FINITE ELEMENT LEARNING MODULES FOR FATIGUE ANALYSIS

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Mechanical Engineering

By

Joshua A. Coffman
Arkansas Tech University
Bachelor of Science in Mechanical Engineering, 2006

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University of Arkansas

ABSTRACT

A fatigue finite element (FE) learning module was developed for use in an undergraduate machine design course. The commercial FE software ANSYS® was used. The module assumes that a student has a basic knowledge of fatigue. The design of the module was based on student learning experience progression described in the Kolb Cycle. The design of the module was also assessed to have no bias for learning styles (Felder-Soloman) and personality types (Myers-Briggs) for typical engineering students. The fatigue FE learning module was assessed using post survey, pre-quiz, and post-quiz in an undergraduate machine design course. Based on assessment results for the pre- and post-quizzes, a multiple-choice checklist form was created based on educational measurement literature to improve quiz quality. The effectiveness of the checklist form was evaluated by assessing the quality of the quizzes developed by instructors for an undergraduate introduction to mechanics course. An experimental group of instructors used the checklist form to write a new quiz, and a control group of instructors wrote a new quiz based only on professional experience. The quizzes from each group were assessed through independent reviewers consisting of engineering faculty and graduate students. The checklist form appears to be a valuable tool for an instructor to develop new multiple-choice quizzes. Three chapters of this thesis were published in the proceedings of three separate American Society of Engineering Education conferences. The fatigue FE learning modules can be found at http://www1.pacific.edu/~abrown/ASEE/.

This thesis is approved for
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Thesis Director:

____

Dr. Joseph J. Rencis, Professor and Head

Thesis Committee:

____

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____

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DEDICATION

This thesis is dedicated to my family, whose sacrifices and hard work through the years have allowed me to concentrate on my studies. It is through their encouragement that I have made my accomplishments.

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Chapter 3: Coffman, J., Liu, J., Brown, A.O., Terdalkar, S., and Rencis, J.J., "Finite Element Learning Module for Improving Knowledge of Fatigue using Commercial Software," *CD-ROM Proceedings of the American Society for Engineering Education (ASEE) Middle Atlantic Section Conference,* University of Loyola, Baltimore, MD, April 24-25, 2009.

Chapter 4: Coffman, J., Rencis, J.J., Jensen, D., Brown, A.O, Liu, J., Kaufman, K., and White, C., "Process for Writing, Revising, and Assessing Multiple-Choice Quizzes," *CD-ROM Proceedings of the 2010 American Society for Engineering Education (ASEE) Annual Conference & Exposition,* Louisville, KY, June 20-23, 2010.

Chapter 1

INTRODUCTION

1.1 Thesis Goal and Objectives

The *goal* of this engineering educational thesis is to develop a fatigue finite element (FE) learning module that uses commercial FE software and can be integrated into an undergraduate machine design course. The following four thesis *objectives* were carried out to accomplish the goal:

1. *Fatigue Finite Element Learning Module.* Develop a fatigue module of a cantilever beam that uses the commercial FE software ANSYS®.
2. *Design of Fatigue Finite Element Learning Module.* Design the fatigue module based on the Kolb Cycle and the learning styles and personality types for a 'typical' engineering student.
3. *Assessment of Fatigue Finite Element Learning Module.* Assess student improvement of a fatigue FE learning module in an undergraduate machine design course.
4. *Multiple-choice Quiz Development Process.* Develop a structured process for creating or revising a multiple-choice quiz and assess the effectiveness of the quizzes developed using this process.

These four objectives above will be addressed in separate sections that follow.

1.2 Fatigue Finite Element Learning Module

In response to the lack of required finite element courses in undergraduate engineering programs, this work developed a fatigue FE learning module that can be integrated into an undergraduate machine design course. This work is a subset of a

National Science Foundation (NSF) Course, Curriculum, and Lab Improvement (CCLI) proof-of-concept project that is aimed at developing FE learning modules for various undergraduate course topics. FE learning modules had been previously developed for the following topics: curved beam, bolt and plate stiffness, lateral frequency of a cantilever beam, lateral vibration of a tapered cantilever beam, steady state heat transfer in a bar, transient heat transfer in a l-bar, cylindrical drag, friction flow in a pipe, probe feed patch antenna, specific absorption rate, transmission parameters of an infinitely long co-axial cable, and a study of the human head.[1,2] The modules are on the website http://www1.pacific.edu/~abrown/ASEE/. The modules were developed using commonly used commercial software that includes ANSOFT, COSMOSFloWorks, COSMOSWorks, and MSC.Nastran. Each FE learning module was developed using a common template. The modules were developed in Microsoft® Office PowerPoint® and Adobe® Acrobat®.

