# APPLIED FATIGUE AND FRACTURE MECHANICS: A MECHANICS COURSE FOR MECHANICAL ENGINEERING TECHNOLOGY

**Michael A. Magill**
**Purdue University**

## ABSTRACT

The purpose of this paper is to provide an overview of a new course at Purdue University. The course is entitled "Applied Fatigue and Fracture Mechanics" and is offered by the School of Technology. This course emphasizes applied principles such as predicting failure loads on flawed structures, brittle fracture, predicting time to failure due to fatigue loading on cracked and uncracked structures, designing to prevent failure, analyzing stress corrosion cracking, and conducting ASTM standard tests. An outline of course topics and laboratory projects is included in this paper along with detailed highlights of effective course activities. This paper demonstrates that the topics of fatigue and fracture mechanics fit well with the mechanical engineering technology (MET) curriculum and the MET student.

## BACKGROUND

The course has two primary components: fatigue and fracture mechanics. This section provides a brief description of these two topics.

The term *fatigue*, in the engineering sense, means the mechanical fatigue of materials. All structural materials (i.e. metals, timber, concrete, plastic, etc.) have an inherent strength to resist loading. Under static loading these materials are very strong. Yet, much like the human body, structural materials become "tired" or fatigued from repeated loading and ultimately will fail at much lower loads. An excellent illustration of this is a coat hanger. The static force required to break a coat hanger is large but if we repeatedly bend the coat hanger back and forth it easily breaks due to material fatigue.

The other topic, *fracture mechanics*, is that segment of solid mechanics concerned with the failure of flawed and brittle materials. Most MET students' understanding of mechanics is based entirely on the principles of strength of materials. Often, however, strength of materials does not accurately describe a material's failure. Frequently, a structure will fail in a brittle manner or because of crack formation. Using the strength of materials approach for predicting structural failures, the applied stress is compared to the yield or tensile strength of the material. The fracture mechanics approach for predicting failure is similar. This approach requires quantifying the relationship between the applied stress and the flaw size. Then the result is compared with the fracture toughness of the material. In fracture mechanics the applied stress and flaw size together constitute the "loading" while the fracture toughness is the material "strength".

## COURSE MOTIVATION

Most industries that employ MET graduates develop, manufacture, or use products that experience dynamic loading (e.g. automobiles, aircraft, pumps, engines, hydraulics, etc). When mechanical failures occur they often can be attributed to fatigue since rarely are mechanical components just statically loaded. The principles associated with mechanical fatigue are not that complicated and are appropriate for mechanical technologists.

The fracture mechanics approach to analysis and design is foreign to most engineering technologists. For many industries, however, fracture mechanics is an integral part of their mechanical analysis. As an example, both the commercial and military aircraft industries, are flying many aircraft beyond their design life. Maintaining the structural integrity of these aging airplanes presents enormous challenges. As another example, the automotive industry continues to seek ways to prevent mechanical failures caused by crack formation and brittle fracture. Also, the offshore structure industry also faces many challenges in the fracture mechanics field. Repetitive wave action on offshore structures causes fatigue cracking. Proper fracture mechanics analysis of these structures can produce large savings.

The areas of fatigue and fracture mechanics provide excellent employment opportunities for mechanical engineering technology graduates. With the increased use of composite materials, high strength materials and lightweight materials, fatigue and fracture mechanics opportunities will continue to emerge. Fracture mechanics is a relatively new field and is rapidly growing. It is rare that a new field or area of expertise emerges with such a clear-cut opportunity for engineering technology. [1]

## METHODOLOGY

The primary objective of this course is to provide students with an understanding of fatigue and fracture mechanics. The course is applied in nature with several laboratory experiments and field trips. Other hands-on activities include case studies, failure analysis projects, and a final major project.

The course is three credit hours and is taught with two hours of lecture and two hours of lab each week. It is a graduate course but easily could be modified to be an elective senior level course. The prerequisites for the course are statics, strength of materials, metallurgy, and differential/integral calculus. Student preparation for this type of course does not require any additional coursework beyond the typical baccalaureate curriculum.

