Teaching Mechanical Design Failure Theories with Use of CAD

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This paper discusses the author's exploration of using CAD to help students with better understanding of failure theories in the course of machine elements. It is a four-semester-credit-hour sophomore-level course in the program of mechanical engineering technology. It is offered in each spring semester. Its prerequisites include the course of Computer-Aided Drafting and Design (CADD), in which we use Siemens Solid Edge, the CAD system used by a number of local industrial companies. The textbook that has been used for the last several years is Machine Elements in Mechanical Design by Robert L. Mott, Prentice Hall.

The first part of the course is on basic static failure theories and fatigue failure theories. We teach analytical methods to predict failure and give an introduction on finite element analysis with a lab.

In the analytical approach, students are taught to select and use equations. The figure below shows as examples some of the equations in the textbook:

$s'_{sn} = 0.577\, s'_n$ (estimate for endurance strength in shear)

$$K_t\tau_{max} < \tau_d = s'_{sn}/N = 0.577\, s_n/N \qquad \textbf{(5–27)}$$

Case F: Reversed Combined Stress

Use Mohr's circle to find the maximum shear stress and the two principal stresses by using the maximum values of the applied stresses.

Case F1: Maximum Shear Stress Theory. Use Equation 5–26.

Case F2: Distortion Energy Theory. Use Equation 5–27.

Case G: Fluctuating Normal Stresses: The Goodman Method

Use the Goodman method that was described in Section 5–8 and illustrated in Figure 5–15. A satisfactory design results if the combination of the mean stress and the alternating stress produces a point in the *safe zone* shown in Figure 5–15. Then you can use the Equation (5–20) to evaluate the design factor for fluctuating loads:

$$\frac{K_t\sigma_a}{s'_n} + \frac{\sigma_m}{s_u} = \frac{1}{N} \qquad \textbf{(5–20)}$$

Case H: Fluctuating Shear Stresses

The preceding development of the Goodman method can also be done for fluctuating shear stresses instead of normal stresses. The design factor equation would then be

$$\frac{K_t\tau_a}{s'_{sn}} + \frac{\tau_m}{s_{su}} = \frac{1}{N} \qquad \textbf{(5–28)}$$

Figure 1 Analytical Equations (Mott)

There is a learning gap in the traditional method of teaching students to use the equations to apply failure theories. It has been observed over the years of author's teaching that when students plug numbers into these equations, they typically overlook the physical meanings of the equations. In other words, while they may be able to use the equations they do not learn well what causes failure for different types of materials under different loading conditions.

Often the physical meanings of the equations are shown much better graphically. As an example, the figure below shows several commonly used fatigue design equations for stress states where the mean stresses are positive. In the figure, Point B (σ_m, σ_a) represents the current stress state. If the ratio (σ_m/σ_a) remains unchanged when they both change, then point A represents the failure state according to the Modified Goodman theory and the ratio OA/OB is the factor of safety N of the design.

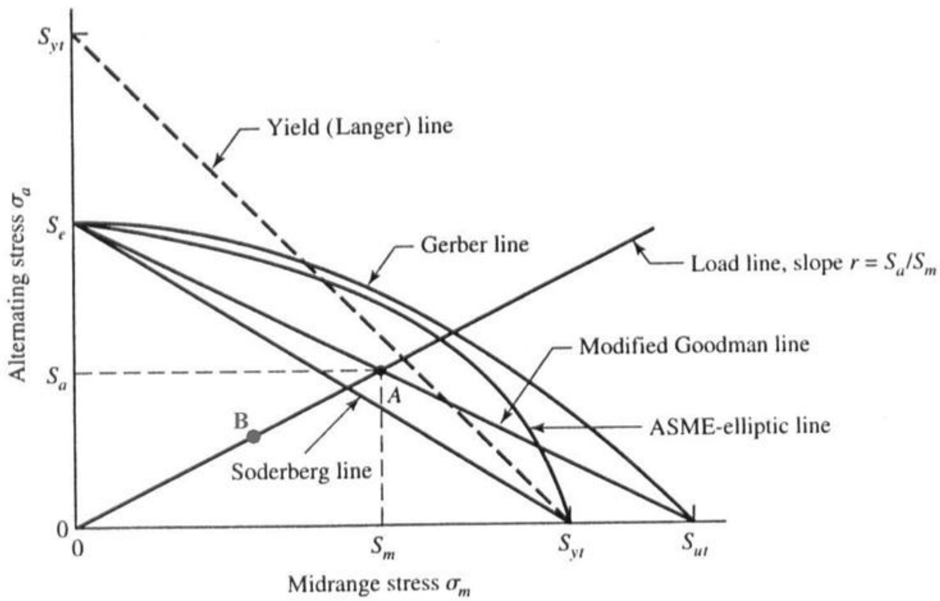

Figure 2 Graphical Forms of Fatigue Design Equations (Shigley & Mischke)

