INNOVATIONS IN TEACHING FRACTURE MECHANICS

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Abstract

An elective course on fracture mechanics is planned to be introduced for the undergraduate students of mechanical engineering. At the present time, some of the topics on fracture mechanics are covered in a course on selection of materials. The present paper discusses specific teaching methods and relevant experimental methodologies for learning fracture mechanics. A proposed syllabus on fracture mechanics is presented. The basic objective of teaching is directed in the following areas of fracture mechanics; basics of fracture mechanics, an ability to relate principles of fracture mechanics to real world applications, and case studies on fracture mechanics applications. Teaching tools discussed in this paper include; cooperative learning, competency based curriculum, discussion based model approach, lecture quiz approach, and other related methods. The course objectives, course methodologies and learning objectives for fracture mechanics course are also discussed. The specific experimental procedures for carrying out the fracture toughness tests and related microstructure analysis are introduced. The direct benefits of experimental exercises in fracture mechanics to materials science/mechanical engineering education have been discussed. The basic/primary objective of these experiments is to give students the hands-on experience. Furthermore, more emphasis is given for improving students’ learning skills and creative thinking by having small group discussions and frequent quizzes on laboratory exercises.

Keywords: Fracture mechanics course; Teaching methods; Laboratory methods; Fracture toughness testing and microstructure analysis.

1. Introduction

A new elective course on fracture mechanics is proposed to be introduced for the undergraduate students in mechanical engineering. Mechanical engineering undergraduates typically study courses like statics, dynamics, introduction to solid mechanics, and engineering mechanics in addition to materials science courses where they get introduced to some of the basic concepts of fracture mechanics and principles. Fracture of engineering materials is one of the oldest fields of investigation for material designers and engineers of mechanical, civil, automotive, naval, and aerospace structures. Now, it is very well established that the ignorance/neglect of the
application of fracture mechanics can be disastrous; since classical design (allowable stress method) based on a fraction of yield strength of the material is not sufficient. The development of new materials and the increased complexity of engineering structures operating in extreme service conditions require an understanding of fracture mechanisms and the development of predictive models for long-term strength and reliability assessment. Thus, it is very essential for mechanical engineering undergraduates to study a course on fracture mechanics.

The teaching styles and modalities used by most engineering faculty are usually based on observation and common sense, and perhaps even familiarity with the "scientific method," which may be a good intuitive model for teaching and learning. Upon close examination of the literature on effective teaching, one quickly recognizes that while "good teaching can be described and evaluated, the art and science of teaching remain in a primitive state of development". However, the combination of selected fundamental principles with existing or emerging teaching technologies can be beneficial for improving the quality of learning and teaching in the classroom. In this paper, some of the classroom teaching and laboratory methods have been discussed. Methods of course assessment are also considered that improve the teaching and learning of fracture mechanics course.

2 Undergraduate elective course on fracture mechanics

Typical components of an undergraduate course on fracture mechanics include; course objectives, learning objectives and course methodology as described below.

2.1 Course objectives

This course familiarizes the student with relevant fracture mechanics concepts, procedures for understanding materials behavior with respect to short and long fatigue cracks. This course provides an understanding of various factors including metallurgical factors that control the fracture resistance of engineering alloys and that should help to develop a facility with the methods of predicting the failure of structural components. Based on an understanding of the mechanisms controlling the strength and fracture resistance of structural materials, this course seeks to develop an appreciation of the procedures used to make rational choices in the selection of materials for structural applications.

2.2 Learning objectives

Upon successful completion of this course, the student will be able to:

- Explain the basic concepts of fracture mechanics for both linear elastic and elastic-plastic regimes.
- Describe the fracture mechanics characterization of fatigue crack growth sustained load fracture and dynamic crack growth.
- Identify various fracture mechanisms and explain the influence of material behavior on fracture mechanics characterization of crack growth.
- Identify initiation and growth of short fatigue crack growth.
• Test for fracture toughness parameters viz. K, G and J.
• Relate principles of fracture mechanics to real world applications.
• Investigate case studies on fracture mechanics applications
• Understand fracture mechanisms and crack growth behavior, the relationships to metallurgical and environmental factors, and to apply these concepts to the prediction of failure.

