An explicit approach to stochastically modeling fatigue crack formation

Michael G. Veilleux

In collaboration with: J D Hochhalter, J E Bozek,
P A Wawrzynek, and A R Ingraffea

DOE CSGF 2008 Fellows’ Conference
June 17, 2008
Washington Court Hotel on Capitol Hill

Outline

I. Introduction: from paperclips to aging aircraft

II. Project scope: the micro-fine details

III. Research highlights

   A. Microstructure model generation

   B. Finite element meshing

   C. Microstructural scale fatigue crack growth analysis

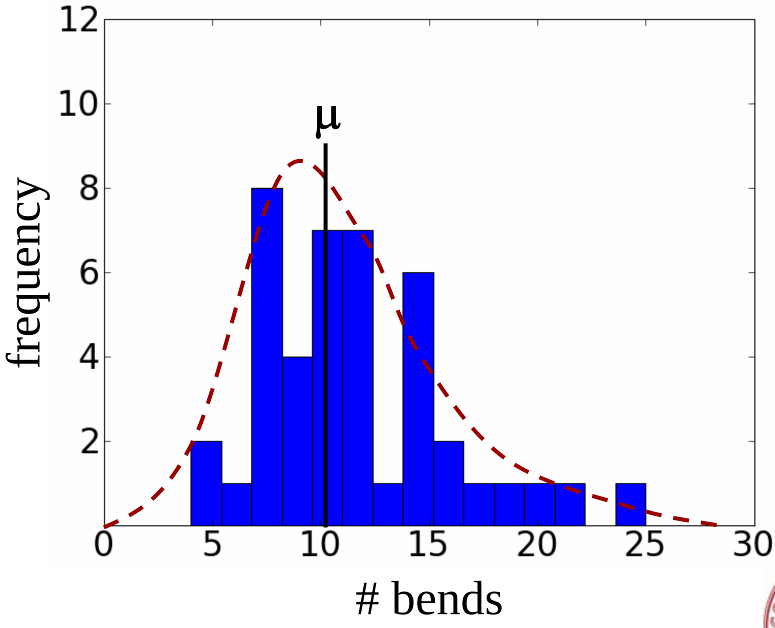
IV. The bigger picture

DOE CSGF

CORNELL UNIVERSITY FOUNDED A.D. 1865

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.* 0.4μ
  - Graduate approach: answer one "simple" question - why?