The FE learning modules are developed to provide students with preliminary hands-on experience in FE method and applications in modeling using commercial software. Each module assumes the student is unfamiliar with the commercial FE software and outlines a step-by-step procedure of modeling the problem. The student should have a background in the topic area of the FE learning module, e.g., in a machine design course the student is assumed to have basic knowledge in fatigue before using a fatigue FE learning module.

This work will develop a new FE learning module in the topic area of fatigue. The module will use the commercial software ANSYS®, since it has not been used in previous modules. Fatigue is a topic commonly found in an undergraduate machine design course.

The fatigue FE learning module introduces basic and complex engineering problems to enhance student learning of the theory and fundamentals of FEM. Students are also introduced to best practices in modeling and problem solving through the use of commercial FE software. This module is discussed in Chapter 2.

1.3 Design of Fatigue Finite Element Learning Module

The design of the previous modules and fatigue FE learning module developed in this work is based on the student learning experience progression of the Kolb Cycle.[1-3] The Kolb Cycle describes a cycle through which learning is achieved through a sequence of four educational experiences: concrete experience, reflective observation, abstract hypothesis and conceptualization, and active experimentation. These different experiences require students to think in ways not typically found in a traditional classroom lecture. The Kolb Cycle has been proven to be an excellent technique to improve student retention of complex numerical methods used to analyze engineering problems.[3-5] The Kolb Cycle in discussed in Section 3.3.2.

The fatigue FE learning module was also designed to accommodate a 'typical' engineering students' learning styles and personality types. The goal of the module is to increase performance of a typical engineering student. The assessment carried out in this work determined if the fatigue FE learning module has bias towards a particular learning style and/or personality type. The learning style of each student was assessed using the Felder-Soloman Index of Learning Styles.[6] The student personality type was assessed using the Jung Typology Test™.[7] The results of the Jung Typology Test reveals the strength of each student's personality type based on Myers-Briggs Type Indicator.

Learning styles are discussed in Section 3.5 and personality types are discussed in Section 3.6.

1.4 Assessment of Fatigue Finite Element Learning Module

An assessment process used post surveys, pre-quizzes, and post-quizzes to evaluate and make improvements to the fatigue FE learning module in a machine design course at the University of the Pacific. The students' opinion of the fatigue FE learning module was evaluated using a post survey upon completion of the module. The post survey format and questions use a common template for all FE learning modules. This ensures present and future FE learning modules are evaluated on how well the educational and analysis objectives are satisfied based on student input. The educational value of the fatigue FE learning module was evaluated using pre- and post-quizzes. The student performance on the pre- and post-quizzes determine how well the educational and analysis objectives are being met. A statistical study of the pre- and post-quiz results allows the content and presentation of the module to be continuously changed to better suit engineering students. The student post survey and pre- and post-quiz assessment results of the fatigue FE learning module can be found in Section 3.7.

1.5 Multiple-choice Quiz Development Process

After reviewing the assessment results for the fatigue FE learning module, there were problems with the quiz questions used in the pre- and post-quizzes. The quiz contained a combination of open-ended and multiple-choice questions. Previous FE learning modules had used entirely multiple-choice quiz questions. Since open-ended questions are more challenging to assess, future FE learning modules will use multiple-choice (closed-ended) questions. A multiple-choice checklist form was created, in this thesis, based on the best practices found in educational measurement literature. The checklist form can be used by instructors to develop new or revise existing multiple-choice quizzes. The effectiveness of the checklist form was assessed in an introduction mechanics course at the United States Air Force Academy. Independent reviewers were used to carry out a quantitative evaluation of new quizzes developed with and without the checklist form. This was the first time a structured process to create multiple-choice quizzes has been cited in engineering education literature. The multiple-choice quiz development process can be found in Chapter 4.

