E_1 E_2 k_s L M t_1 t_2 \left(t_1 + t_2\right)}{4 E_2{}^2 I_2 k_s L t_2 + 4 E_1{}^2 I_1 t_1 \left(k_s L + b E_2 t_2\right) + E_1 E_2 \left(4 I_2 t_1 \left(k_s L + b E_2 t\right) + k_s L t_2 \left(4 I_1 + b t_1 \left(t_1 + t_2\right)^2\right)\right)}$$



Nonlinear Beam Analysis

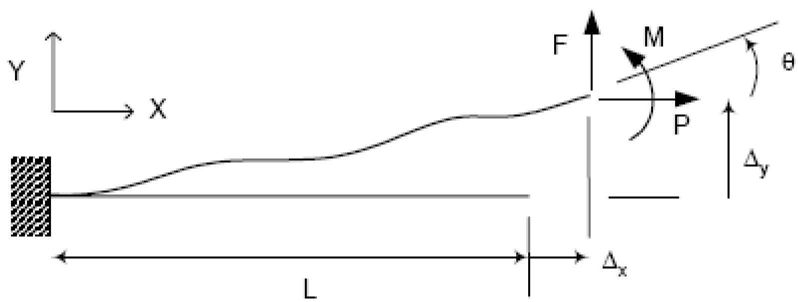
Governing Equations:

$$\frac{E}{\rho} = \frac{M}{I}$$

$$\frac{1}{\rho} = \frac{Y''}{\left(1+Y'^2\right)^{3/2} \approx 1}$$

$$M(X) = M + F(L+\Delta_x - X) - P(\Delta_y - Y)$$

$$EIY'' = M + F(L+\Delta_x - X) - P(\Delta_y - Y)$$



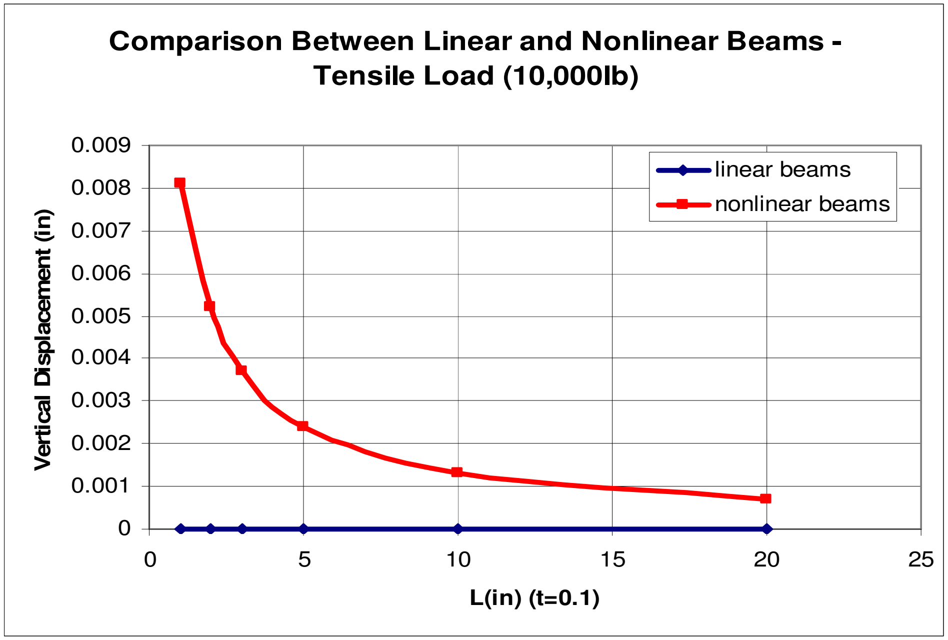
End displacement of the beam:

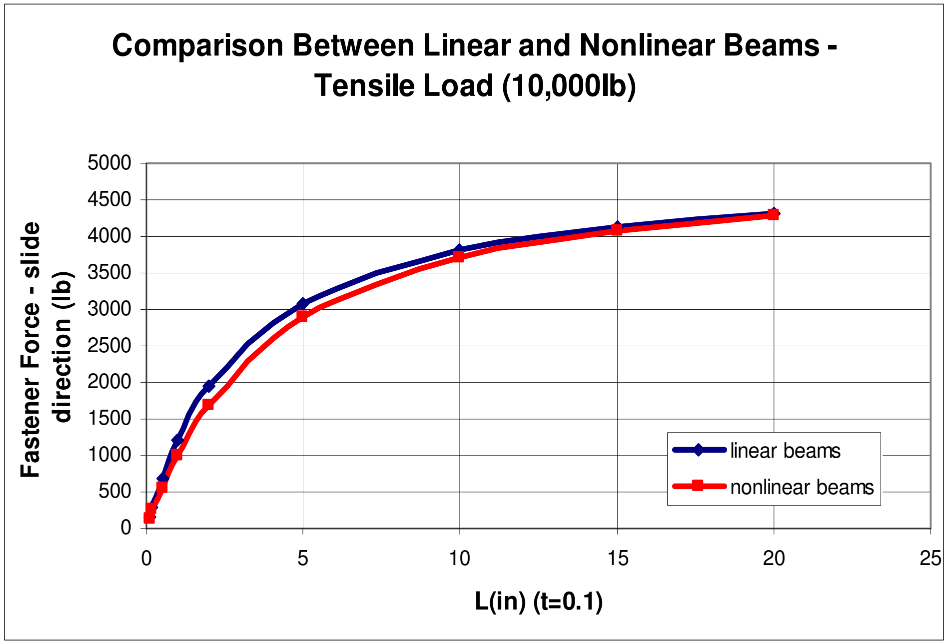
$$\begin{pmatrix} \delta_y \\ \theta \end{pmatrix} = \begin{bmatrix} \frac{k - \tanh(k)}{k^3} & \frac{\cosh(k) - 1}{k^2 \cosh(k)} \\ \frac{\cosh(k) - 1}{k^2 \cosh(k)} & \frac{\tanh(k)}{k} \end{bmatrix} \begin{pmatrix} f \\ m \end{pmatrix}$$

$$\delta_x = \frac{pt^2}{12} - \begin{pmatrix} \delta_y & \theta \end{pmatrix} \begin{bmatrix} r_{11} & r_{12} \\ r_{12} & r_{22} \end{bmatrix} \begin{pmatrix} \delta_y \\ \theta \end{pmatrix}$$