Introduction: flying aircraft

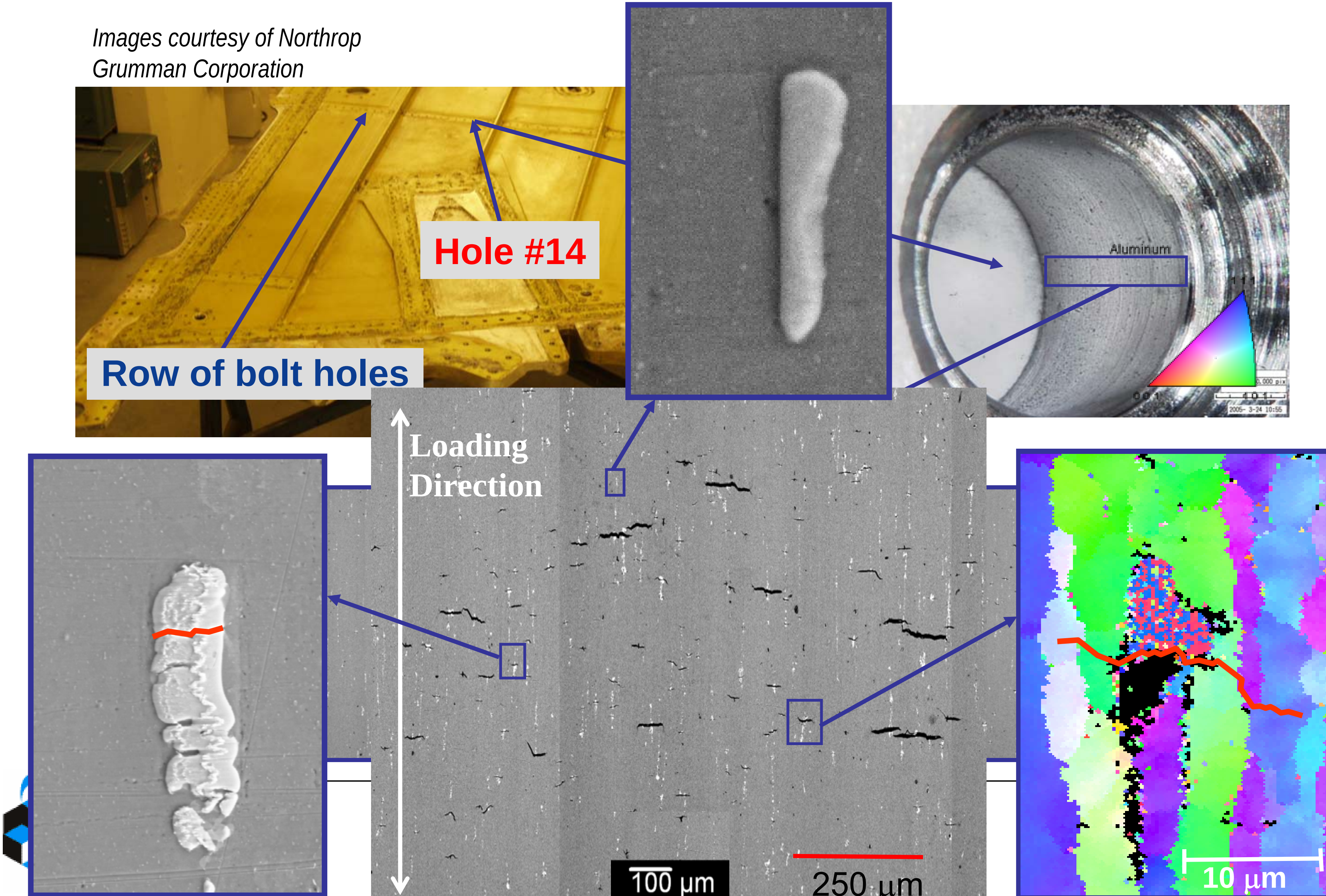
- A more important example of uncertainty:
  - On April 28, 1988, the fuselage of an Aloha Airlines aircraft, a B-737-200, breaks apart in mid-flight, at approximately 7,000 meters above sea level
- What to do about uncertainty?
  - Traditional approach: apply generous safety factors and frequent inspections
  - 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

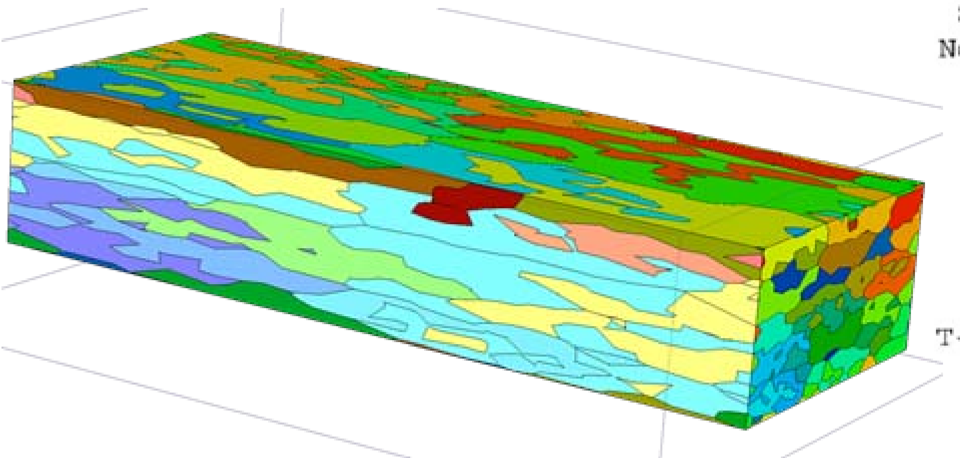
Image source:
http://en.wikipedia.org/wiki/Aloha_Airlines_Flight_243