1.6 Thesis Outline

In the second chapter, a FE learning module of a cantilever beam subjected to fatigue loading was analyzed using ANSYS® and verified by analytical methods. This module was developed by Josh Coffman. This chapter was published in the proceedings of 2008 American Society of Engineering Education (ASEE) Midwest Section Meeting and presented by Josh Coffman at the University of Tulsa in Tulsa, Oklahoma. Chapter 2 was co-authored with Sachin S. Terdalkar (Ph.D. candidate at University of Arkansas), Dr. Joseph J. Rencis (thesis advisor), and Dr. Ashland O. Brown (Professor at University of the Pacific).

In the third chapter, a fatigue FE learning module of a rotating shaft was integrated into an undergraduate machine design course, and the module's effectiveness was assessed. The module was developed by Dr. Ashland O. Brown at the University of the Pacific. Dr. Jiancheng Liu integrated this module into his undergraduate machine design course at the University of the Pacific. This chapter was published in the proceedings of 2009 ASEE Middle Atlantic Section Meeting and presented by Josh Coffman at Loyola

University in Baltimore, Maryland. Chapter 3 was co-authored by Dr. Jiancheng Liu (Assistant Professor at University of the Pacific), Dr. Ashland O. Brown (Professor at University of the Pacific), Sachin S. Terdalkar (Ph.D. candidate at University of Arkansas), and Dr. Joseph J. Rencis (thesis advisor).

In the fourth chapter, a structured process was presented to develop a new or revise an old multiple-choice quiz. The effectiveness of the process was assessed in an undergraduate introduction to mechanics course at the United States Air Force Academy under the supervision of Dr. Daniel Jensen (Professor). This chapter was published in the proceedings of 2010 ASEE Annual Conference & Exposition and presented by Josh Coffman in Louisville, Kentucky. Chapter 4 was co-authored by Dr. Joseph J. Rencis (thesis advisor), Dr. Daniel Jensen (Professor at United State Air Force Academy), Dr. Ashland O. Brown (Professor at University of the Pacific), Ms. Christina White (doctoral candidate at Columbia University), Dr. Jiancheng Liu (Assistant Professor at University of the Pacific), and Ms. Kristen Kaufman (master's student at University of Texas at Austin).

Chapter 5 states the conclusions of this engineering education thesis. Following Chapter 5 are the appendices containing the two FE learning modules.

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Chapter 2

INTEGRATING FATIGUE ANALYSIS INTO A MACHINE DESIGN COURSE OR FINITE ELEMENT COURSE

2.1 Abstract

Fatigue is a major topic addressed in undergraduate and graduate machine design courses. Practicing engineers today commonly solve fatigue problems by hand coupled with static finite element analysis. More recently fatigue modules have been incorporated into a few commercial finite element codes which are emerging as a powerful numerical tool. A literature review of machine design textbooks, finite element textbooks, engineering educational journals, and engineering educational conference papers reveals that the topics of fatigue and finite elements addressed together are almost non-existent. In this work a simple cantilever beam fatigue example is considered and is solved by hand and the commercial finite element code ANSYS® Academic Teaching Introductory Release 11.0. The hand solution is included to emphasize the importance of verification when solving a problem using the finite element method. The target audience of this paper is an instructor who would like to integrate fatigue into a finite element course or fatigue finite element (FE) analysis into a machine design course.

2.2 Introduction

Fatigue is a material based phenomenon that causes failure in machine parts at stress values much lowers than static yield strength of the material. Fatigue failure is due to repeated or cyclic loading and unloading or fluctuating reversal in loading after a large number of cycles. Fatigue failures are estimated to occur in 80-90% of all machine component failures and account for a 4% loss in the gross domestic product of the United States and Europe.[1]

Fatigue failures are commonly found in components used for the automotive and aerospace industries. High cycle fatigue in the automotive industry is common in suspension systems, engine components, and components in the power train that include the transmission, drive shafts, and wheel assemblies. A connecting rod is an example of an engine component that experiences large stresses and a high number loading cycles. The connecting rod provides a linkage from the piston head to the crankshaft. The fatigue analysis of a connecting rod can be found in the ANSYS® on-line white paper.[2] Some fatigue failures in automobiles can be life critical, but in aerospace applications any fatigue failure may result in tragic losses of life. Sources of high cycle fatigue in large aircraft include turbo-jet engines, landing gear assemblies, fuselage coverings, and the connection points of wings. In aerospace applications materials may be used that do not have endurance limits due to weight concerns. An example of fatigue failure in the fuse pin connections of the jet engines to the wing of a commercial airliner is studied in Zahavi.[3] Both industries sometime require a full-scale model to verify the fatigue life.