2.3 Course methodology

The instruction for this course is of an interactive lecture style format. A series of guest lectures increase the breadth of knowledge presented. The first half of the semester concentrates on basic concepts of elastic, elastic-plastic fracture mechanics. The second half of the semester focuses on fracture toughness testing principles, methods of metallographic examination. The following are the typical course contents of fracture mechanics.

• **Introduction**: Significance of fracture mechanics and overview.
• **Linear elastic fracture mechanics**: An elastic stress field approach, crack tip plasticity, the energy balance approach, LEFM testing.
• **Elastic-plastic fracture mechanics**: Basic aspects of elastic-plastic fracture mechanics, EPFM testing, Failure assessment using EPFM.
• **Fracture mechanics concepts for crack growth**: Fatigue crack growth, Sustained load Fracture, Dynamic crack growth and arrest.
• **The energy of fracture**: Griffith’s theory of fracture.
• **A Stress field theory of fracture**: Principles and FEM analysis
• **Experimental methods for K and J determination**: Principles and ASTM test methods
• **Fracture toughness testing and applications**
• **Fatigue and creep-fatigue interactions**: Basic principles and experimental methods
• **Designing against fracture**: Typical case studies to demonstrate application of design curves to prevent premature/catastrophic fracture.

3. Teaching methods

Classroom teaching methods specifically discussed for fracture mechanics course are; cooperative learning, active-learning approach, discussion model approach, lecture quiz approach, brainstorming, small group discussion, case studies, and report-back sessions.

3.1 Cooperative learning

The basic meaning of the word cooperation is to work together to accomplish shared goals. In cooperative activities individuals seek outcomes that are beneficial to themselves and beneficial to all other group members. In other words, cooperative learning is the instructional use of small
groups so that students work together to maximize their own and each other's learning. Class members are organized into small groups after receiving instruction from the teacher and they work through the assignment until all group members successfully understand and complete it. Cooperative efforts result in participants striving for mutual benefit so that all group members gain from each other's efforts. In cooperative learning, students perceive that they can reach their learning goals if and only if the other students in the learning group also reach their goals.\(^4\,\!\!^5\)

Students' learning goals usually structured to promote cooperative, competitive, or individualistic efforts. In competitive situations, students work against each other to achieve a goal that only one or a few can attain. In competition there is a negative interdependence among goal achievements; students perceive that they can obtain their goals if and only if the other students in the class fail to obtain their goals.\(^5\) In individualistic learning situations students work alone to accomplish goals unrelated to those of classmates and are evaluated on a criterion-referenced basis. The positive benefits of cooperative learning compared with competitive and individualistic efforts are; (a) higher achievement and greater productivity, (b) more caring, supportive, and committed relationships, and (c) greater psychological health, social competence, and self-esteem.

The essential components of cooperation are positive interdependence, face-to-face promotive interaction, individual and group accountability, interpersonal and small group skills, and group processing.\(^6\) Systematically structuring those basic elements into group learning situations helps ensure cooperative efforts and enables the disciplined implementation of cooperative learning for long-term success.

The following FIVE basic components/elements that are important for the successful practicing of cooperative learning will be introduced for the fracture mechanics course.

**Positive interdependence**

Positive interdependence is successfully structured when group members perceive that they are linked with each other in a way that one cannot succeed unless everyone succeeds. The positive outcomes of interdependence are; (a) each group member's efforts are required and indispensable for group success and (b) each group member has a unique contribution to make to the joint effort because of his or her resources and/or role and task responsibilities.

**Promotive interaction**

Students need to do real work together in which they promote each other's success by sharing resources and helping, supporting, encouraging, and applauding each other's efforts to achieve. There are important cognitive activities and interpersonal dynamics that can only occur when students promote each other's learning. This includes orally explaining how to solve problems, teaching one's knowledge to others, checking for understanding, discussing concepts being learned, and connecting present with past learning.

