An explicit approach to stochastically modeling fatigue crack formation

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Outline

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III. Research highlights
   A. Microstructure model generation
   B. Finite element meshing
   C. Microstructural scale fatigue crack growth analysis

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Introduction: bending paperclips

- A simple example of uncertainty from my first engineering course:
  1) Take a box of paperclips and bend each paperclip, repeatedly back-and-forth until the paperclip breaks, i.e. cause fatigue failure in each clip
  2) Count the number of bends it takes to break each clip
  3) Plot a histogram/distribution of the results

- What to do about uncertainty?
  - Undergraduate approach: apply generous factors of safety, e.g. 0.4\(\mu\)
  - Graduate approach: answer one "simple" question - why?
Introduction: flying aircraft

- A more important example of uncertainty:
  - On April 28, 1988, the fuselage of an Aloha Airlines aircraft, a B-737-200, breaks apart in mid-flight, at approximately 7,000 meters above sea level

- What to do about uncertainty?
  - Traditional approach: apply generous safety factors and frequent inspections
  - State-of-the-art approach: use advanced experimental and computational capabilities to answer a “simple” question – why is there variability in the number of load cycles to failure? (and, can we predict the stochastic behavior that causes this variability?)

April 28, 1988: Aloha Airlines Flight 243

Project scope: getting down to the micro details

Images courtesy of Northrop Grumman Corporation

Hole #14

Row of bolt holes

Loading Direction

100 μm

250 μm

10 μm
Research highlights: generating microstructures

- μbuilder 1.1 – non-convex, elongated grain shapes

- μbuilder 2.0 – uses cellular automata to create realizations of input statistics

SEM of 7075-T651 (R. Campman, CMU) showing non-convex, stretched grain shapes
Research highlights: inserting particles that crack

1) Sample experimentally recorded particle statistics to create a digital realization

2) Reduce to a computationally tractable set of particles that directly influence crack growth:
   a) Filter out particles that are experimentally determined to be inconsequential: those that are sub-surface or smaller than 6 μm²
   b) Sample a response surface, developed from 2592 finite element analyses (4 TB of data) covering the range of likely particle configurations, to determine which of the remaining particles will crack
Research highlights: finite element meshing

- Developed an in-house, fully automated, 3D unstructured tetrahedral discretizing routine: resulting mesh conforms to internal and external surfaces, e.g. region interfaces and cracks.

- Improvements made to create high quality meshes of realistic microstructures:
  - A mesh size seeding routine, with octree and rangetree algorithms, to improve mesh gradients nearby small geometrical features.
  - A parallel routine: meshes each region, i.e. grain or particle, on a separate processor
    - Still creates conforming meshes at interfaces
    - Mesh time reduced by $O(m)$ where $m = \# \text{regions per model} = O(100)$
    - Resulting finite element model size: $O(10^7)$ degrees of freedom
Research highlights: modeling cracks

- Observed phenomena:

- Simulating crack trajectory:
  - Incubation (first flight) - use filter to determine and insert cracked particles
  - Nucleation (10-100 flights) and microstructure-governed crack propagation (O(10,000) flights) - use the appropriate damage criterion based on microstructural physics, e.g. one of the following:
    - Max. accumulated slip on a single system: $D_1$
    - Max. accumulated slip on a single plane: $D_2$
    - Total accumulated slip: $D_3$
    - Total work: $D_4$
    - Fatemie-Socie parameter: $D_5$

Illustration of Stage I crack at no load (a), full tensile load (b), and back to no load (c), from: C. Laird, 1967.
Research highlights: modeling cracks*  

\[ D_1 = \max_{\alpha} \gamma^\alpha \]

\[ D_2 = \max_{\alpha} \gamma^p \]

\[ \gamma^\alpha \equiv \text{accumulated slip on system } \alpha \]

\[ \gamma^p \equiv \text{accumulate d slip on plane } p \]

\[ \tau^\alpha_p \equiv \text{shear stress on plane } p \text{ and system } \alpha \]

\[ D_3 = \gamma \]

\[ D_4 = \max_{\alpha} \int_0^t \sum_{\omega=1}^3 \left| \gamma^p_p \right| \left( 1 + 0.5 \left( \frac{\sigma_n^p}{\sigma_0} \right) \right) dt \]

\[ D_5 = \max_{\alpha} \int_0^t \sum_{\omega=1}^3 \left| \gamma^p_p \right| \left( 1 + 0.5 \left( \frac{\sigma_n^p}{\sigma_0} \right) \right) dt \]

\[ g_0 = \text{initial resistance to slip on each system} \]

\[ \sigma_n^p \equiv \text{normal stress on plane } p \]

*Work completed in collaboration with D. Littlewood, RPI
Research highlights: modeling cracks

- Simulating crack growth rate:
  
  • Use a crack growth rate criterion, e.g.:
    \[ \frac{da}{dN} = G(\Delta CTD - \Delta CTD_{TH}) \]

    where \( G \) and \( \Delta CTD_{TH} \) are material parameters, and \( \Delta CTD \), change in crack tip displacement, is computed.

  • Explicit approach: update crack geometry and re-mesh
The bigger picture: a multiscale approach

- Model of 3D Structure
- 3D Structural Field Analysis
- 3D Realistic Microstructure Model
- Simulate Microstructural Damage Processes:
  - Crack Incubation in Particles
  - Crack Nucleation into Grains
  - Microstructurally Small Crack Propagation
- Analyze Microstructure for Higher Physical Fidelity,
  Update Structure Damage State and Fields
- Apply B.C.’s from Structural Model
Physics-based modeling of an extreme event...

...before it occurs!
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