Fatigue is a major topic that is addressed in undergraduate and graduate machine design courses and textbooks by Shigley[4,5] and Norton.[6,7] A machine design course is required most of the time in undergraduate mechanical engineering programs. In academia or industry fatigue problems have traditionally been solved by hand or an in-house computer program specialized for a particular of fatigue application.

The finite element method (FEM) is a computational tool that has been used extensively the past thirty years in industry and is now a standard engineering tool for both analysis and design. When FEM first appeared in the 1960's it was introduced into the engineering curriculum at the graduate level. As the method and computer technology matured, FEM was introduced at the undergraduate level in engineering and engineering technology programs, even in some two-year engineering technology programs. FEM is today primarily offered as an elective undergraduate course in mechanical, civil, and aeronautical engineering programs.[8]

Fatigue analysis that once was carried out by hand and/or in-house computer programs is now done using commercial FEM software. Fatigue modules have recently been integrated into commercial FEM codes that include ABAQUS®[9], ALGOR®[10], ANSYS®[11], COMSOL®[12], COSMOSWorks®[13], and Pro/ENGINEER®.[14] The usage of FEM in fatigue analysis does not go without limitations. An absence of actual loading data throughout the life of the components will not allow for the accurate results for life prediction. A second limitation of FE fatigue analysis is the random variance in material performance even in materials of the same type.

This paper will first review educational literature that considers both fatigue and FEM. A simple cantilever beam example is then solved by hand and the FEM commercial code ANSYS®. The target audience of this paper is an instructor who wants to integrate fatigue into a finite element course or fatigue finite element analysis into a machine design course.

2.3 Literature Review

A literature review of machine design textbooks, FEM textbooks, engineering educational journals, and engineering education conference papers revealed that fatigue and FEM addressed together are almost non-existent and have only appeared recently. This causes a knowledge gap between fatigue analysis and FE analysis.

A machine design course typically relies on a textbook that contain one or more chapters on fatigue theory and design. Early machine design textbooks did not provide any background in FEM and commonly just mention FEM. For example, the popular machine design textbook by Shigley[4,5] (1977-2006), did not mention FEM until the eighth edition in 2008.[15] Other textbooks briefly mention how FE analysis is a powerful engineering tool.[16,17,18] Newer and applied approaches in textbooks, such as Juvinall[19] (2000), Norton[7,8] (2000 and 2006), Shigley[15] (2008), and Ugural[20] (2004) provide an introduction to FEM in sections or entire chapters. The textbook by Edwards and McKee[21] (1991) discusses fatigue and FEM together. At the end of chapter nine the need for computer-aided fatigue design is described; however, no examples are considered. The authors' discussion also includes analysis types available in software and commercial FE codes.

Two FEM textbooks mention fatigue and discuss its importance for designing machine components. The textbook by Adams and Askenazi[22] (1999) provides a review of fundamental fatigue analysis principles. In the chapter on nonlinear analysis both authors state that accurate stresses are required to estimate fatigue life or damage. Also stated is that the stresses are highly dependent on how accurately the material properties are defined. They also state that future FEM codes will employ stochastic methods to allow "automated" fatigue life analysis.[22] The second FEM textbook by Zahavi[23] (1992) discusses that reducing the geometric stress concentration factor will increase fatigue life. Zahavi mentions fatigue a few other times, but only to state the importance of fatigue design, never actually using FE to predict fatigue life.[23] These two textbooks[22,23] never apply FEM to a fatigue example.