As shown in engineering textbooks of mechanical design, the algebraic design equations for estimating factors of safety are derived from the graphical relations shown in the above. For years, the algebraic forms have been highlighted because of convenience of implementation and higher accuracy over traditional graphical methods.

Nowadays Nowadays the graphical method is very implementable. On a CAD, lines, curves and points can be easily constructed and distances can be easily measured. Using CAD, the graphical method leads to same accuracy as the analytical method

Since the graphical interpretation provides the original ideas of the failure theories, teaching students the graphical method gives them better knowledge of the failure theories, prepares them better for learning of other failure theories later in their careers, and provide them with a graphical method in communicating with their future peers.

Our textbook by Robert Mott has one example of finding out the factor of safety of brittle materials under static loading via graphical approach. In the example as shown below, the stress state is shown by point A and the factor of safety is computed as OA_f/OA. In the example, students are asked to scale OA_f and OA from the diagram. In the past, my students had difficulties with following the example because the design factor of safety from scaled OA_f and OA was not in good consistency with the analytical result.

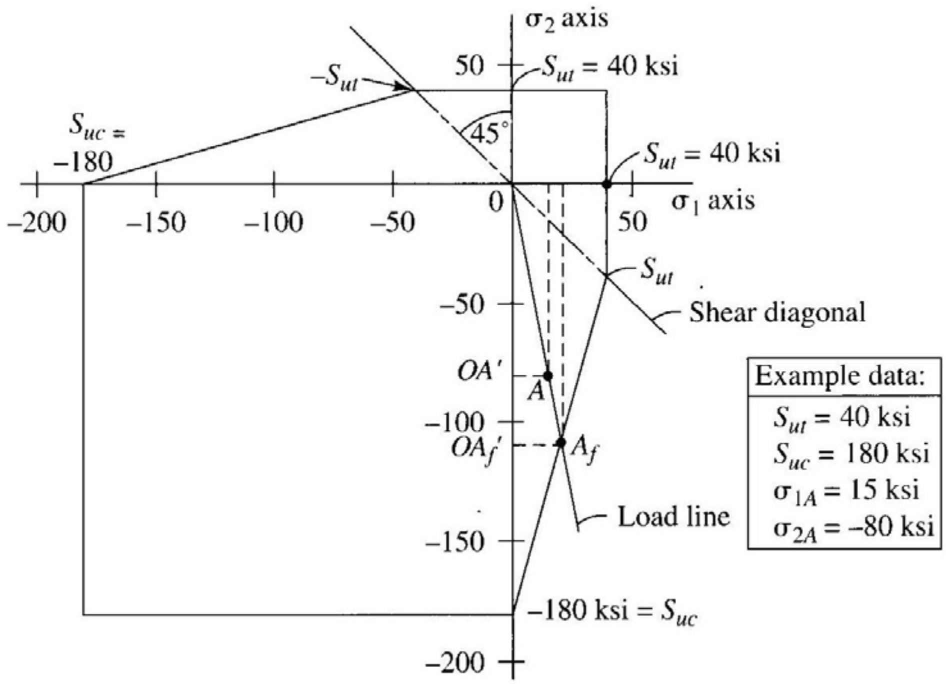

Figure 3 Graphical View of Modified Mohr's Theory (Mott)

In the spring 2008 semester, we changed to use the CAD system to implement the graphical method. Excellent agreement between the algebraic method and the graphical method resulted. Below is the CAD drawing that we use to teach the method is the classroom. In the CAD drawing, point A is the current stress state, and the design factor of safety is the length of OA_f over the length of OA.