The textbook used for this course is <u>Mechanical Behavior of Materials</u> [2]. Originally, <u>Fracture and Fatigue Control in Structures</u> [3] was used. Both texts are appropriate for engineering technology students. <u>Mechanical Behavior of Materials</u> does an outstanding job of reviewing strength of materials and transitioning to the concepts of fracture mechanics. The <u>Fracture and Fatigue Control in Structures</u> text has an applied approach and gives many empirical tables and graphs. Another book that is frequently used as a reference is <u>Deformation and Fracture Mechanics of Engineering Materials</u> [4]. This book is much like <u>Mechanical Behavior of Materials</u> but more comprehensive. Supplemental materials also are provided on the topics of shot peening, finite elements analysis of cracks, stress intensity factor tables [5], and ASTM Standards [6].

## COURSE CONTENT AND STRUCTURE

The course has two primary topics, fatigue and fracture mechanics. The emphasis is on applied principles such as predicting failure loads on flawed structures, predicting time to failure due to fatigue loading on cracked and uncracked structures, designing to prevent failure, analyzing stress corrosion cracking, and conducting ASTM standard tests. There are several secondary topics such as shot peening, nondestructive inspection, and finite element analysis of cracks. Table 1 gives an outline of the course content and structure.

The lecture sections follow the traditional lecture format. The lectures are mixed with an occasional group or individual analysis of a mechanical failure. Three videos are shown during the semester to supplement those topics that are difficult to illustrate in the laboratory. The videos used are Fracture Toughness: Its Role in Engineering Design [7], Principles of Failure Analysis: General Procedures for Failure Analysis [8], and Principles of Failure Analysis: Types of Failure and Stress [9]. There are several excellent videos on fatigue and fracture available.

Several types of course assignments are given. Most assignments contain short analytical problems from the end of each chapter, much like a strength of materials course. Some of the assignments require an essay solution to various types of fatigue and fracture mechanics situations. Several of the assignments are case study projects analyzing different mechanical failures. A major final project involving an analytical and experimental component is required.

The class laboratory assignments vary in format. Some assignments are conducted as a group demonstration while others are individual student experiments. A written report is required after all of the labs. Most of the lab tests follow an ASTM Standard.

The course includes three field trips to local industries. One of the field trips is to a facility that performs shot peening. This tour gives the students an opportunity to see a manufacturing process for preventing crack formation. Another field trip is to a laboratory that performs various methods of nondestructive crack inspection. During this short two hour tour the students are introduced to the most common inspection techniques used in industry. The third field trip is to a company that uses fracture mechanics methods for product design and failure prevention. The students get see fracture mechanics used in real life applications.

## HIGHLIGHTS OF EFFECTIVE COURSE ACTIVITIES

1. One effective course activity is to have students bring example failures from home and work. The author’s approach is to have the class perform a failure analysis on each example as a group. When the class is primarily mature graduate students and seniors this format is very productive. Some example failures examined thus far include a jack-hammer bit, brake backing plate, bicycle frame, doorstop lever arm, transmission gears, bicycle axle, and fatigue specimens from an industrial research project.

2. The laboratory experiments help solidify the lecture topics plus give the course an applied flavor. The compact tension test for determining material fracture toughness fits well as one of the first experiments. This experiment dramatically illustrates to students the catastrophic nature of a brittle failure and that it can occur well below the yield strength. Another intriguing experiment is the fatigue crack propagation test. In this experiment the students calculate the predicted time to failure from the principles learned in lecture. These concepts become more meaningful to the students after seeing an actual fatigue failure.

3. The field trips are very successful and help the students connect with industry on these topics. The experience of seeing engineers deal with real-life fatigue and fracture problems leaves a lasting impression.

4. The final project gives students an opportunity to independently attempt a full-scale mechanical analysis. These projects have proven successful with several creative problems. A sample of intriguing final projects include a fracture mechanics analysis of rock climbing carabiners, S-N curve of coat hanger failure, fatigue failure of piston rods, brittle fracture of a telescope bracket, and fracture of a bike frame.

5. Videos do an excellent job of communicating the concepts and supplementing the regular lectures and laboratory experiments. The best videos can be expensive, however. The videos used in this course range between $80 and $300.