A literature review of fatigue textbooks reveals FEM as an analysis tool is addressed on a very limited basis. Fatigue textbooks that mentioned FEM usually discuss how it is used to determine stresses and some other discussions include the use of FEM to study fracture mechanics and the analysis of plasticity in crack propagation. Zahavi[3] has a fatigue design textbook that clearly ties fatigue with FEM as a tool for determining static stresses in three-dimensional machine components. Several examples are considered using static stresses to determine the fatigue life of machine components.[3]

The consideration of fatigue and FEM together in educational journals and conference papers is very limited and has only appeared recently. A review of educational journals yielded no papers that consider both fatigue and FEM. A conference paper by Hagigat[24] (2005) explains the general concept of fatigue and also emphasizes that a major contributor to high cycle fatigue failures is vibration. Hagigat[24] states that using mode shapes and S-N curves will yield an accurate fatigue analysis. However, no fatigue analysis is presented, nor is any actual FE analysis used for determining fatigue life. In regard to the use of commercial FE software with fatigue capabilities, Hagigat[24] states, "...from an educational point of view, it is recommended that these capabilities not be used initially. After a student understands the concepts by going through the steps in this article, he/she can then use the additional capabilities of the software correctly. A lack of knowledge of the theory behind the more advanced capabilities of the software can lead to the incorrect use of the software." Still no direct computation of fatigue life was carried out using FE software.

2.4 Educational Goals and Objectives

This work is part of a larger scale project to develop FE learning modules for undergraduate engineering courses[8] that will be available 24/7 to the world-wide community on the internet. The project goals and project objectives have been divided into developmental, educational, and assessment.

The *project developmental goal* is to develop FE learning modules in different engineering areas that are easily accessible and require minimal instructor effort. The *project developmental objectives* to accomplish this goal are as follows:

1. *Integrate into Different Courses.* Develop FE learning modules that can be integrated into different types of undergraduate engineering and introductory finite element courses.
2. *Time and Accessibility.* Develop FE learning modules that require minimal classroom time to be integrated into a course with minimal instructor preparation, and are easily accessible.

The *project educational goal* is to provide undergraduate engineering students with understanding of a specific engineering topic and FE theory, along with an ability to apply commercial FE software to typical engineering problems. The educational goal will be accomplished through four *project educational objectives* based on Bloom's Taxonomy[25] and ABET Criterion 3 for Engineering Programs[26] as follows:

1. *Engineering Topics (Comprehension; 3a, 3k).* Understand the fundamental basis of engineering topics through the use of finite element computer models.
2. *FE Theory (Comprehension; 3a).* Understand the fundamental basis of FE theory.

3. *FE Modeling Practice (Application; 3a, 3e, 3k).* Be able to implement a suitable finite element model and construct a correct computer model using commercial FE software – integrates objectives #1 and #2 above.

4. *FE Solution Interpretation and Verification (Comprehension and Evaluation; 3a, 3e).* Be able to interpret and evaluate finite element solution quality, including the importance of verification – integrates objectives #2 and #3 above.

The *project educational objectives* address three of six Bloom's Taxonomy levels, i.e., *comprehension, applications, and evaluation,* but a future follow up project will address all six. The educational outcomes above were mapped to ABET Criterion 3 Program Outcomes for Engineering Programs so that instructors can integrate an exercise into their in-house ABET assessment process.

The *project assessment goal* is to accurately and comprehensively assess each educational objective. The assessment goal will be accomplished through two *project assessment objectives* as follows:

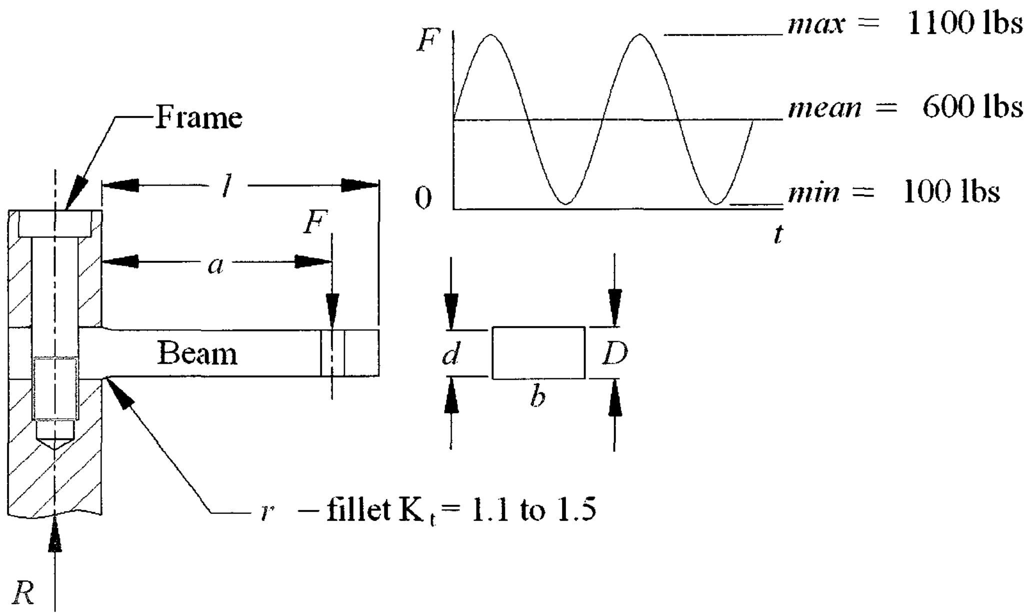
1. *Assessment System.* Develop and implement a closed loop (iterative) assessment system.