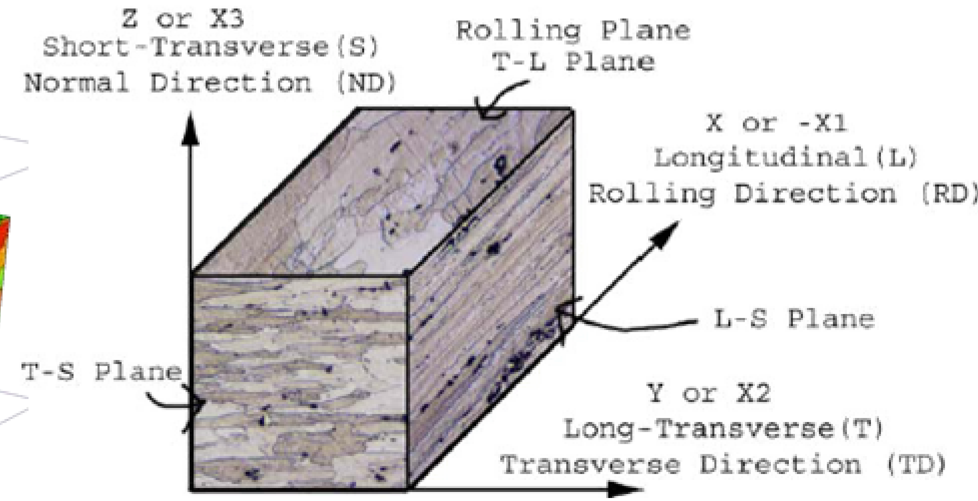
Project scope: getting down to the micro details

