Life Prediction Methodology for Ceramic Matrix Composites

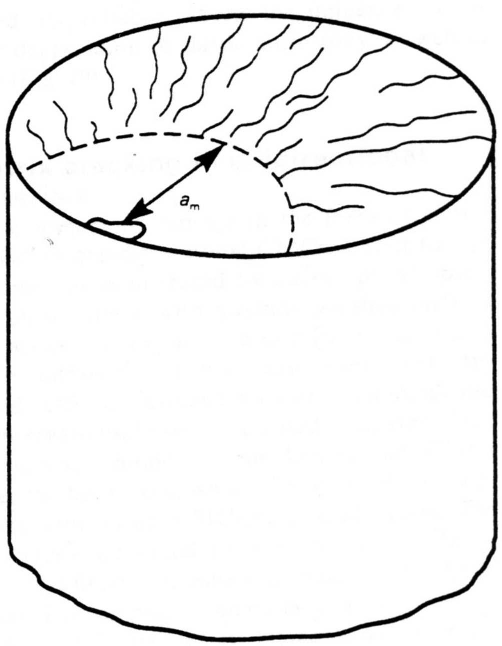
Scott Case and Howard Halverson
Materials Response Group
Department of Engineering Science and Mechanics
Virginia Tech

Outline:

- Micromechanics based life prediction
  - Single mechanism models
  - Multiple mechanism models
- Phenomenological (residual strength) based life prediction
- Multi-level modeling
- Structural analysis (finite element integration)

Example of Single Mechanism Model:

Assume that crack growth is the mechanism for fiber failure at elevated temperatures.



Crack growth is dictated by the Paris Law

$$\frac{da}{dt} = AK^{\beta}, K = Y\sigma(t)\sqrt{a}$$

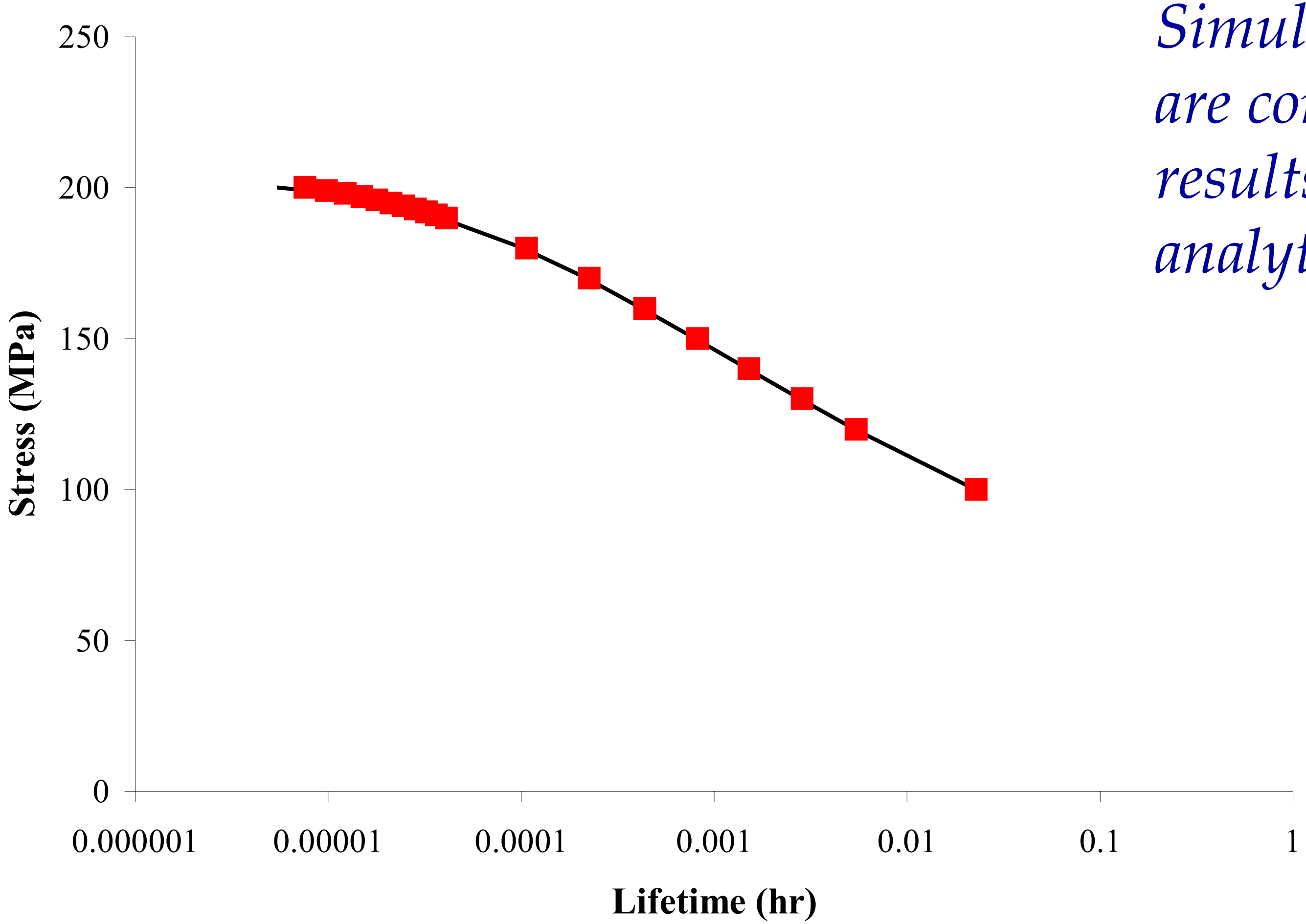
So with time the strength of an individual fiber is

$$\sigma(t) = \left[\sigma_i^{\beta-2} - \left(\frac{\beta}{2} - 1\right) AY^2 K_{Ic}^{\beta-2} \int_0^t \sigma_{app}(t')^{\beta} dt'\right]^{-\frac{1}{\beta-2}}$$

Iyengar & Curtin (1997)

Virginia Tech

Single Mechanism Results:

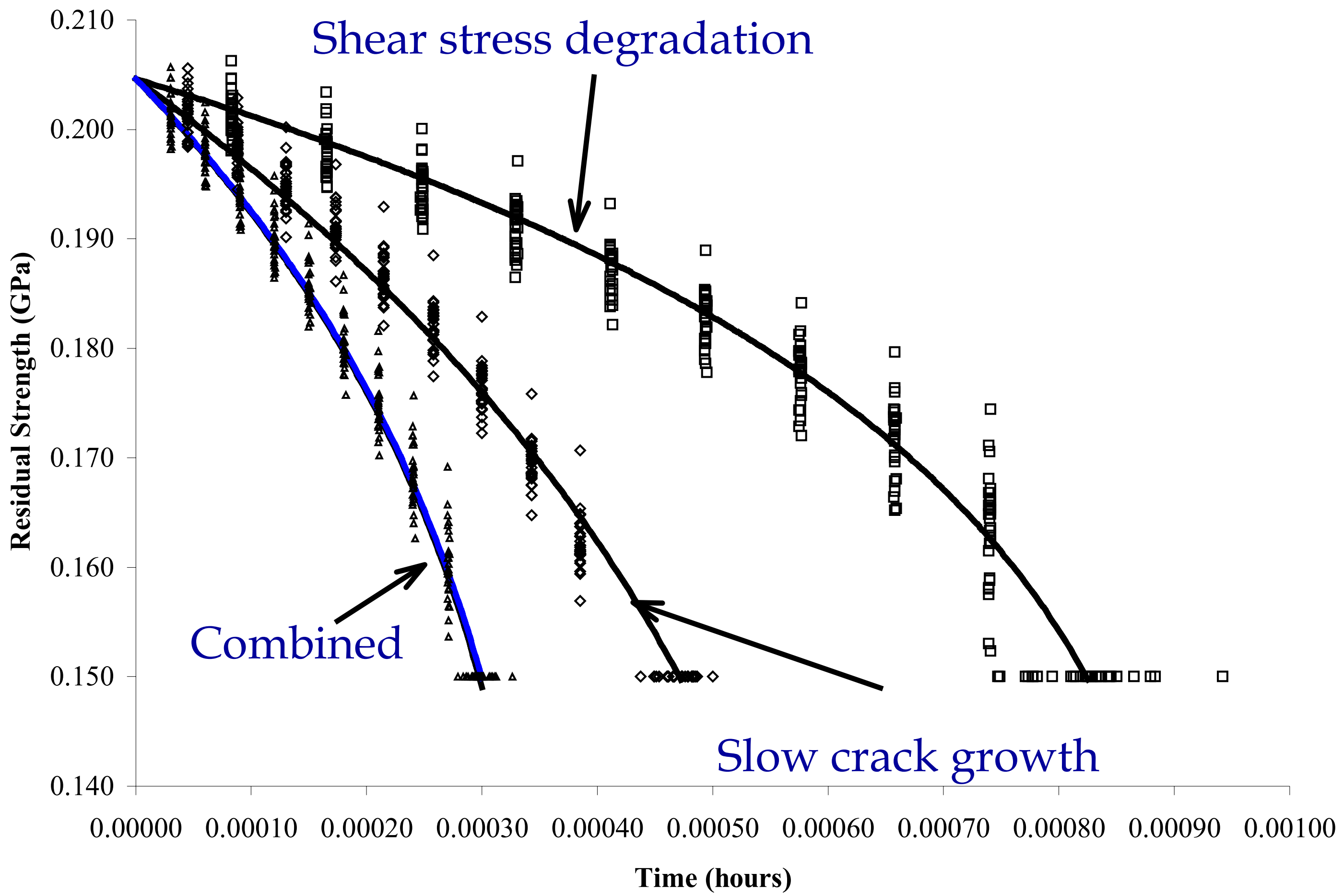


Simulation results are compared to the results of an analytical expression

Multiple Mechanism Models:

- Analytic solutions are difficult to obtain
- Simulation approach readily combines multiple mechanisms
- Example
  - slow crack growth
  - interfacial asperity creep

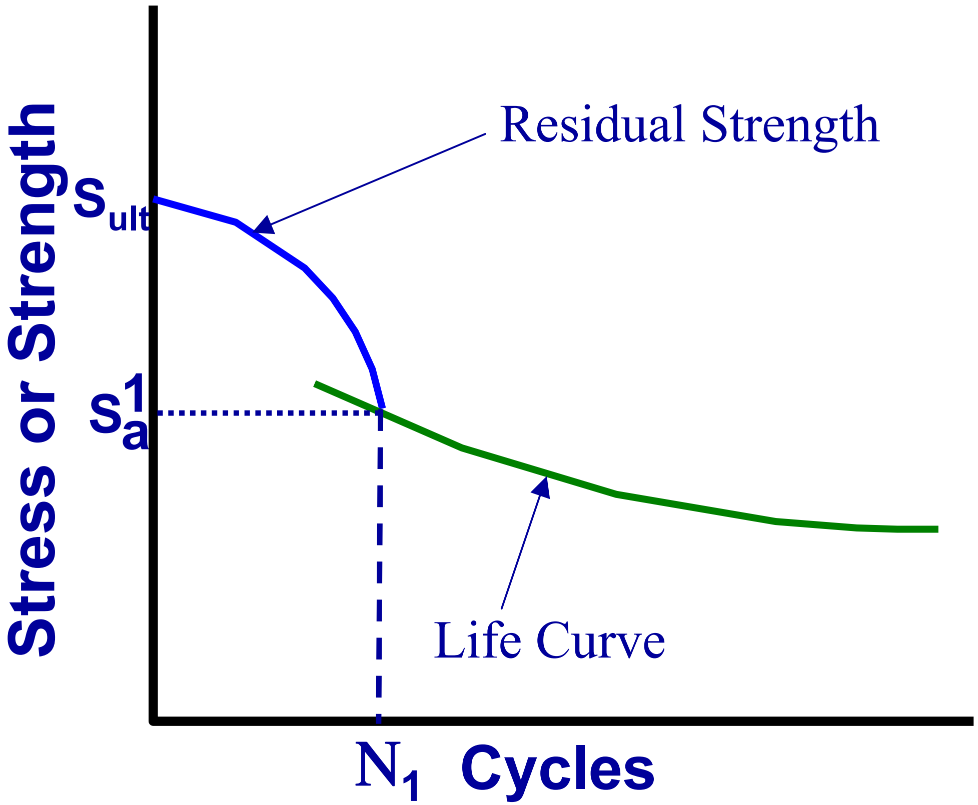
Multiple Mechanism Result:



Virginia Tech

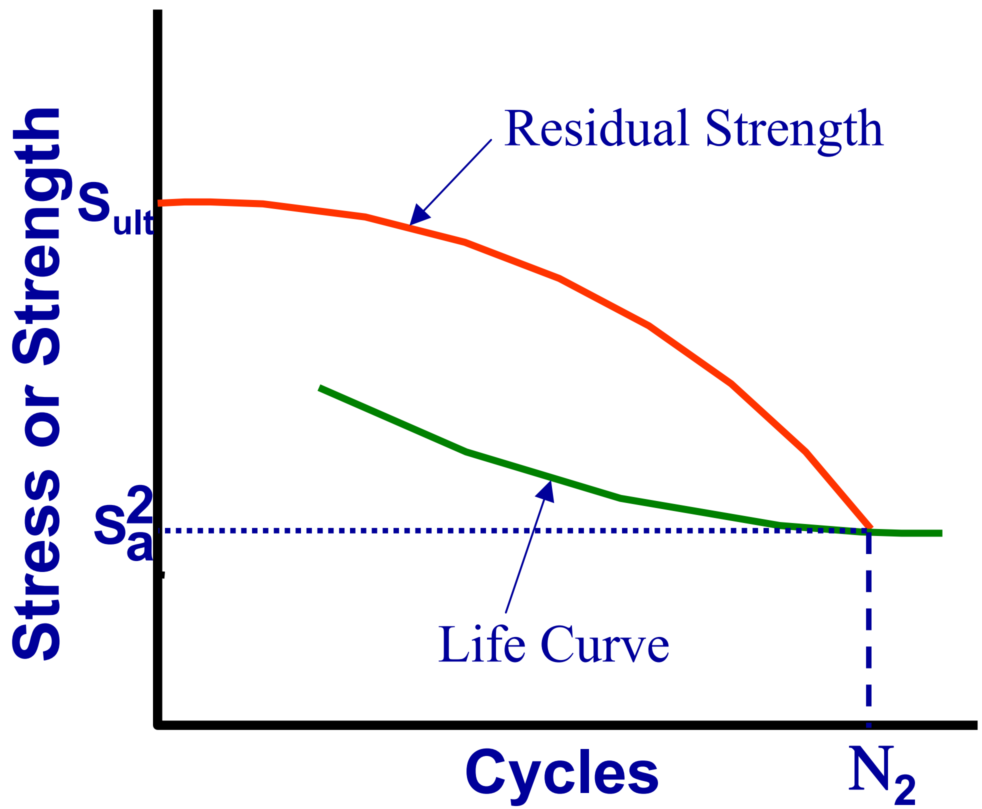
Remaining Strength Predictions:

- Track remaining strength during the fatigue process
- Define a scalar failure function based upon tensor strength and stresses; use this failure function for calculations
- May include the effects of changing loading conditions
- May be directly validated experimentally, unlike Miner's rule



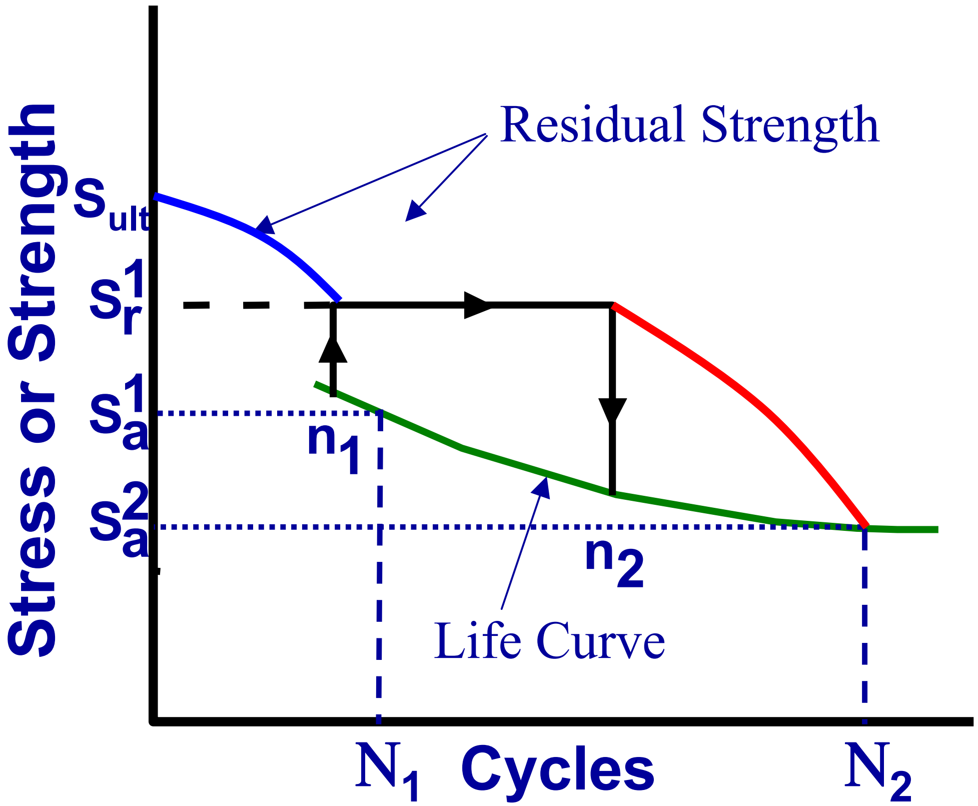
Remaining Strength Predictions:

- Track remaining strength during the fatigue process
- Define a scalar failure function based upon tensor strength and stresses; use this failure function for calculations
- May include the effects of changing loading conditions
- May be directly validated experimentally, unlike Miner's rule



