AE 737 - MECHANICS OF DAMAGE TOLERANCE

Lecture 1

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OUTLINE

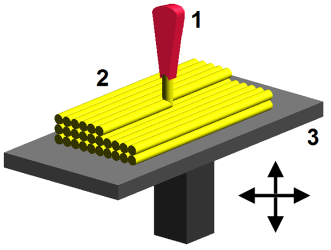
ABOUT ME

FAMILY

EDUCATION

- B.S. in Mechanical Engineering from Brigham Young University
    - Worked with ATK to develop tab-less gripping system for tensile testing composite tow specimens
    - Needed to align the specimen, as well as grip it without causing a stress concentration
- M.S. and Ph.D. from School of Aeronautics and Astronautics at Purdue University
    - Worked with Boeing to simulate mold flows
    - First ever mold simulation with anisotropic viscosity

- No simulation is currently able to predict fiber orientation from these processes
- Part of the challenge is that we only have information from initial state and final state
- I want to quantify intermediate stages using a transparent mold



- Composites are being used in 3D printing now
- Printing patterns are optimized for isotropic materials
- Sometimes composites hurt more than they help when not utilized properly

- Name
- Student status (Undergrad, Masters, Ph.D)
- Full time or part time student?
- One interesting thing to remember you by

SYLLABUS AND SCHEDULE

- Printed notes from Dr. Bert L. Smith and Dr. Walter J. Horn
- Will be available starting Thursday, bring $25 cash or check to AE offices to pick up your copy
- Homework will be given in handouts
- Textbook is an assimilation of knowledge from many sources, provides excellent practical applications of fracture mechanics
- Supplemental textbooks are listed in the syllabus and in the text for further study

OFFICE HOURS

- I will e-mail everyone in the course a Doodle link we can use to find the optimal office hours
- Let me know if you do not receive the e-mail, you may need to update your information in Blackboard
- Take advantage of office hours, this is time that I have already set aside for you
- If the regular office hours do not work for your schedule, send me an e-mail and we can work out a time to meet
- While in person visits are often the most helpful, I will always try to answer questions as best as I can via e-mail

TENTATIVE COURSE OUTLINE

- Section 1 - fracture mechanics
  - Stress intensity (19-26 Jan)
  - Plastic zone (28 Jan - 4 Feb)
  - Fracture toughness (9-16 Feb)
  - Residual strength (18-25 Feb)
  - Exam 1 (8 March)

TENTATIVE COURSE OUTLINE

- Section 2 - fatigue
  - Crack growth (10-24 Mar)
  - Crack propagation (29 Mar - 5 Apr)
  - Exam 2 (14 April)

- Section 3 - damage tolerance
    - Damage tolerance (7-21 Apr)
    - Test methods (26-28 Apr)
    - Finite elements (3-5 May)
    - Non-Destructive Testing (time permitting)
    - Final project (due 5 May)

GRADES

- Grade breakdown
  - Homework 15%
  - Exam 1 .... 30%
  - Exam 2 .... 30%
  - Final Project 25%
- Follow a traditional grading scale

A	A-	B+	B	B-	C+	C	C-	D+	D	D-	F
93-100	90-93	87-90	83-87	80-83	77-80	73-77	70-73	67-70	63-67	60-63	0-60

FINAL PROJECT

- Perform residual strength, fatigue and damage tolerance analysis on a real part
- Examples: car axle, fuselage panel, wing panel, landing gear, bike pedal
- Individual project
- More discussion after Exam 1

CLASS EXPECTATIONS

- Consider the cost (to you or others) of your being in class
- I ask that you refrain from distracting behaviors during class
- When you have something more important than class to take care of, please take care of it outside of class

COURSE OVERVIEW

- In linear elasticity, we generally consider materials in their pristine state
- Realities of manufacturing, cyclic loads, and unforeseen loads result in a material which is something other than pristine
- In this course we will develop methods for predicting the strength of a material with some damage (residual strength)
- We will learn to predict the rate at which damage will grow (fatigue)