Images courtesy of Northrop Grumman Corporation

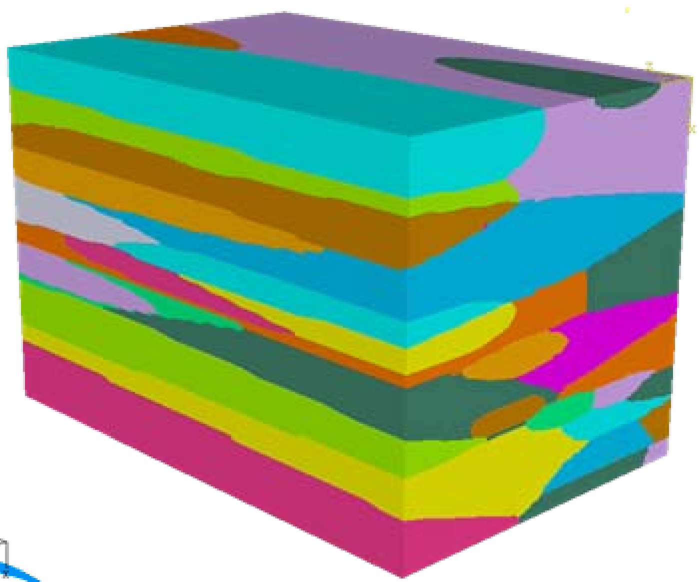


Research highlights: generating microstructures





SEM of 7075-T651 (R. Campman, CMU) showing non-convex, stretched grain shapes



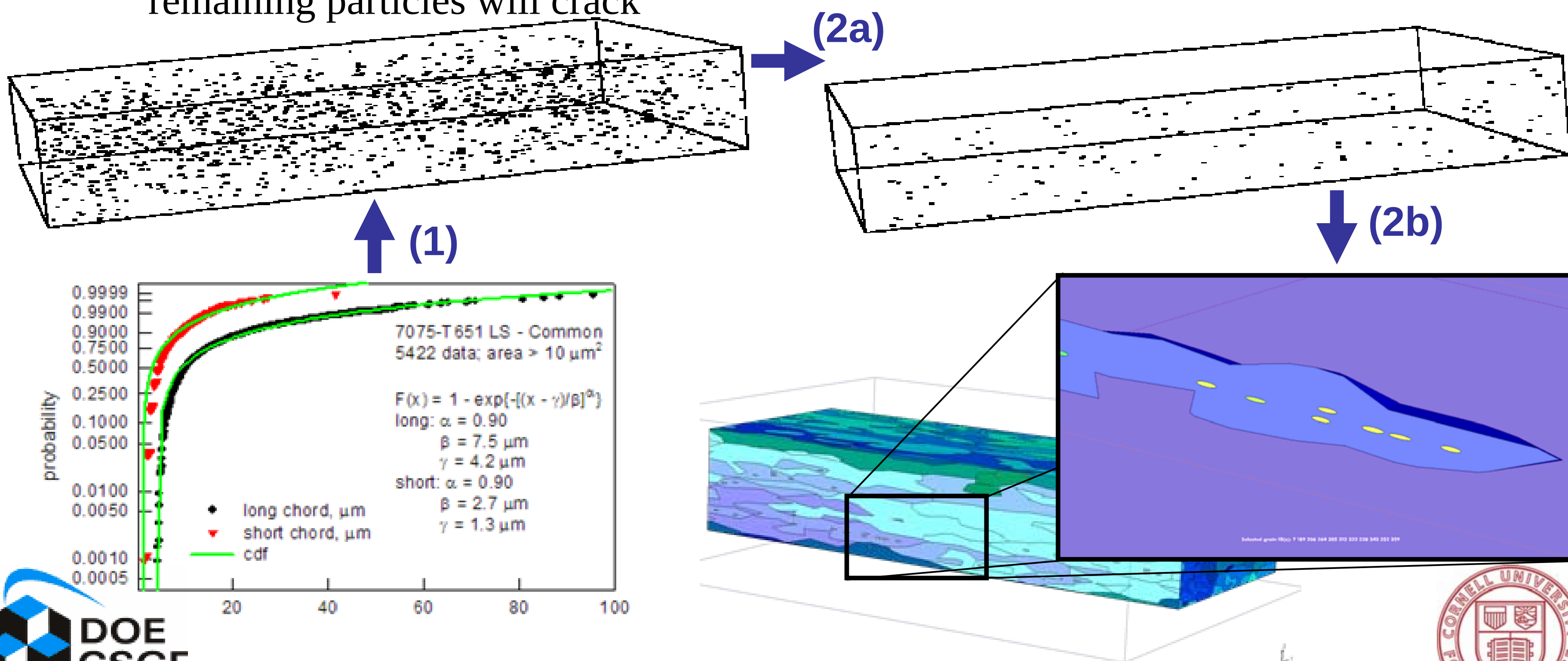
- μbuilder 1.1 – non-convex, elongated grain shapes