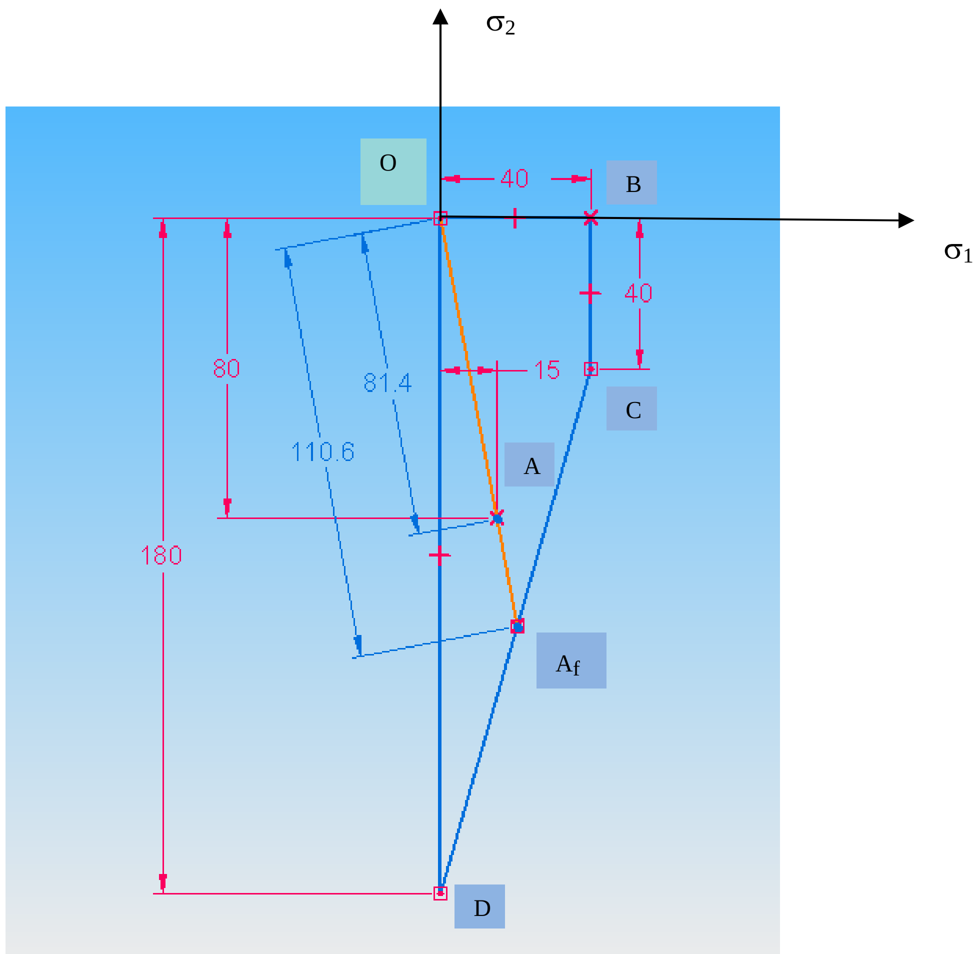

Figure 4 CAD for Modified Mohr Theory

The implementation steps in the example are as follows:

1. Draw a σ_1- σ_2 coordinate system.
2. Draw a strength line polygon OBCD, according to the maximum-normal-stress theory and the Modified Moore theory.
    - OB = the material ultimate tensile strength $s_{ut,}$ which is 40 kpsi in this example

- BC = s_{ut}
- OD = the material ultimate compressive strength s_{uc}, which is 180 kpsi in this example

3. Draw point A to represent to the current stress state of the point under study. In this example, point A has
   - σ_1 = 15 kpsi
   - σ_2 = -80 kpsi
4. Draw a line from O to A; extend the line until it meets with CD. Point A_f is the intersection of extension of OA with line CD.
5. The design factor of safety is
   - N = OA_f / OA

Moreover, we have extended the graphical method to a number of other fatigue failure theories. Below as an example is a student's homework.