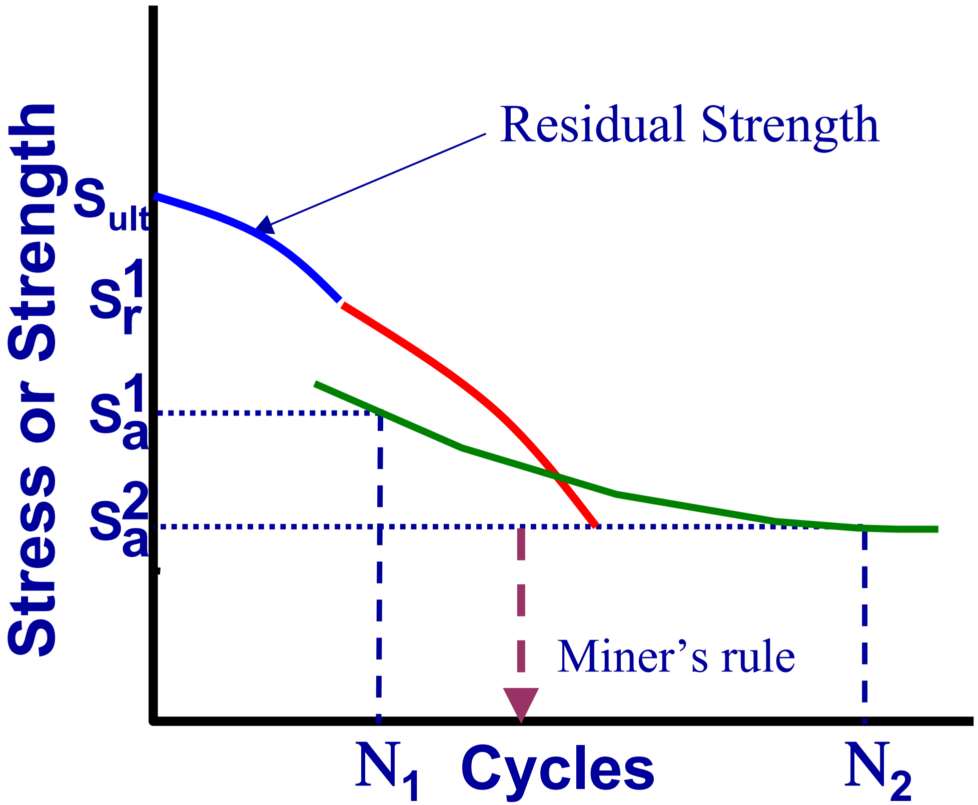
Remaining Strength Predictions:

- Track remaining strength during the fatigue process
- Define a scalar failure function based upon tensor strength and stresses; use this failure function for calculations
- May include the effects of changing loading conditions
- May be directly validated experimentally, unlike Miner's rule



Remaining Strength Predictions:

- Track remaining strength during the fatigue process
- Define a scalar failure function based upon tensor strength and stresses; use this failure function for calculations
- May include the effects of changing loading conditions
- May be directly validated experimentally, unlike Miner's rule



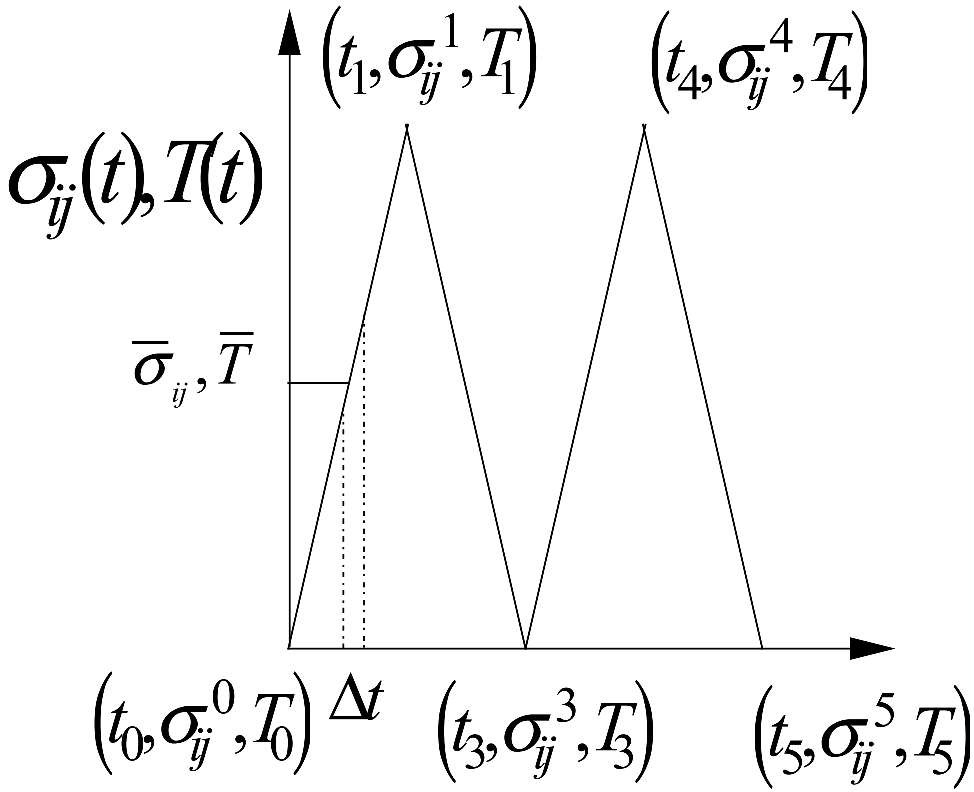
Virginia Tech

Approach for Variable Loading with Rupture and Fatigue Acting:

- Divide each step of loading into time increments
- Treat each increment as a stress rupture problem (constant applied stress and temperature)
- Reduce residual strength due to time dependent damage accumulation
- Refine number of intervals until residual strength converges
- Input next load level
- Check for load reversal. If load reversal, increment by 1/2 cycle and reduce residual strength due to fatigue damage accumulation

$$n_2^{\,0} = \left(\frac{1 - Fr_1}{1 - Fa_2}\right)^{\frac{1}{j}} N_2$$

$$\Delta Fr = -(1 - Fa_2)\left\{\left[\frac{n_2^{\,0} + 1/2}{N_2}\right]^j - \left[\frac{n_2^{\,0}}{N_2}\right]^j\right\}$$