**Individual and group accountability**

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Two levels of accountability must be structured into cooperative lessons. The group must be accountable for achieving its goals and each member must be accountable for contributing his or her share of the work. Students learn together so that they subsequently can gain greater individual competency.

*Teaching students the required interpersonal and small group skills*

Cooperative learning is inherently more complex than competitive or individualistic learning because students have to engage simultaneously in task work (learning academic subject matter) and teamwork (functioning effectively as a group)

*Group processing*

In group processing, group members discuss how well they are achieving their goals and maintaining effective working relationships. Continuous improvement of the processes of learning results from the careful analysis of how members are working together and determining how group effectiveness can be enhanced.

### 3.2 Active learning approach

In the context of the classroom, "active learning" may be defined as anything that *involves students in doing things and thinking about the things they are doing*. When active learning activities include the use of technology (e.g., multimedia applications), it is advisable to keep in mind that technology "tools" must be used in the framework of knowledge of learning and teaching for a particular application. Active learning approach consists of integrating innovative laboratory techniques with computer modeling and visualization tools to create an interactive and collaborative team-oriented environment for students to dynamically participate in their own learning. The goal of the "active learning" curriculum is to create an effective learning environment where students enjoy "hands-on" experiences through laboratory experiments and computer simulations and illustrations. In general, most students in sciences and engineering have difficulty in mastering fundamental concepts and basic principles; one possible reason for this deficiency in student learning may be that the classical lecture-mode of teaching by itself is not sufficient for students to grasp basic concepts. When learning advanced materials, it is important for students to develop physical visualization and conceptual understanding of the material structure at several levels (microstructure, constituents, and lay-up assemblies) and their properties and behaviors (orientation-dependent properties due to anisotropy).

### 3.3 Discussion model approach

This approach is a deviation from the conventional classroom lectures to engage students actively in the class. A discussion model is used to understand and interpret the topics of fracture mechanics. This model aims to make small-group discussion more meaningful and effective in light of growing class sizes. Typical class size is 20. The course structure involves 3-hr class discussions that compliment 3 hr weekly lectures. During each session, the 20 students’ discussion group is divided into subgroups of 5 students; each sub-group is given 1 or 2 topics
(under which specific problems are highlighted) to discuss. After about 15 minutes of preparation, the sub-groups are encouraged to debate/discuss the issues with each other; the professor acts as a discussion facilitator and summarizes key issues raised during the 3-hr discussion. Another more important consequence is that the teaching method should shift in emphasis from passive lecturing to mentoring and small group tutorials. Small group tutorials would also enable students to participate more actively in group discussions and further develop their listening and speaking skills.

3.4 Lecture quiz approach

The class-room lectures on fracture mechanics topics include several lecture quizzes as a continual assessment component. The main aim of the lecture quiz is to let the lecturer have a better gauge of whether the students have grasped the main concepts/principles taught in each lecture on specialty topics relating to fracture mechanics. Typically, 15-20 short questions (demanding specific answers) in the form of multiple-choice, true/false or computation are asked in each lecture quiz. Students are allowed to discuss the questions and hand in the answers in small groups. It also promotes cooperative learning among the students as well as allows them to relate to and reflect instantly on what they have just learned.

3.5 Brainstorming

In brainstorming, listening exercise that allows creative thinking for new ideas and encourages full participation because all ideas equally recorded. In the classroom brainstorm sessions are encouraged during every week of lectures. It also draws on group's knowledge and experience. Facilitator (instructor/professor) is the one who normally selects the topic/issue for brainstorming.

3.6 Small group discussion

Small group discussion allows participation of everyone and people often feel more comfortable in small groups. The basic requirement for the successful application of a small group discussion is that the moderator needs to prepare specific tasks or questions for group to answer.

3.7 Case studies

Case studies are considered for several topics of fracture mechanics to develop analytic and problem solving skills that allows for exploration of solutions for complex issues. This also allows student to apply new knowledge and skills.