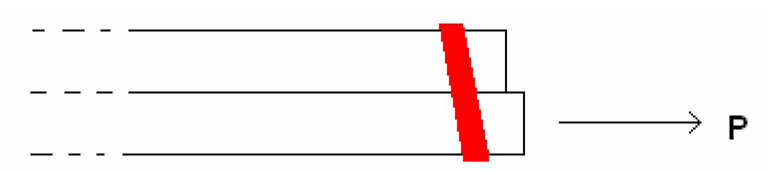
$$r_{11}, r_{12}, r_{22} = f(p)$$

Comparison Between Linear and Nonlinear Beams – Tension Only

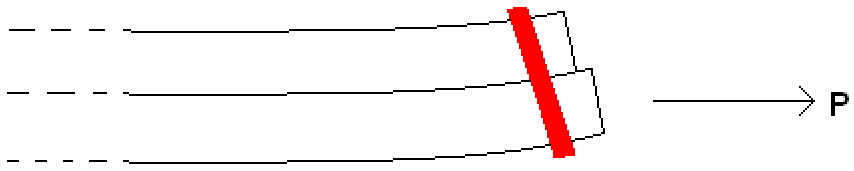




Linear Beam Deformation



Nonlinear Beam Deformation



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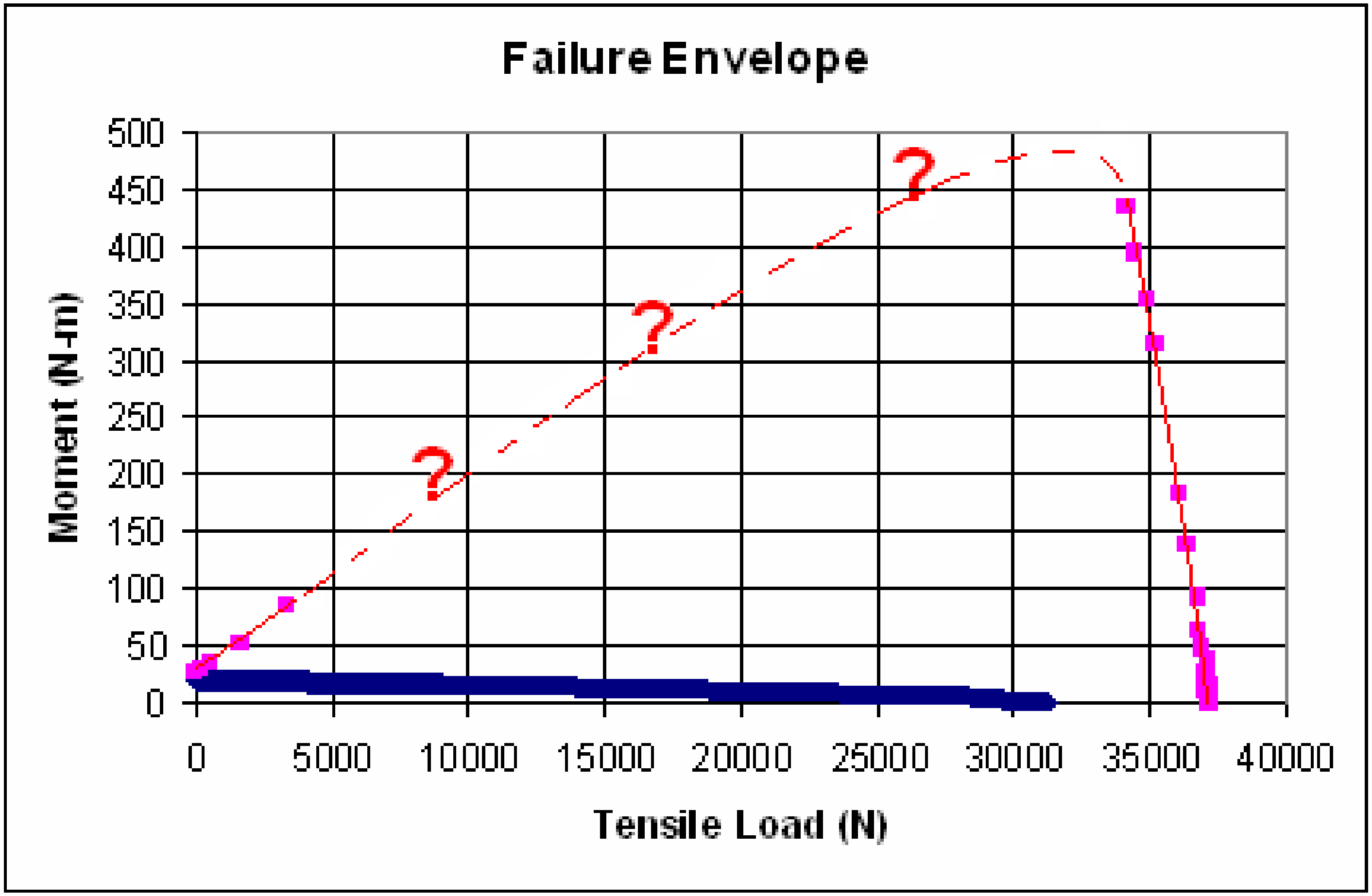
Failure Envelope Between N and M



Work in Progress / Future Work

- Refine FEA models and procedures
- Develop analysis capabilities
- Understand disbond/delamination propagation around the fastener in 3-D
- Consider multiple fasteners and multiple failure modes
- Perform parametric/sensitivity studies
- Identify key variables for design and optimization
- Design validation experiments

A Look Forward

- **Benefit to Aviation**
  - The present method allows engineers to design damage tolerant composite structures for a predetermined level of reliability, as required by FAR 25.
  - The present study makes it possible to determine the relationship among the reliability level, inspection interval, inspection method, and repair quality to minimize the maintenance cost and risk of structural failure.
- **Future needs**
  - A standardized methodology for establishing an optimal inspection schedule for aircraft manufacturers and operators.
  - Enhanced damage data reporting requirements regulated by the FAA.
  - A comprehensive system of characterizing material and processing variability for damage tolerant bonded structures.

The Probabilistic Model