Life prediction based on material state changes in ceramic materials

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Outline:

- Residual Strength Modeling philosophy
- Model implementation (CCLife code)
- Development of Micromechanical Models
- Incorporation in Finite Element Analysis (*ANSYS*)
- Summary
Objectives in Lifetime Prediction

Effort:

- To develop a life-prediction method for composites based on an understanding of the relevant damage processes
- To validate the method by comparing with existing experimental evidence
Remaining Strength Predictions:

- Track remaining strength during the time-dependent 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
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**Implication:** $n_1$ cycles at $S_a^1$ is equivalent to $n_2^0$ cycles at $S_a^2$
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Failure occurs when residual strength equals applied load.
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

\[
\begin{align*}
  n_2^0 &= \frac{1}{F_{a_2}} - \frac{F_{r_1}}{N_2} \\
  \Delta F_r &= -b - \frac{F_{a_2}}{N_2} n_2^0 + \frac{1}{2} \frac{F_{a_2}}{N_2} n_2
\end{align*}
\]
Implementation for Ceramic Matrix Composites: 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 as a function of stress level and temperature
- 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
- Originated under EPM program
Stiffness Reduction Data for Nicalon/E-SiC 2-D Woven Composite [0/90]_{2s}:

![Graph showing stiffness reduction data for different stress levels.](image-url)
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:
Fatigue 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}:

Interrupted Fatigue Test Results

\[ R = -1 \]

\[ \sigma_{max} = 13 \text{ ksi} \]

![Graph showing normalized remaining strength and failure function over fatigue cycles.](image)
Validation: Mission loading profile
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Validation results: Trapezoidal loading profile

- Trapezoidal 1:1:1:1
- Trapezoidal 1:1:1:1 Prediction
All results for Nicalon/E-SiC 2-D Woven Composite $[0/90]_{2s}$:

Experimental Repetitions to Failure

Predicted Repetitions to Failure

- 1100°C Rupture
- 982°C Rupture
- 700°C Rupture
- 982°C Rupture
- 982°C Mission Loading
- 1100°C 0.5 Hz Fatigue
- 1100°C Trapezoidal
- 1100°C Trapezoidal
- 950°C Rupture
- 950°C Spike & Hold

[Diagram showing experimental and predicted repetitions to failure with various symbols for different conditions and temperatures.]
Validation with Oxide/Oxide System:

- Begin with fatigue tests at room temperature and stress-rupture tests at 1093°C on a Nextel 610 reinforced alumina-yttria composite.
- Represent the changes in remaining strength due to these mechanisms with a residual-strength based model.
- Create predictions based on the summation of damage due to the action of both mechanisms.
- Verify predictions with fatigue tests at 1093°C.
Basic Inputs:

- Ambient Fatigue
- 1093°C Stress-Rupture

Stress (MPa) vs. Cycles/Seconds

-5 MPa / decade
-35 MPa / decade
Fatigue Testing:

- An increase in hysteresis loop area - consistent with degradation of interface frictional stress
- A decrease in composite stiffness - associated with composite delamination
Rupture Testing:

- In stress-rupture tests there is little evidence of modulus decrease
- Strength reduction is accomplished by the degradation of the Nextel fibers
Elevated Temperature Fatigue:

*Sum the changes in remaining strength due to each mechanism acting independently*
Analysis of Hi-Nicalon/SiC Composite:

Attempt to relate center-hole notched composite behavior to coupon behavior

ANSYS user-programmable functions and macros used to generate stress profile, track element strength, and determine failed elements
Quasi-Static Tensile Behavior:

- **Stress (MPa)** vs. **Strain (%)**
  - **Unnotched Behavior**
  - **Notched Experiment**
  - **ANSYS Result**
Integration with FEA: SiC/SiC Recession Analysis
Summary and Conclusions:

• Life prediction analysis based on residual strength has been developed and applied to ceramic matrix composite systems.

• Validation studies include:
  – SiC/SiC composites of various geometries and loading conditions.
  – Nextel 610 reinforced alumina-yttria.

• Successful integration into commercial finite element packages.
In Memoriam:

We will continue to invent the future through our blood and tears and through all our sadness.... We will prevail....

Prof. Liviu Librescu   Prof. Kevin Granata