4. Laboratory experimental methods for learning fracture mechanics

Fracture mechanics laboratory is aimed at conducting experiments to give hands-on experience for students in the area of fracture toughness, failure analysis, and fracture prediction. These include the development of fracture mechanism maps for advanced materials. Materials included are biomaterials, smart materials, polymers and their composites, ceramics and ceramic
composites, carbon-carbon composites. Studies in these materials are motivated by their potential use in advanced industrial applications. Mechanical tests include tensile, fracture toughness, and microhardness tests. The characterization tools include optical and electron microscopy. The results of understanding and modeling fracture phenomena find applications in:

- Ranking materials with respect to fracture resistance and reliability
- Optimization of material morphology for enhanced fracture and fatigue resistance
- Quantitative evaluation of long-term strength and reliability of structures

4.1. Educational contribution of experiments

Instructional lectures on each experimental method (in a group of maximum 5 students) are given during each group’s laboratory classes. Each group has one laboratory class of 3 hrs duration per week. The ultimate goal of these practical exercises is to provide hands-on experience for students in understanding and analyzing mechanical properties and microstructures in advanced materials. These also include, teaching learning skills and creative thinking during experimental projects/exercises.

Teaching learning skills

The acquisition of process skills, i.e. learning how to learn, is equally important, if not more important, than the acquisition of knowledge itself. Process skills refer to the abilities to source, analyze, screen, prioritize and apply a mass of information to solve the problem at hand.

Teaching creative thinking

Small group discussions are conducted to improve creative thinking skills. Creative thinking is especially important in formulating problems and exploring alternative methods.

4.2. Tensile test

Three tensile tests are carried out by each group of students. The tensile tests on engineering materials are performed using a microprocessor controlled UTM. Standard pulley-fixtures are used for tensile testing thin metallic wires. The load–displacement curve is obtained to evaluate various tensile parameters.

At the end of the test, students get hands-on experience on the machine and the knowledge to determine design stress (proof stress/yield strength/tensile strength), stiffness, toughness, and ductility of a given engineering material.

4.3. Three-point bend test for fracture toughness

Three fracture toughness tests are carried out by each group of students. Three-point bend test is carried out using an UTM (Universal Testing Machine). Plane strain fracture toughness (KIC) is a materials parameter of considerable engineering significance. The American Society for Testing
Materials (ASTM) has developed detailed procedures for determining $K_{IC}$. Frequently, a standard compact test (CT) specimen is used to experimentally determine the fracture toughness of materials. The critical value of $K$ at fracture is calculated using the expression:

$$K_{IC} = \left( \frac{P_f}{BW^{1/2}} \right) f(a/w)$$

$P_f$ is the fracture load, $B$ is the specimen thickness, $W$ is the specimen width, and $f(a/w)$ is a calibration function/correction factor. Variations of this procedure are recommended for polymers, ceramics and very thin metallic wires where the considerations for loads, rates and gripping are quite difficult. To obtain toughness values for very thin materials, a test very similar to the hardness test is frequently used.

At the end of this exercise, the students are able to learn the skills of carefully initiating and propagating a crack till fracture. In addition, the students are able to appreciate the effect of material thickness on fracture toughness (plane stress and plane strain conditions) of a material.

4.4. Microhardness test procedure for determining fracture toughness in brittle materials

Ten microhardness measurements are carried out by each group of students. Knoop microhardness test is used particularly for very thin layers. The long diagonal is seven times as long as the short diagonal. With this indenter shape, elastic recovery can be held to a minimum. The Knoop test is conducted in the same manner, and with the same tester, as the Vickers test. However, only the long diagonal is measured, except for the projected area hardness (PAH) test. The Knoop hardness is calculated from:

$$HK = \frac{14.2L}{d^2}$$

Where the load $L$ is in Kgf and the long diagonal $d$ is in µm.

In the present study, microindentation studies were performed for determining the fracture toughness of a biomaterial like Ti-6Al-4V/Vitallium alloy/stainless steel. In this technique, microindentations were made on the polished surface of a wire using a diamond indenter. As a result, the cracks are formed at the corners of the indent marks. The size of the cracks were measured, and from the knowledge of the stress intensity parameter for this geometry (obtained from standard tables), reasonable estimates of the fracture toughness were obtained.