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

DOE CSGF

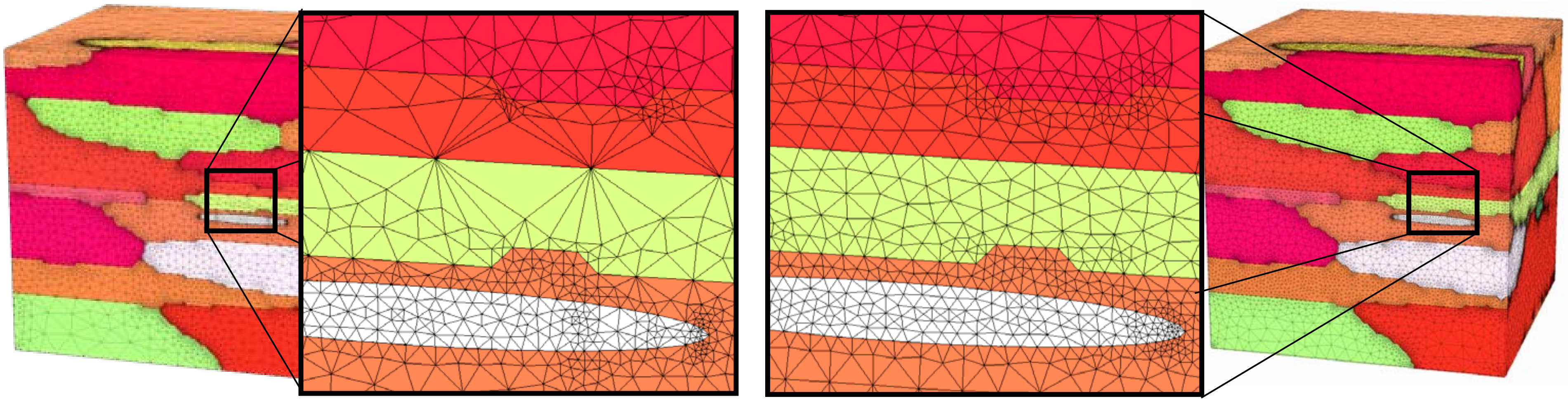
Research highlights: inserting particles that crack

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 μm^2
   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