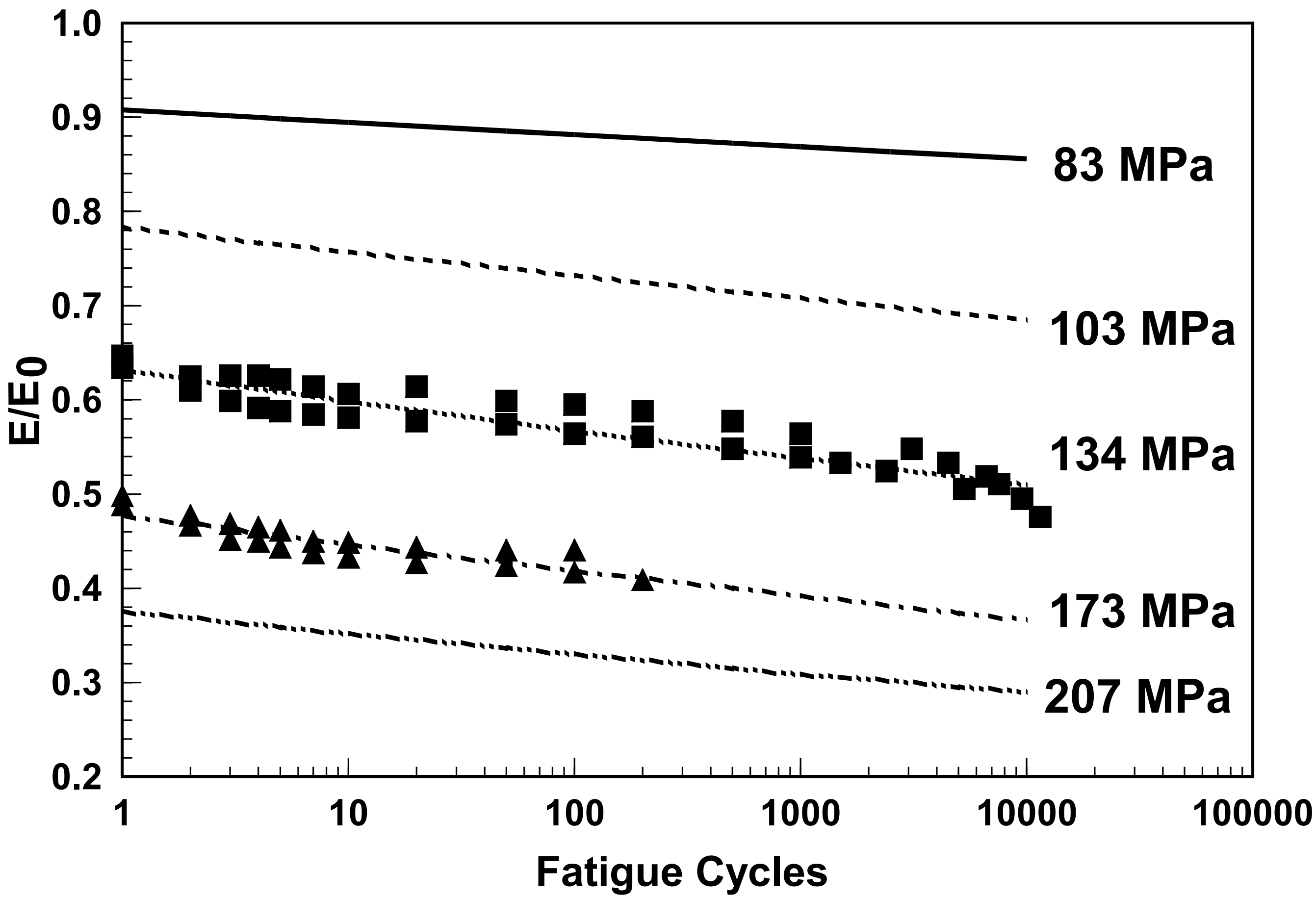


Virginia Tech

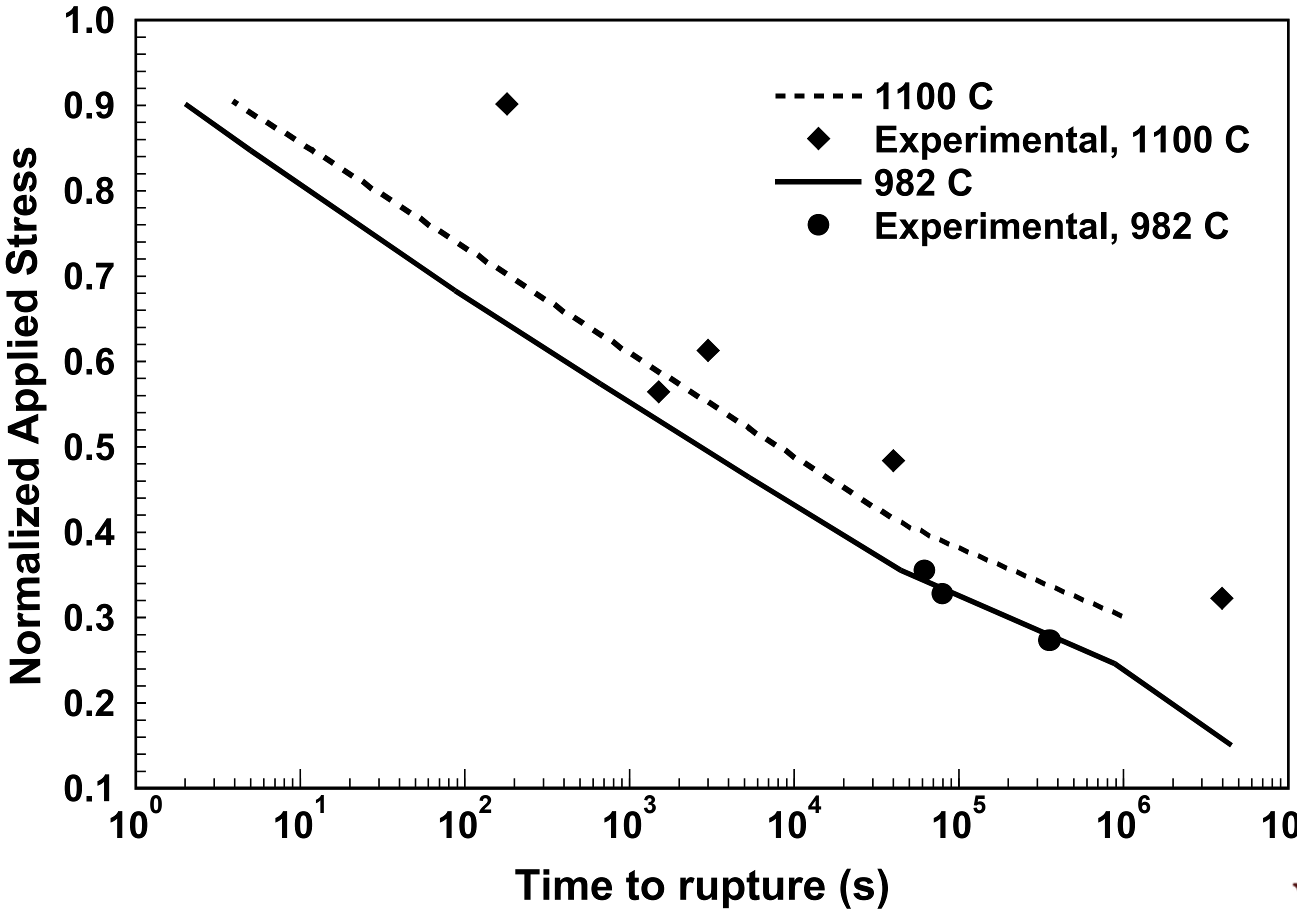
Implementation: CCLife Program

- Begin with matrix stiffness reduction as a function of time and stress level
- Use a simple stress model (2-D, laminate level) to calculate failure function as a function of time, stress, and temperature
- Fit stress rupture data
- Use incremental approach previously presented to sum influence of changing stresses (rupture influence)
- Adaptively refine increments until residual strength converges to some prescribed tolerance
- Account for cyclical loading by counting reversals and reducing remaining strength

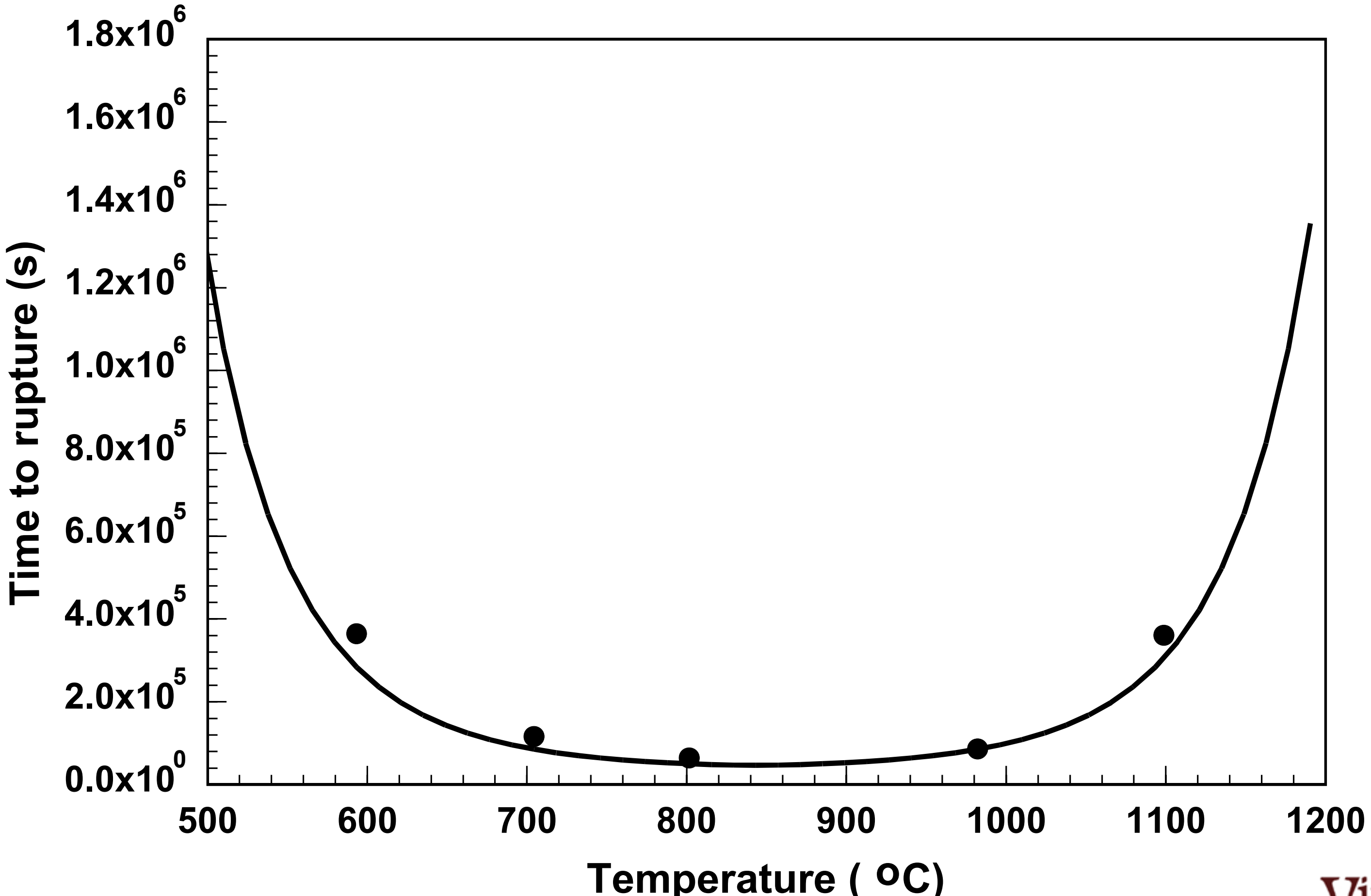
Stiffness Reduction Data for Nicalon/ E-SiC 2-D Woven Composite $[0/90]_{2s}$:



Stress Rupture Data for Nicalon/ E-SiC 2-D Woven Composite $[0/90]_{2s}$:

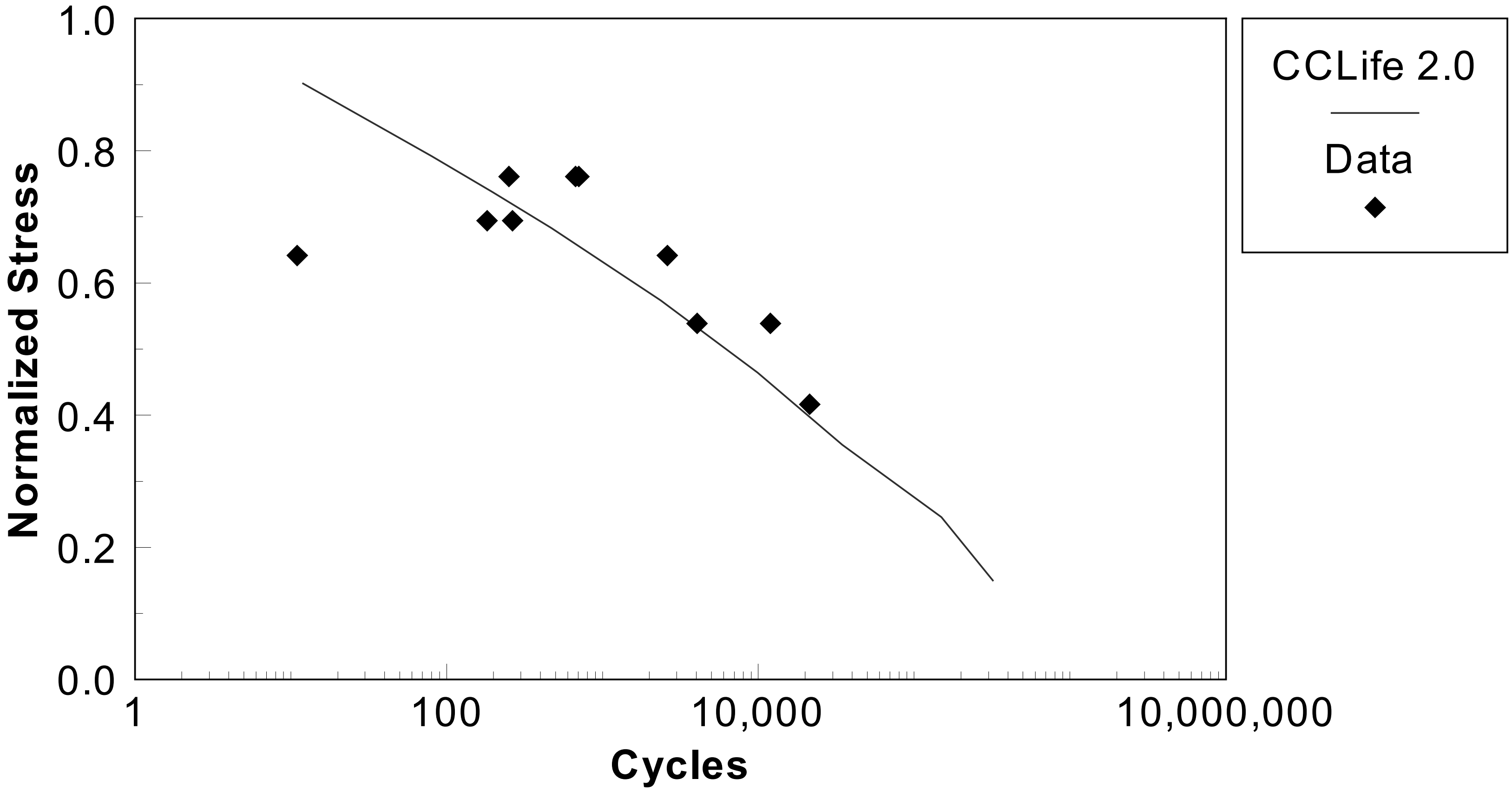


Stress Rupture Data for Nicalon/ E-SiC 2-D Woven Composite $[0/90]_{2s}$:



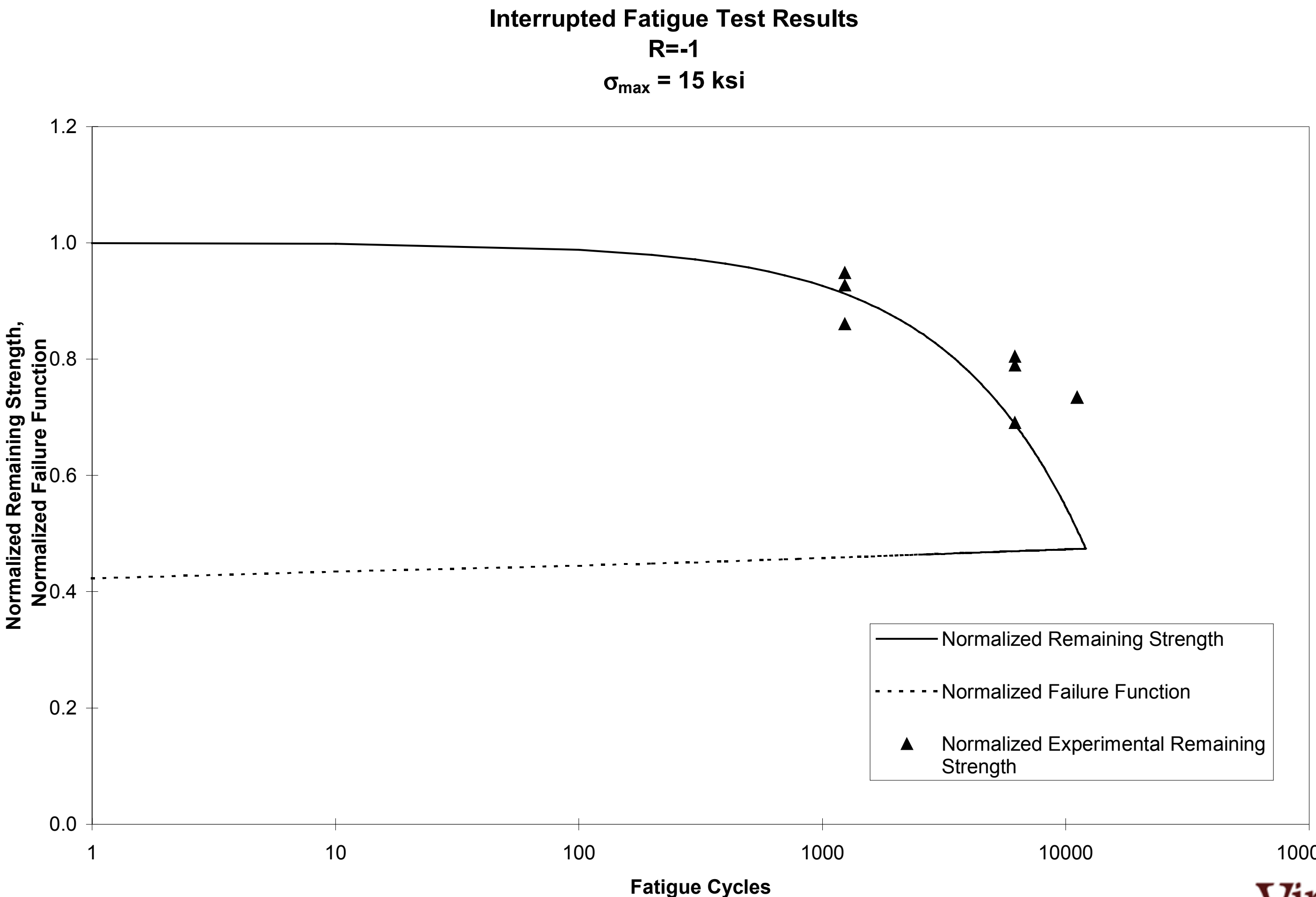
Virginia Tech

Fatigue Data for Nicalon/ E-SiC 2-D Woven Composite $[0/90]_{2s}$:



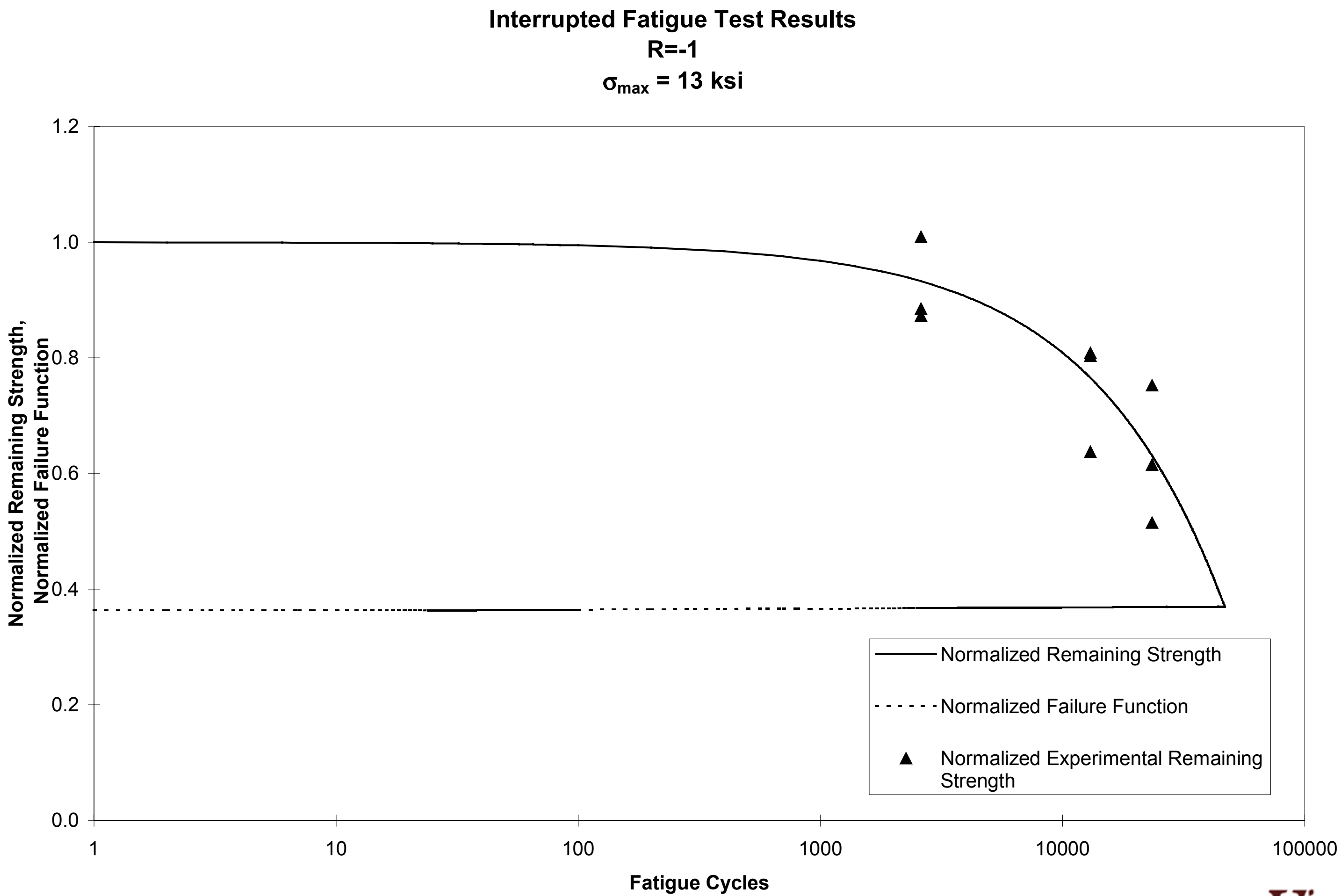
Virginia Tech

Residual Strength Data for Nicalon/ E-SiC 2-D Woven Composite $[0/90]_{2s}$:

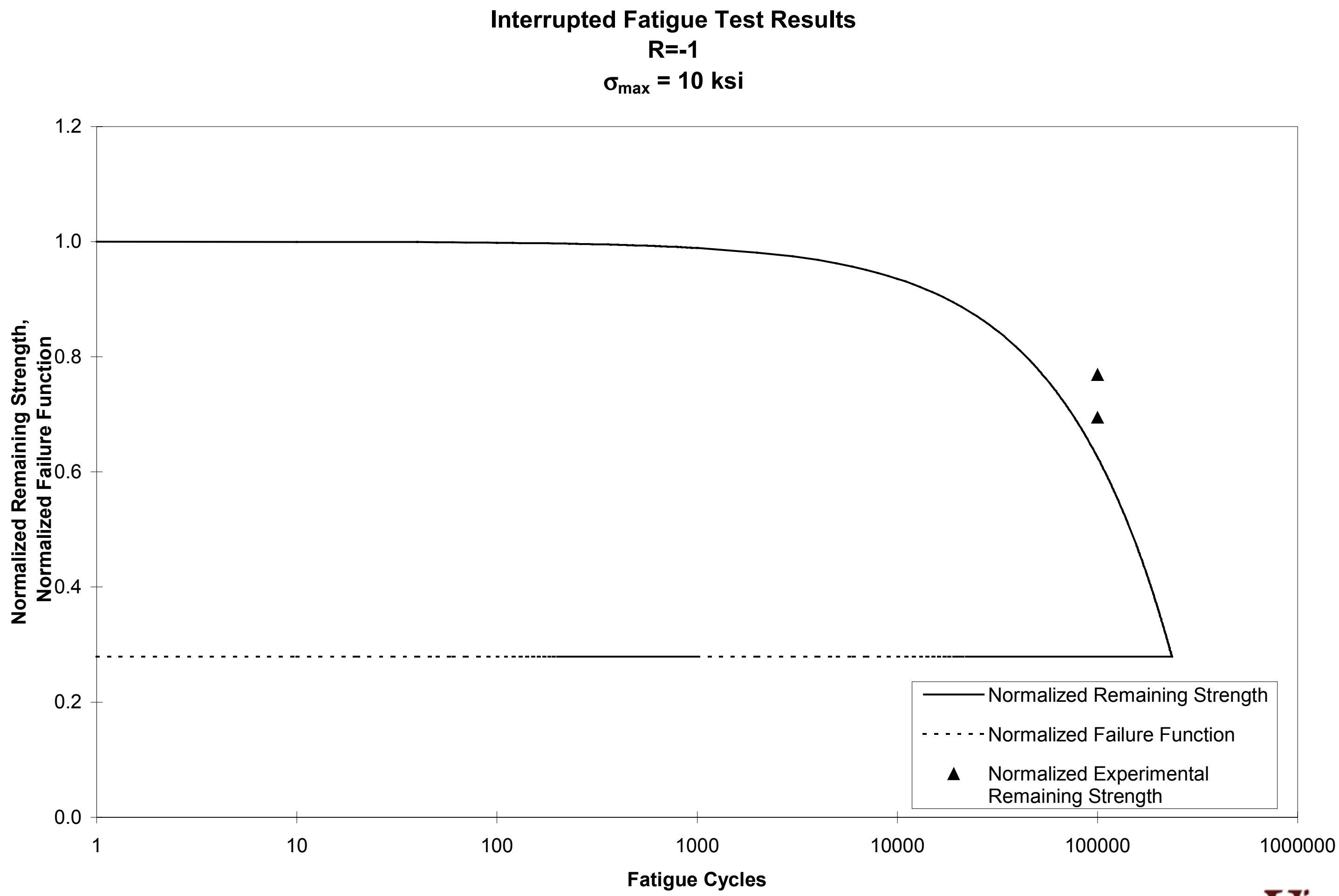


Virginia Tech

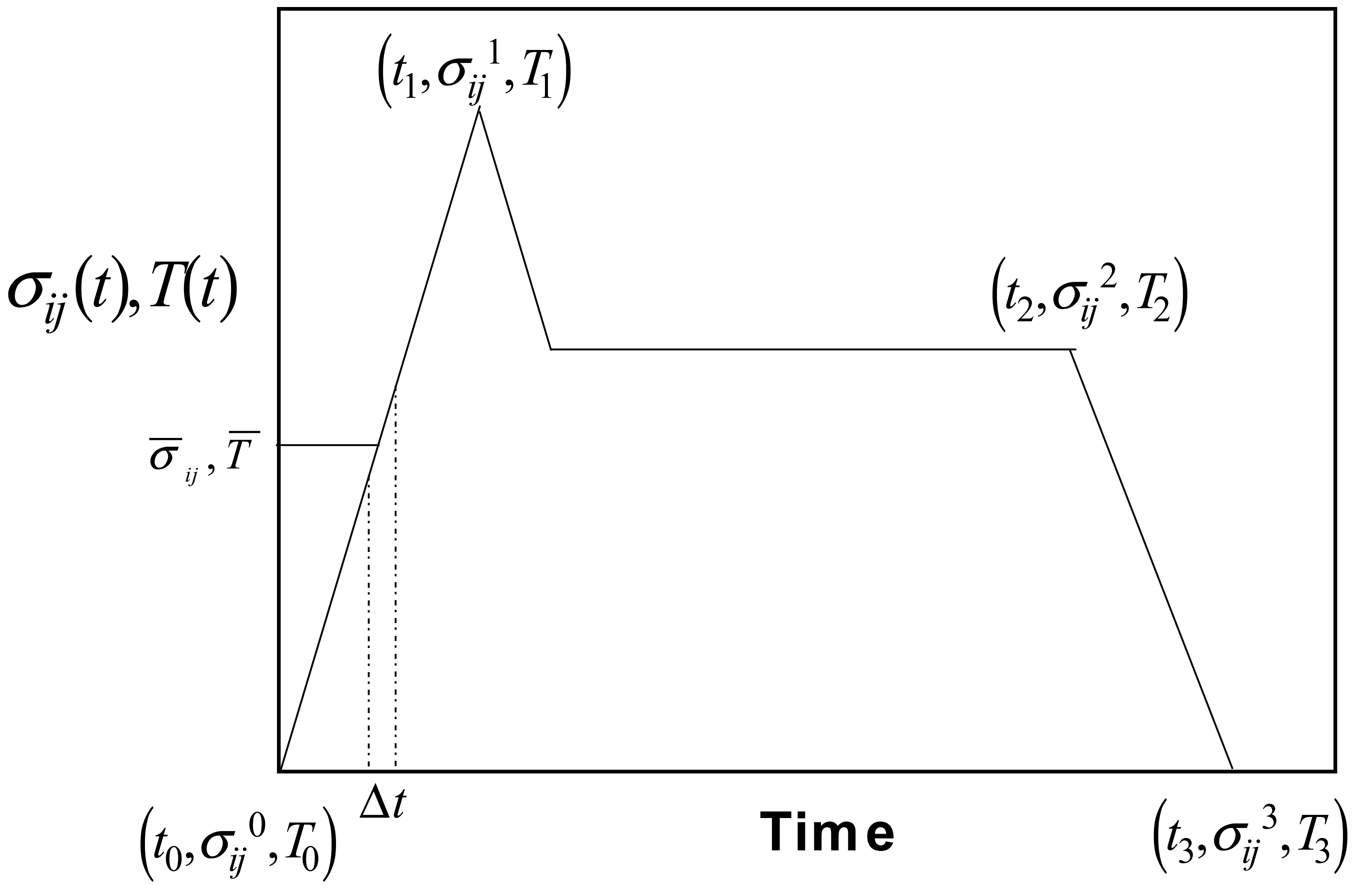
Residual Strength Data for Nicalon/ E-SiC 2-D Woven Composite $[0/90]_{2s}$:



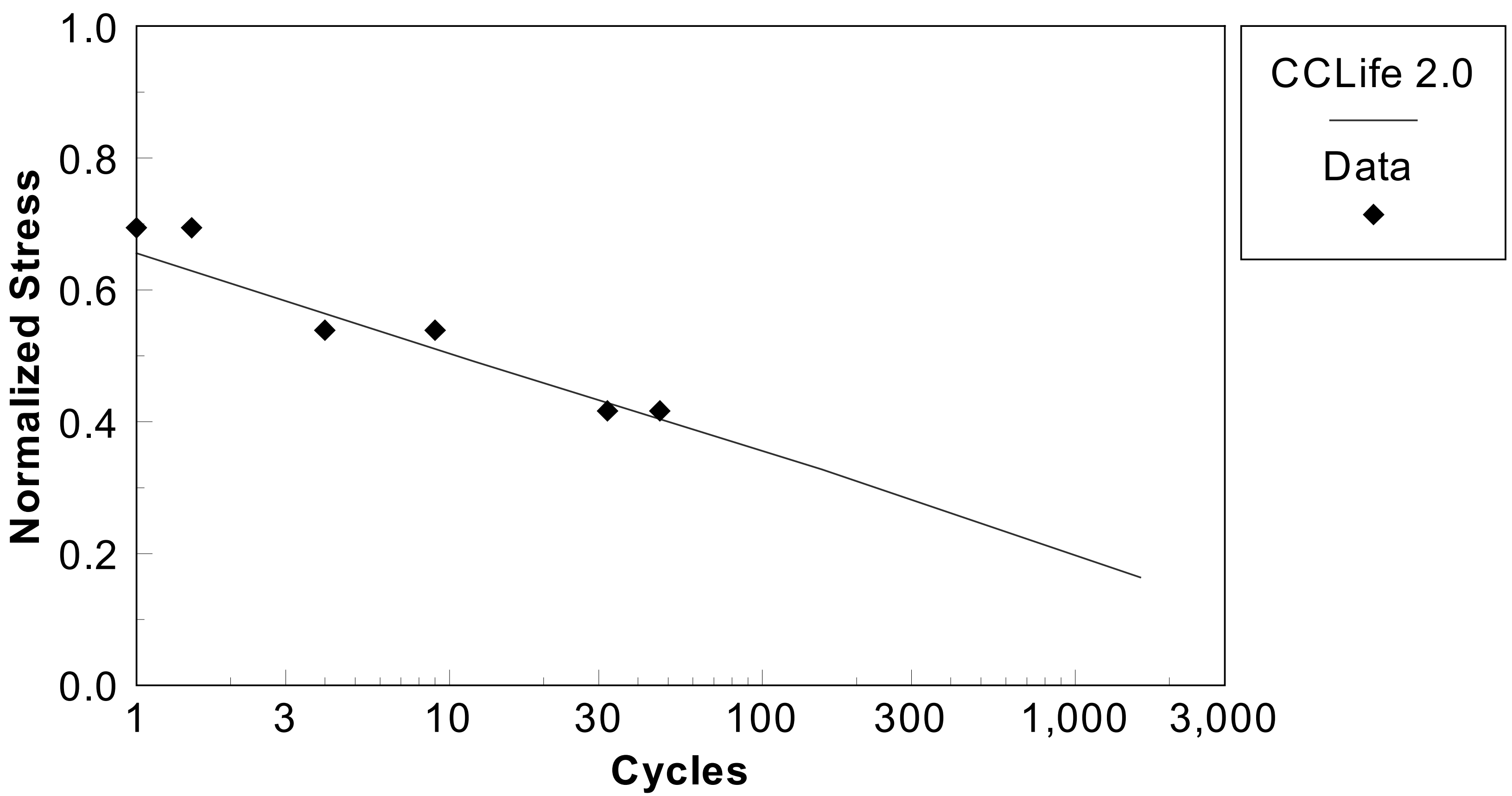
Residual Strength Data for Nicalon/ E-SiC 2-D Woven Composite $[0/90]_{2s}$:



Validation: Mission loading profile

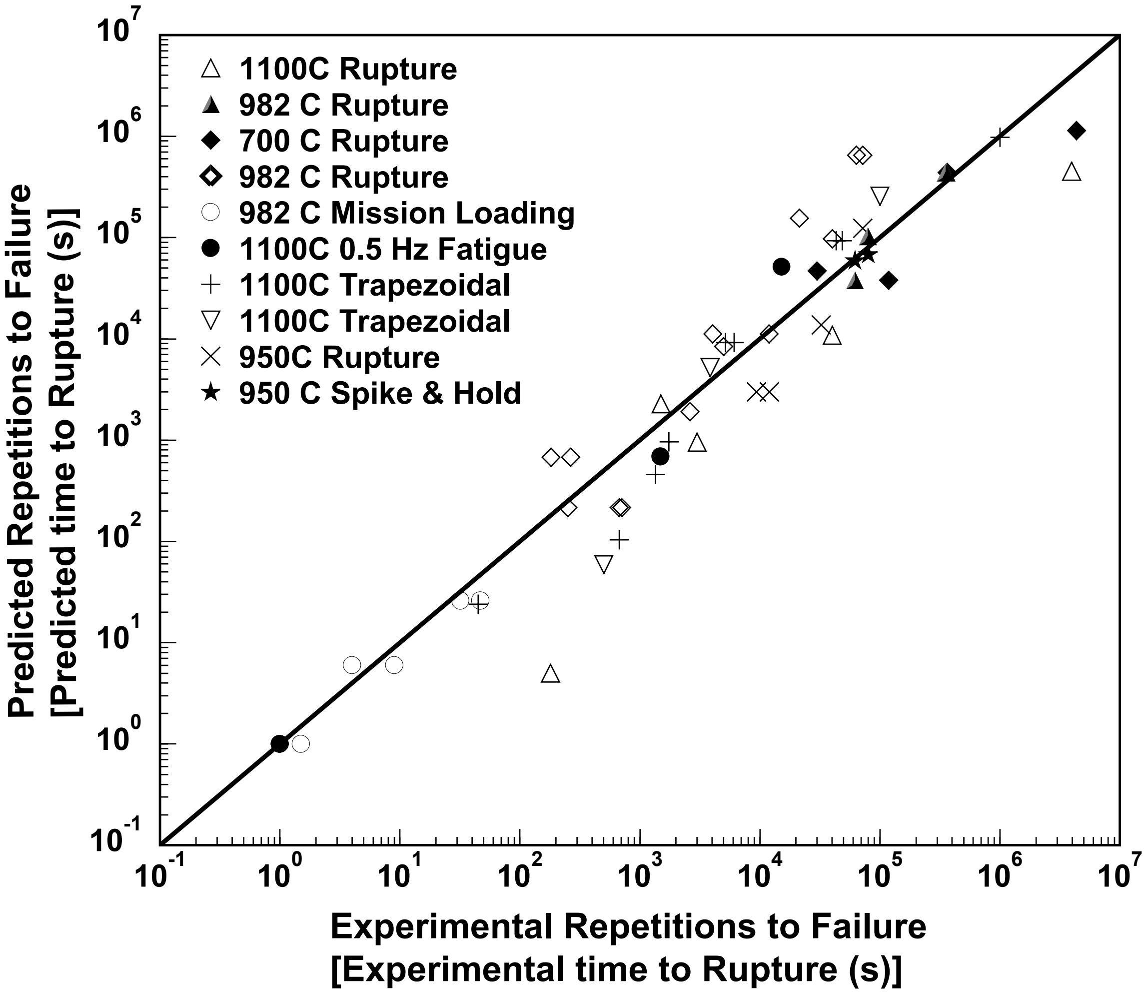


Validation: Mission loading profile

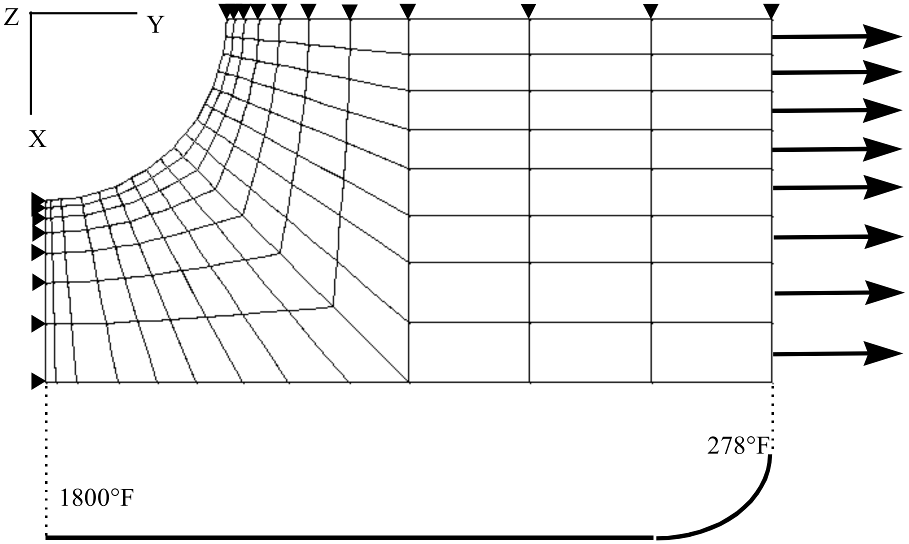


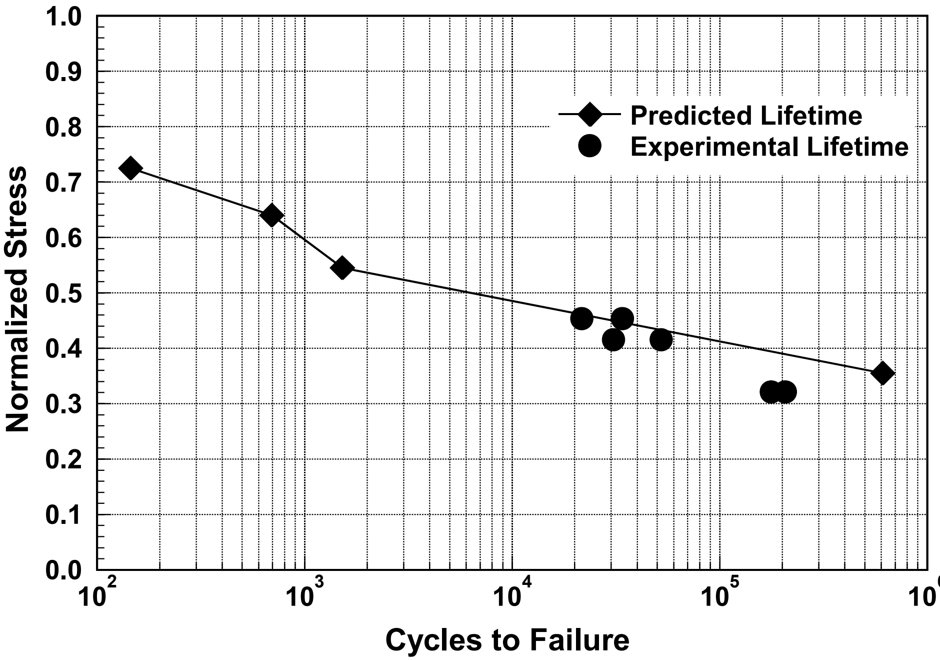
Virginia Tech

All results for Nicalon/ E-SiC 2-D Woven Composite $[0/90]_{2s}$:



Integration with FEA:



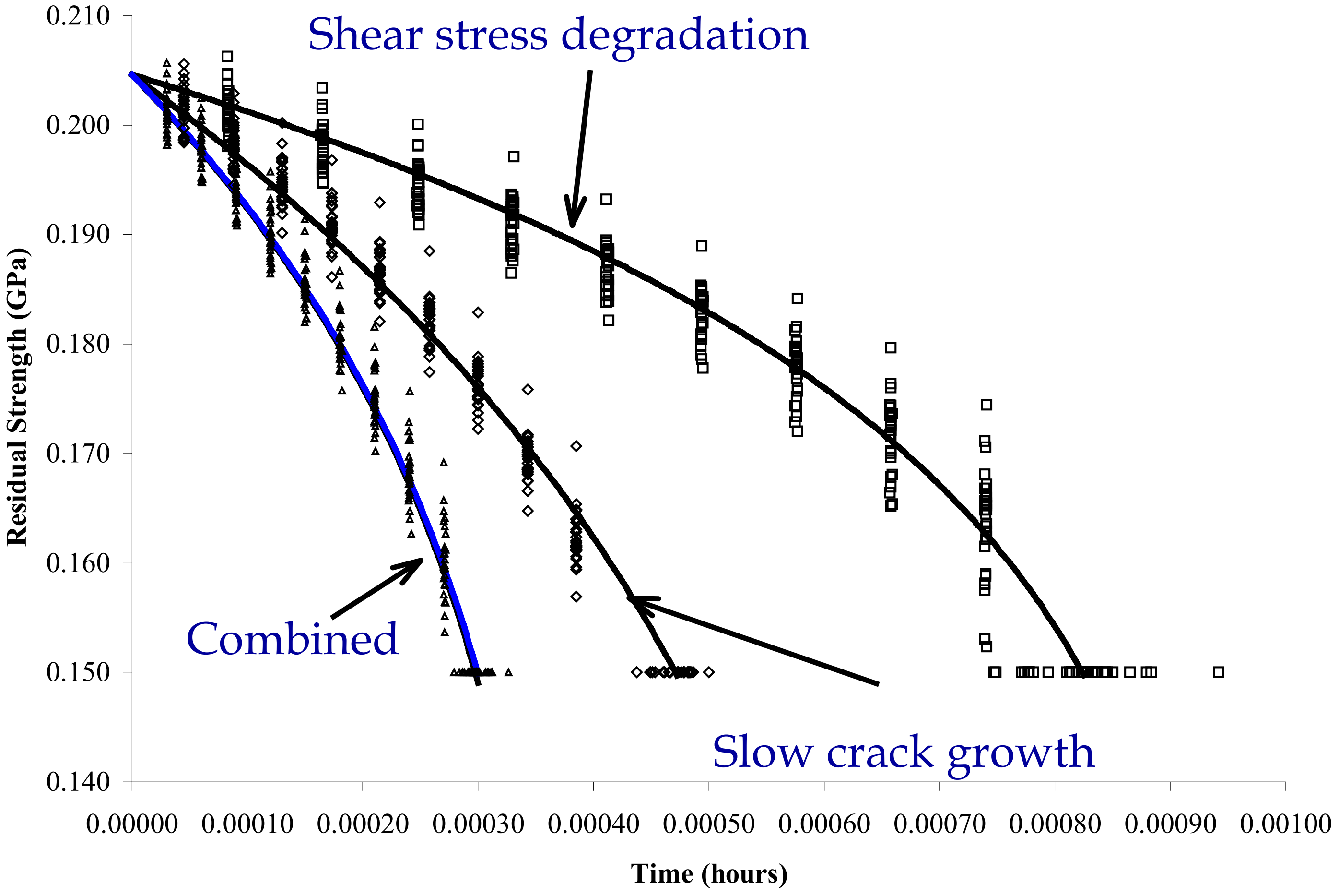


Idea: Use Micromechanical Model Results as Input to Residual Strength Model

- ***Why?***
  - Micromechanical models (particularly simulations) tend to be computationally intensive, but they can include details of material behavior
  - Residual strength approaches are normally empirically based which casts doubts on their applicability for general conditions

Virginia Tech

Multiple Mechanism Result:



Virginia Tech

Conclusions:

- Micromechanical models, while powerful for modeling material behavior, are somewhat limited
  - Inputs are often difficult to obtain
  - Computationally intensive
- Residual strength (and other phenomenological approaches)
  - Simpler to implement
  - Details of material behavior are obscured
- Possible means of exploiting strengths of both approaches has been examined

Virginia Tech