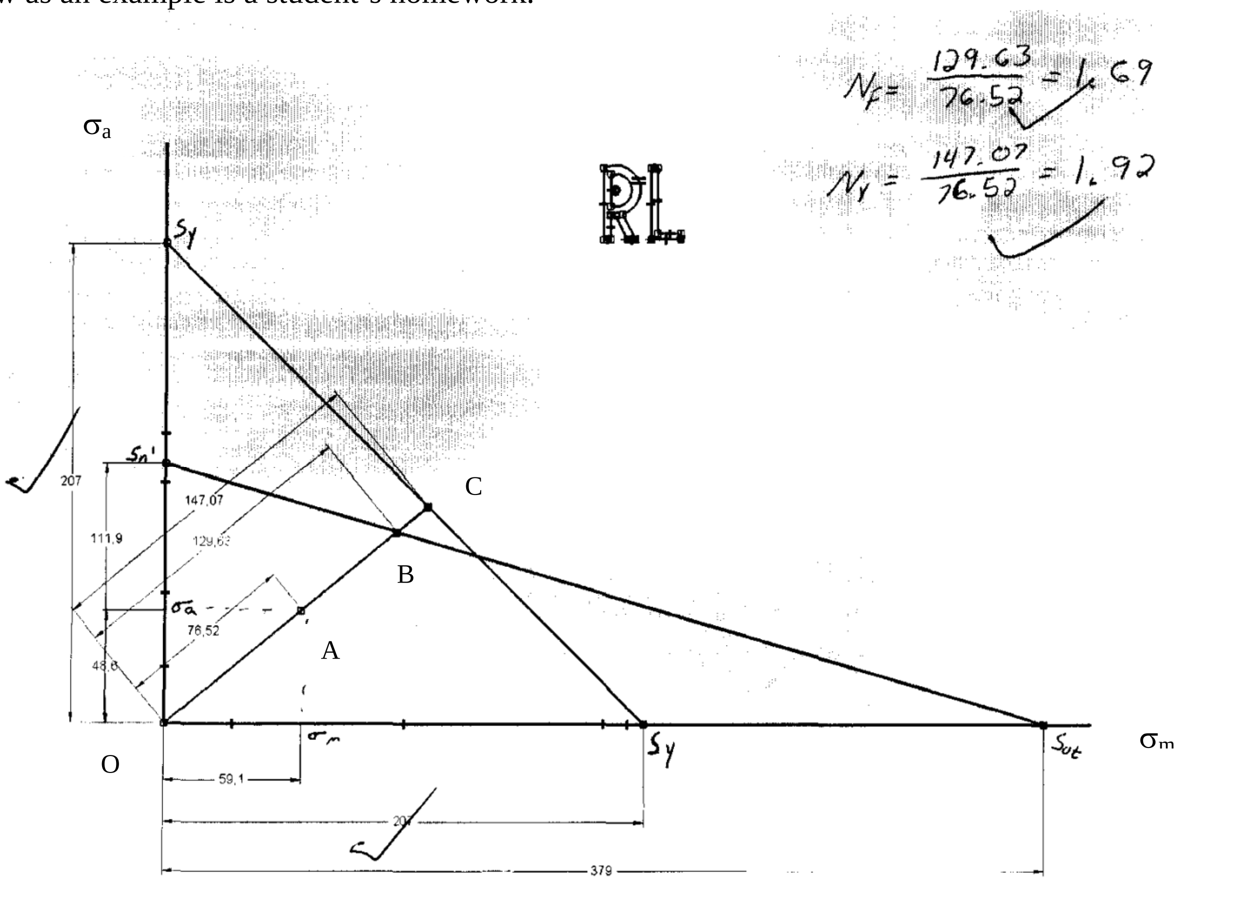

Figure 5 Student's CAD Work for Fatigue Design

In this student's homework for fatigue design

- σ_m - σ_a coordinate system is used
- The line from the s_y point on the σ_m axis to the s_y point on the σ_a axis is the yield strength line
- The line from the s_{ut} point on the σ_m axis to the s_n' point on the σ_a axis is the fatigue strength line
- Point A is current stress state of the point under study
- N_f, factor of safety against fatigue = OB / OA
- N_y, factor of safety against yielding = OC / OA

Most students learned to apply the graphical method very well. The average grade of the graphical homework assignments is about 85%. The students would do even better when we give a handout of the CAD construction to the students in the spring of 2009.

A survey of students has been conducted on the helpfulness of the CAD method with their learning of the failure theory. The survey question is this: the graphical method for the modified Moore theory of predicting brittle failure helps me with a better understanding of the failure theory. The choices are

5 -- strongly agree
4
3
2
1 - strongly disagree

The responses are

20% - choice 5
40% - choice 4
40% - choice 3

which has an average of 3.8.

References:

1. Mott, Robert L. Machine Elements in Mechanical Design, Prentice Hall
2. Shigley, Joseph E. and Charles R. Mischke, Mechanical Engineering Design, McGraw-Hill
3. Juvinall, Robert C and Kurt M. Marshek, Fundamentals of Machine Component Design, Wiley.
4. Solid Edge, Siemens

Zhongming (Wilson) is associate professor of mechanical engineering technology. He has been with Purdue University Fort Wayne since 1987. He had his graduate studies at Steven Institute of Technology.