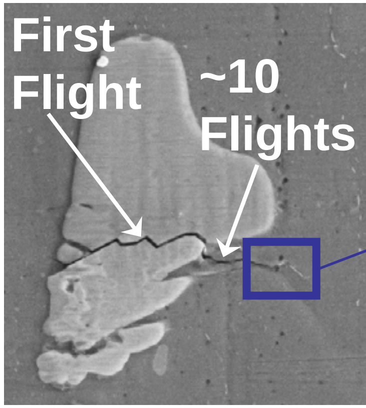


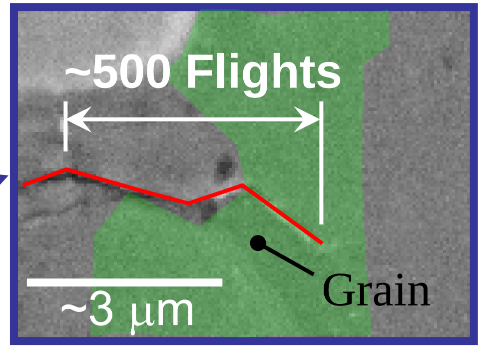
Original mesh *Improved mesh*

  - 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 = # regions per model = O(100)*
    - Resulting finite element model size: $O(10^7)$ degrees of freedom

Research highlights: modeling cracks

- Observed phenomena:





SEM images courtesy of Northrop Grumman Corporation

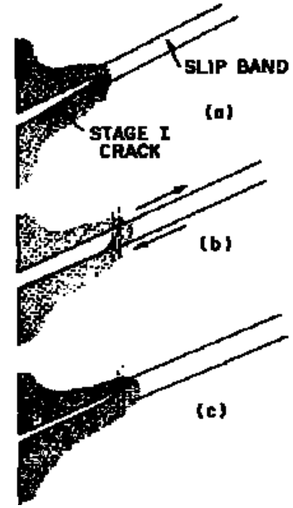


Illustration of Stage I crack at no load (a), full tensile load (b), and back to no load (c), from:

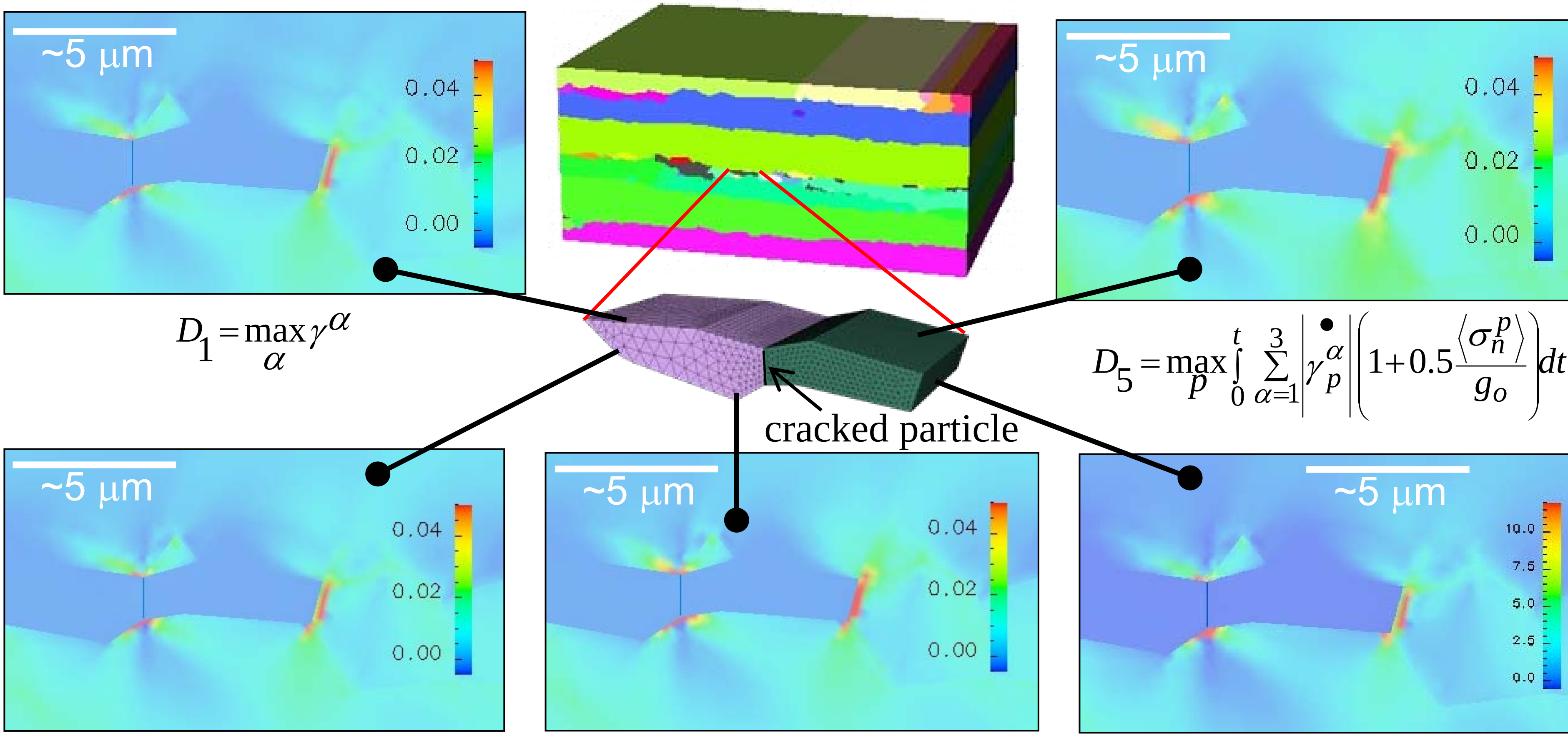
C. Laird, *1967*.