- There are many ways to address the problem of damage in a material
    1. Infinite-life design
    2. Safe-life design
    3. Damage tolerant design
- To ensure damage tolerant design, we must ensure that crack growth is always stable
- Another important concept of damage tolerant design is to include multiple load paths, so failure in one part does not cause critical failure of the whole structure

DAMAGE TOLERANCE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- A B-17 collided with a Germain plane during WWII
- In spite of the damage, the B-17 was able to fly 90 minutes and land safely

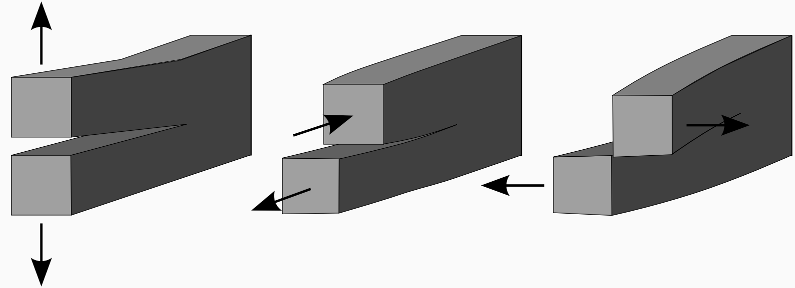

711

- An example of multiple damaged sites occurred on a Boeing 737 in 1988
- Damage around multiple rivet holes connected and a full piece of the fuselage was blown off
- The plane was able to land safely
- This particular instance led to the study of ”Multiple Site Damage”

FRACTURE MECHANICS

- *Linear Elastic Fracture Mechanics* is the study of the propagation of cracks in materials
- There are some corrections we add to account for plasticity
- In this course we will not follow the full mathematical development of fracture mechanics (there is a separate course dedicated to that)
- Instead we will take some results and apply them

- In fracture mechanics we consider three different modes
- Mode I is known as the ”opening mode”
- Mode II is known as the ”sliding mode”
- Mode III is known as the ”tearing mode”



Mode I: Opening

Mode II: Sliding

Mode III: Tearing

STRESS INTENSITY

- A key finding from Linear Elastic Fracture Mechanics (LEFM) is known as the *Stress Intensity Factor*
- The stress intensity factor is often written in this form

$$K = \sigma\sqrt{\pi a}\beta \tag{1.1}$$

- Where K is the stress intensity factor, σ is the applied stress, a is the crack length, and β is a dimensionless parameter depending on geometry
- Be careful that although the notation is similar, the *Stress Intensity Factor* is different from the *Stress Concentration Factor* from strength of materials
- We are usually most concerned with Mode I, but there will be a unique stress intensity factor for each mode, we label these K_I, K_{II}, and K_{III}
- If no subscript is given, assume Mode I

- For brittle materials (where ”linear” fracture mechanics assumptions hold true) we can find the full stress field near the crack in terms of the stress intensity factor

$$\begin{aligned}
\sigma_x &= \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \\
\sigma_y &= \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \\
\tau_{xy} &= \frac{K_I}{\sqrt{2\pi r}} \sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}
\end{aligned} \tag{1.2}$$

- Similarly for Mode II we find

$$
\begin{aligned}
\sigma_x &= \frac{-K_{II}}{\sqrt{2\pi r}} \sin\frac{\theta}{2}\left(2+\cos\frac{\theta}{2}\cos\frac{3\theta}{2}\right)\\
\sigma_y &= \frac{K_{II}}{\sqrt{2\pi r}} \sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}\\
\tau_{xy} &= \frac{K_{II}}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)
\end{aligned}
\tag{1.3}
$$

- And for Mode III

$$
\begin{aligned}
\tau_{xz} &= \frac{-K_{III}}{\sqrt{2\pi r}} \sin\frac{\theta}{2} \\
\tau_{yz} &= \frac{K_{III}}{\sqrt{2\pi r}} \cos\frac{\theta}{2}
\end{aligned}
\tag{1.4}
$$

PLOTTING

- Plotting is an important part of graduate work, and this course
- There are many software programs which can generate good scientific plots
    - Microsoft Excel
    - MATLAB
    - Maple
    - Mathematica
    - Python
    - R
    - Plot.ly
- You are welcome to use whatever software you desire, I will use Python for a quick demonstration