This specific test gives an opportunity for students to determine fracture toughness through microhardness tests by correlation method.

4.5. Optical and electron microscopy

Students are given the hands-on experience in learning the basic principles, methods, and operation of these microscopes. Optical microscope is used for characterizing the microstructures while electron microscope is utilized for understanding the basic modes (ductile/brittle/fatigue/etc.,) of fracture in materials.
5. Methods of assessment

The following methods are used to assess student performance and the effectiveness of the course in both lecture and laboratory classes.

5.1 Assessment of students’ performance\textsuperscript{10, 11}

Students are assessed in the following areas of fracture mechanics.

- Basics of fracture mechanics
- An ability to relate principles of fracture mechanics to real world applications
- Case studies on fracture mechanics applications

To effectively assess the above three components of learning by the students, the following criteria\textsuperscript{12} are used.

- an ability to apply knowledge of mathematics, science, and engineering (ABET Criterion 3a)
- an ability to design and conduct experiments, as well as analyze and interpret data (ABET Criterion 3b)
- an ability to design a system, component, or process to meet desired needs (ABET Criterion 3c)
- an ability to function on multidisciplinary teams (ABET Criterion 3d)
- an ability to identify, formulate, and solve engineering problems (ABET Criterion 3e)
- an ability to communicate effectively (ABET Criterion 3g)
- integration of subject matter, concepts, issues and principles including to subject matter covered previously

Typical laboratory quizzes, each of about 15 min (with about 15 questions) is given at the end of each laboratory experiment/exercise. These are usually multiple choice type questions to evaluate students’ understanding/perception of each experiment. A small group technical discussion is encouraged at the end of each experiment to refresh student’s understanding/perception. Students of each group are required to turn-in their written laboratory report before the commencement of next experiment. At the end of the course, individual as well as cumulative performance of students is evaluated based on the above mentioned criteria.

5.2 Evaluation of laboratory experiments

The following criteria\textsuperscript{12} are used to evaluate/rate each laboratory experiments:

- The lab seemed to be well thought out.
- The lab was properly set up beforehand.
- Lab handouts were well prepared and clear.
- Handouts were available on time.
- The experiment was interesting.

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Questions and problems were reasonable.
Data from labs were available on time
The effort was educational and instructive.

These evaluations are made every month to assess the progress of laboratory experiments. Regular feedback from the students on each of those experiments was also collected to supplement the evaluation/rating process.

5.3 Lecture course assessment process

The faculty member teaching fracture mechanics course is recognized as an expert for the course subject matter and is relied on to develop appropriate tools for assessing each of the course learning objectives. The assessment tools used are; homework, term project, laboratory reports, quizzes, testing, small group discussions are used. For the lecture classes, students are given three tests (one each month) and a comprehensive final exam besides a project work (includes written report and oral presentation during the last two weeks of each semester) on selected topics of fracture mechanics at the end of the semester.

The instructor is expected to determine if the students satisfactorily achieve the course learning objectives. The instructor is only asked to determine how many students satisfactorily achieve each objective. It is assumed that instructors will continually consider proactive course improvements that will more effectively present course material even if the minimal levels are achieved. However, if these levels are repeatedly not achieved it is assumed that either student preparation, or prerequisite course requirements, should be improved. In other words, if the course coverage is overly ambitious, and the number of course learning objectives should be reduced.

6. Summary

Cooperative learning, active learning approach, discussion model approach, lecture quiz approach and other relevant classroom teaching methods are considered very effective for teaching and learning fracture mechanics topics. Specifically designed laboratory experiments enable students to appreciate the basic and practical concepts of fracture mechanics and also gain hands-on experience. In teaching fracture mechanics, special emphasis is given on basics and principles of fracture mechanics to real world/modern applications. Several case studies discussed during classroom teaching sessions on fracture mechanics applications are towards meeting those objectives.

Bibliography


**Biography**

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