- 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

Criterion: Crack extends when $D_i \geq D_{i,critical}$ and in the direction of $D_{i,max}$

DOE CSGF

Research highlights: modeling cracks*



$$D_1 = \max_{\alpha} \gamma^{\alpha}$$

$$D_5 = \max_{p} \int_0^t \sum_{\alpha=1}^{3} \left|\dot{\gamma}_p^{\alpha}\right| \left(1 + 0.5\frac{\langle \sigma_n^p \rangle}{g_o}\right) dt$$

$$D_2 = \max_{p} \gamma^{p}$$

$$D_3 = \gamma$$

$$D_4 = \max_{p} \int_0^t \sum_{\alpha=1}^{3} \left|\dot{\gamma}_p \tau_p^{\alpha}\right| dt$$

$\gamma^{\alpha} \equiv$ *accumulated slip on system* α

$\gamma \equiv$ *accumulated slip on all slip systems*

$g_o \equiv$ *initial resistance to slip on each system*

$\gamma^{p} \equiv$ *accumulated slip on plane* p

$\sigma_n^{\alpha} \equiv$ *normal stress on plane* p

$\tau_p^{\alpha} \equiv$ *shear stress on plane* p *and system* α

Work completed in collaboration with D. Littlewood, RPI

DOE CSGF

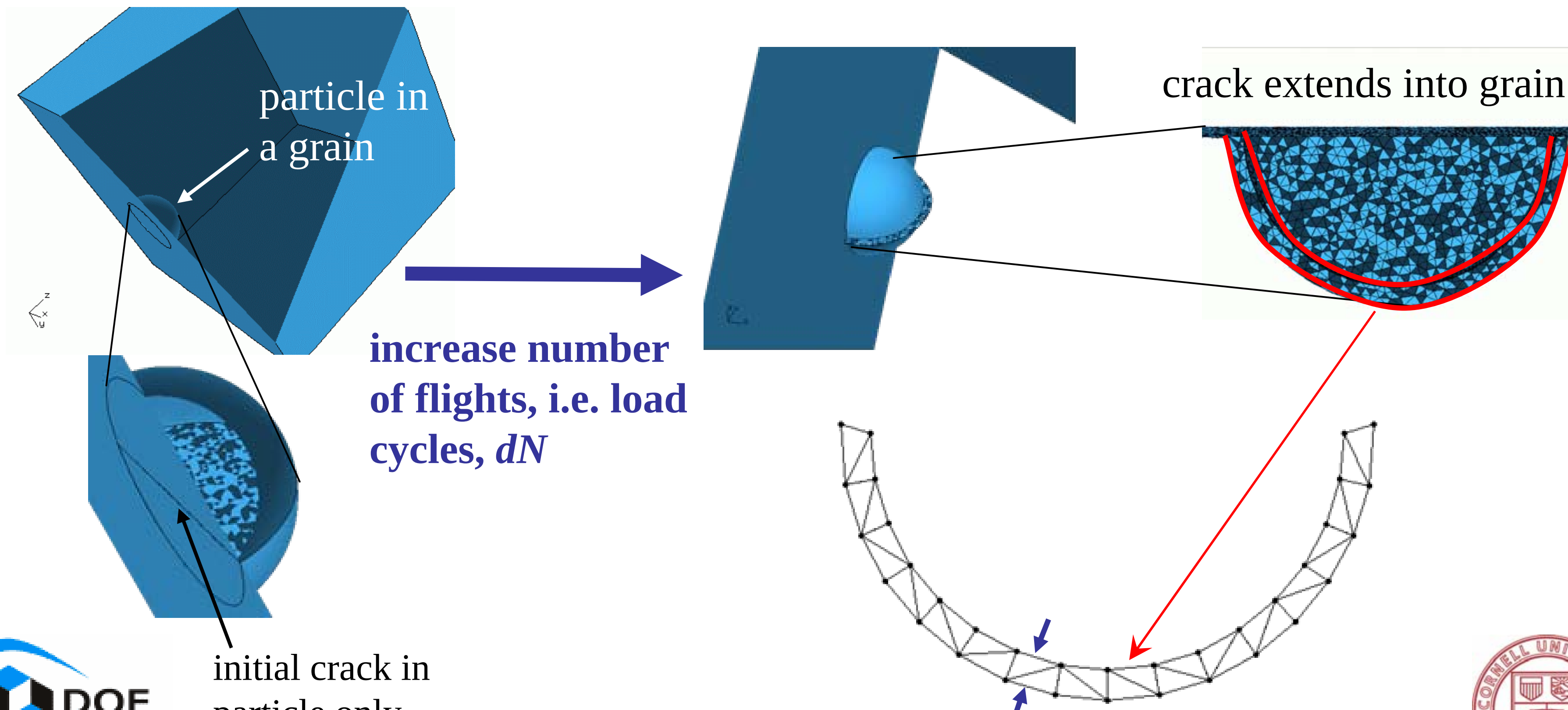
Research highlights: modeling cracks

- Simulating crack growth rate:
  - Use a crack growth rate criterion, *e.g.*:

$$\frac{da}{dN} = G\left(\Delta CTD - \Delta CTD_{TH}\right)$$

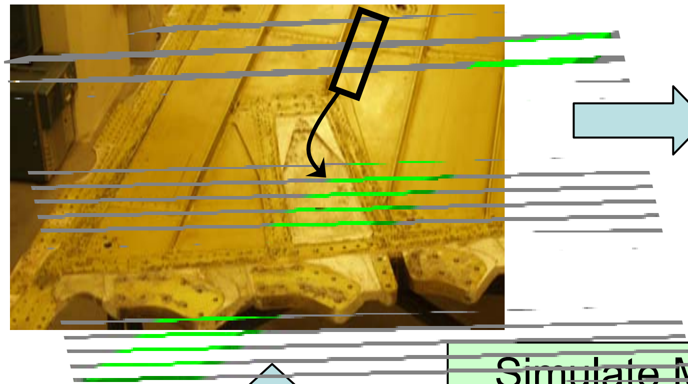
where G and ΔCTD_{TH} are material parameters, and ΔCTD, change in crack tip displacement, is computed