6. The laboratory equipment required to properly run the experiments is costly. An axial fatigue machine costs around $100,000. Several of the fatigue experiments can be modified to use a simple rotating fatigue machine. If the proper equipment isn't available some of the experiments can be done creatively with hypothetical data.

## CONCLUSION

A new course in "Applied Fatigue and Fracture Mechanics" is being successfully taught at Purdue University. The course has a strong emphasis on applied principles. The topics and principles of fatigue and fracture mechanics are well suited for the mechanical engineering technology curriculum and the mechanical engineering technology student. Following completion of this course, students are better prepared to tackle the mechanical failure problems that they will encounter in industry.

## REFERENCES


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## MICHAEL MAGILL

Michael Magill is an Associate Professor in Mechanical Engineering Technology at Purdue University. Prior to 1995 he was on the Engineering Technology faculty at Oklahoma State University for eleven years. In the summers he works as a structural inspector on major construction projects. He received his B.S. and M.S. degrees in Mechanical Engineering and his Ph.D. in Civil Engineering--all from Oklahoma State University. He is a registered professional engineer and has received numerous teaching awards.

| ***PERIOD*** | ***TOPIC*** |
|---|---|
| 1 | Introduction/Historical Background |
| 2 | Review Strength of Materials/Metallurgy |
| 3 | **LAB** (Introduction & Guidelines) |
| 4 | Introduction to Fracture Mechanics |
| 5 | Stress Analysis Cracked Members – Linear Elastic Fracture Mechanics |
| 6 | **LAB** (Tensile Test: Notch Toughness Testing) |
| 7 | Stress Intensity Factor (SIF) Calculations |
| 8 | Stress Intensity Factor (SIF) Calculations |
| 9 | **LAB** (Lecture on Crack Tip Opening Displacement (CTOD)) |
| 10 | Resistance Force/ASTM Standard Tests |
| 11 | ASTM Standard Tests/ASTM Test Specimens |
| 12 | **LAB** (Charpy V Notch Test (CVN), ASTM E23) |
| 13 | Fracture Toughness Effects: Temperature & Loading Rate |
| 14 | Fracture Toughness Effects: Constraint |
| 15 | **EXAM #1 / LAB** (Compact Tension Test (CPT), ASTM E399) |
| 16 | Correlating Fracture Mechanics & Fracture Mechanics Test Results |
| 17 | Fracture Mechanics Design vs. Traditional Design Approach |
| 18 | **LAB** (CPT: Thick Plate vs. Thin Plate – Plane Strain Study) |
| 19 | Introduction to Fatigue |
| 20 | Fatigue Tests |
| 21 | **LAB** (Fast Load Rate vs. Slow Load Rate) |
| 22 | Fatigue Crack Initiation |
| 23 | Fatigue Crack Propagation (FCP) |
| 24 | **LAB** (Field Trip – Nondestructive Crack Inspection Laboratory) |
| 25 | FCP: Effects of Mean Stress, Frequency, & Stress Concentrations |
| 26 | Fatigue and Fracture Behavior of Welded Components |
| 27 | **EXAM #2 / LAB** (Fatigue CPT, ASTM E647) |
| 28 | Corrosion Fatigue |
| 29 | Corrosion Fatigue |
| 30 | **LAB** (Corrosion Crack: Wedge Opening Loading Specimen (WOL)) |
| 31 | Mixed Mode Loading |
| 32 | Finite Element Method to Calculate Stress Intensity Factors |
| 33 | **LAB** (Finite Element Method) |
| 34 | Fracture and Fatigue Control |
| 35 | Fracture and Fatigue Control |
| 36 | **LAB** (FCP: Mixed Mode - Slanted Edge Crack) |
| 37 | Shot Peening |
| 38 | Shot Peening |
| 39 | **LAB** (Field Trip – Shot Peening) |
| 40 | Fracture Criteria/Fitness for Service |
| 41 | **EXAM #3** |
| 42 | **LAB** (Field Trip – Fracture Mechanics Analysis and Design) |
| 43 | Project Presentations |
| 44 | Project Presentations |
| 45 | **LAB** (Project Presentations) |

Table 1. Outline for Applied Fatigue and Fracture Mechanics course