- To make a good scientific plot, we must first decide what we are plotting, and which plot style will best illustrate our data
- Let us consider the Mode I stresses near a crack tip

$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)$$
$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)$$
$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}$$

- One interesting plot could be to examine stress magnitudes along the crack propagation direction as we get farther away from the crack
- In this case we would have $\theta = 0$.
- Since θ is a constant, it is not ideal to use a polar plot, instead we will use a standard rectangular plot

- Since we are looking at stresses near the crack tip, it is convenient to normalize the distance by the crack length
- If substitute for θ and K_I we have

$$\sigma_x = \frac{\sigma\sqrt{\pi a}\beta}{\sqrt{2\pi r}}$$
$$\sigma_y = \frac{\sigma\sqrt{\pi a}\beta}{\sqrt{2\pi r}}$$
$$\tau_{xy} = 0$$

- Since σ_x and σ_y are identical for this case, we consider only one, and normalize by the applied stress. After simplification

$$\frac{\sigma_x}{\sigma\beta} = \frac{1}{\sqrt{2}}\frac{1}{\sqrt{(r/a)}}$$

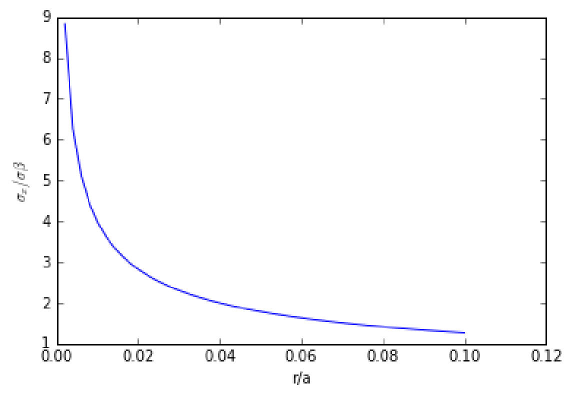


Figure 1: σ_x for a Mode I crack plotted vs. normalized distance from crack tip, r/a.

- Since we found $\sigma_x = \sigma_y$ for $\theta = 0$, we decide it might be better to look at a polar plot using θ as a variable
- To make a polar plot in this style, we need a function such that $r = f(\theta)$
- To do this we consider a constant stress value, we will solve for and plot the distance, r at which the stress is equal to the same constant value for each of the three stress terms

$$\sigma_x = C = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)$$
$$\sigma_y = C = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)$$
$$\tau_{xy} = C = \frac{K_I}{\sqrt{2\pi r}} \sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}$$

- After solving for r we find

$$r = \frac{K_I^2}{2C^2\pi} \cos^2 \frac{\theta}{2} \left(1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2}\right)^2$$

$$r = \frac{K_I^2}{2C^2\pi} \cos^2 \frac{\theta}{2} \left(1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2}\right)^2$$

$$r = \frac{K_I^2}{2C^2\pi} \sin^2 \frac{\theta}{2} \cos^2 \frac{\theta}{2} \cos^2 \frac{3\theta}{2}$$

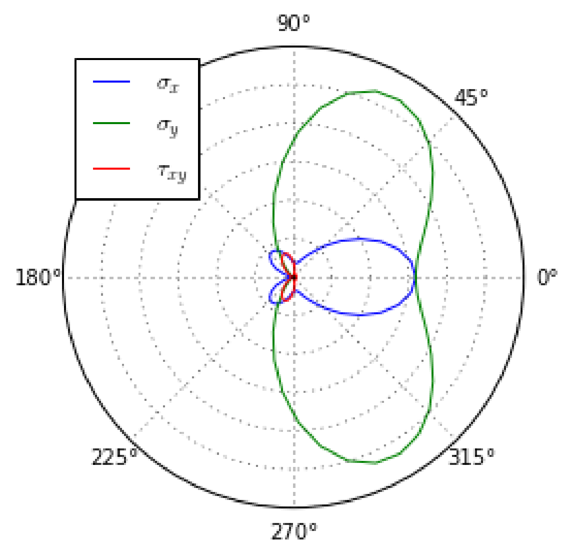


Figure 2: Polar plot for constant stress contours near the crack tip for Mode I