  - Explicit approach: update crack geometry and re-mesh

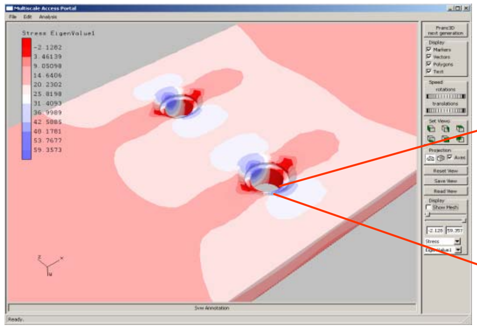


The bigger picture: a multiscale approach

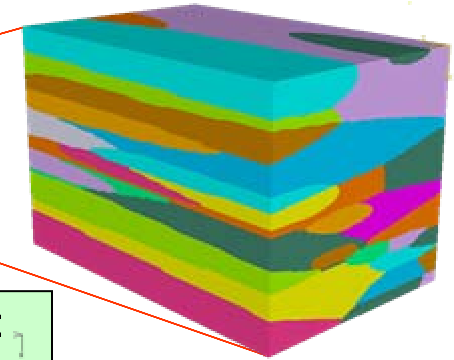
Model of 3D Structure



3D Structural Field Analysis

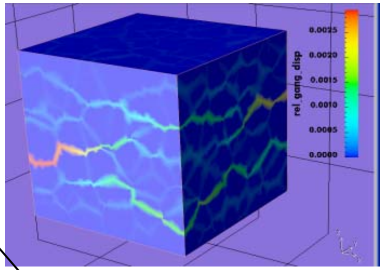


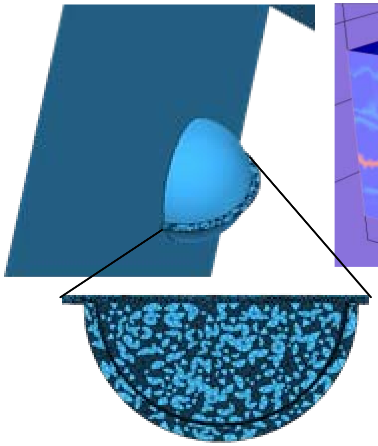
3D Realistic Microstructure Model



Simulate Microstructural Damage Processes:
Crack Incubation in Particles
Crack Nucleation into Grains
Microstructurally Small Crack Propagation

Apply B.C.'s from Structural Model



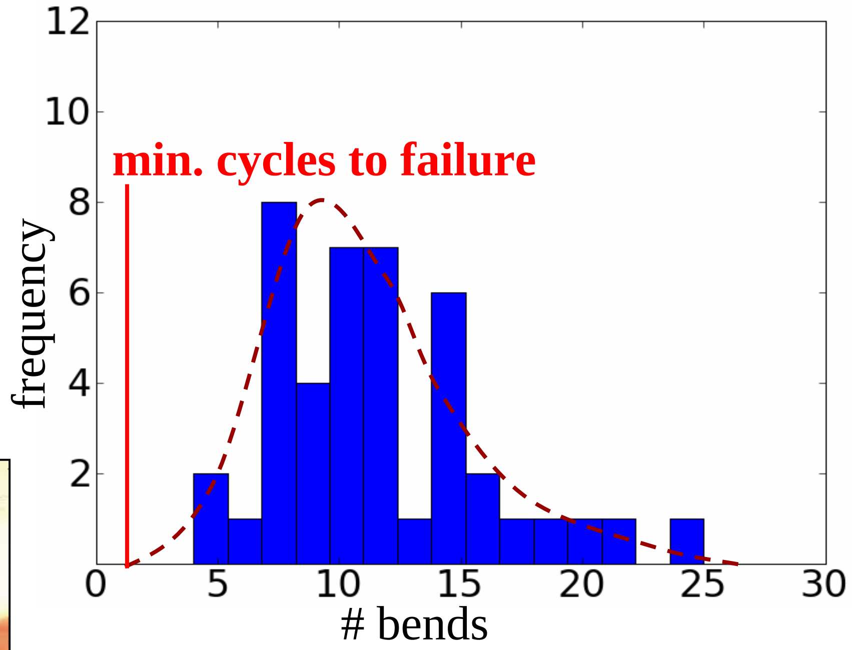


Analyze Microstructure for Higher Physical Fidelity, Update Structure Damage State and Fields

The bigger picture: end product

Physics-based modeling of an extreme event…

…before it occurs!



Acknowledgements

- DOE CSGF and the Krell Institute
- My research advisor, Dr. Anthony Ingraffea
- My practicum advisor, Dr. Rebecca Brannon at Sandia National Laboratories
- The Cornell Fracture Group
- The DARPA SIPS program and collaborators therein from Northrop Grumman, Rensselaer Polytechnic Institute, Lehigh University, and Carnegie Mellon University
- All of you!

DOE CSGF

KRELL institute

CORNELL UNIVERSITY FOUNDED A.D. 1865