2. *Learning Styles.* Gain insight into the effectiveness of the FE learning modules across various personality types and Learning Styles.

The assessment program for the fatigue FE learning module will be carried out in the future and is discussed in the Future Work section at the end of this paper.

2.5 Example Problem Overview

The fatigue example is shown in Figure 2.1 and can be found in the machine design textbook by Norton.[6,7] Both the second[6] and third editions[7] contain this example problem. This example problem was selected since it is in a commonly used machine design textbook and has a hand solution. This example will be analyzed using the version of ANSYS® Academic Teaching Introductory Release 11.0. The authors have also developed a FE fatigue module based on a simply supported beam in the machine design textbook by Nisbett and Budynas.[15]



Geometric Properties	Material Properties
l = 6.0 in	SAE 1040 Normalized Carbon Steel
a = 5.0 in	$E = 30 \times 10^6$ psi
r = 0.5 in	ρ = 0.2834 lb/in^3
d = 1.0 in	υ = 0.28 (Poisson's Ratio)
b = 2.0 in	S_{ut} = 80 kpsi
D = 1.125 in	S_y = 60 kpsi

Figure 2.1 Cantilever beam subjected to a fluctuating load.[6,7]

The problem states that a feed roll assembly is supported on both ends by cantilever brackets. This assembly is subjected to an applied fluctuating load of 200 lbs at a minimum and 2200 lbs at a maximum. For analysis purposes, this means that a single bracket is modeled using half of the applied fluctuating load. The schematic of the bracket, geometric properties, applied fluctuating load, and material properties are shown in Figure 2.1. An additional design requirement is that the maximum vertical deflection does not exceed 0.02 in. Other design criteria include an operating environment of 120°F, maximum cantilever length of 6 in, and only ten brackets will be manufactured. Norton[6,7] assumes that the parts are machined due to the low volume that will be manufactured.

Norton[6,7] applies some assumptions in this example. First, the bracket will be clamped between what is assumed to be rigid plates. The load is applied in a small hole near the tip of the beam. Following the example explicitly, the hole's stress concentration effects will be neglected for the hand and FEM analyses because the bending stresses near the free end of the beam are very low. The bracket will have a selected material that will allow for 10^9 loading cycles or an infinite fatigue life.

The analyses will include the following: frequency/modal analysis, static displacement analysis, static stress analysis, and fatigue life analysis. Each analysis will be carried out first by hand based on Norton[6,7] and then by the commerical FEM code ANSYS®. The hand solution is included to emphasize the importance of verification when solving a problem using FEM.

2.6 Finite Element Model

The cantilever beam was modeled with the commercial FE code ANSYS® and used the plane stress, PLANE42, a four node quadrilateral element. The geometry, material properties and loading are shown in Figure 2.1. The same FE mesh was used for the modal/frequency, static displacement, static stress, and fatigue analyses. The mesh size was determined based on a convergence study of stresses since a finer mesh is required to obtain accurate stresses compared to deflections and frequencies. The FE mesh consists of 1,329 nodes and 1,224 elements as shown in Figure 2.2. Each node has two degrees of freedom (DOF) and the mesh has 2,658 DOFs. The bracket mounts are located at the vertical left-hand side of the beam in Figure 2.2 and these DOF were fixed in the horizontal and vertical directions.

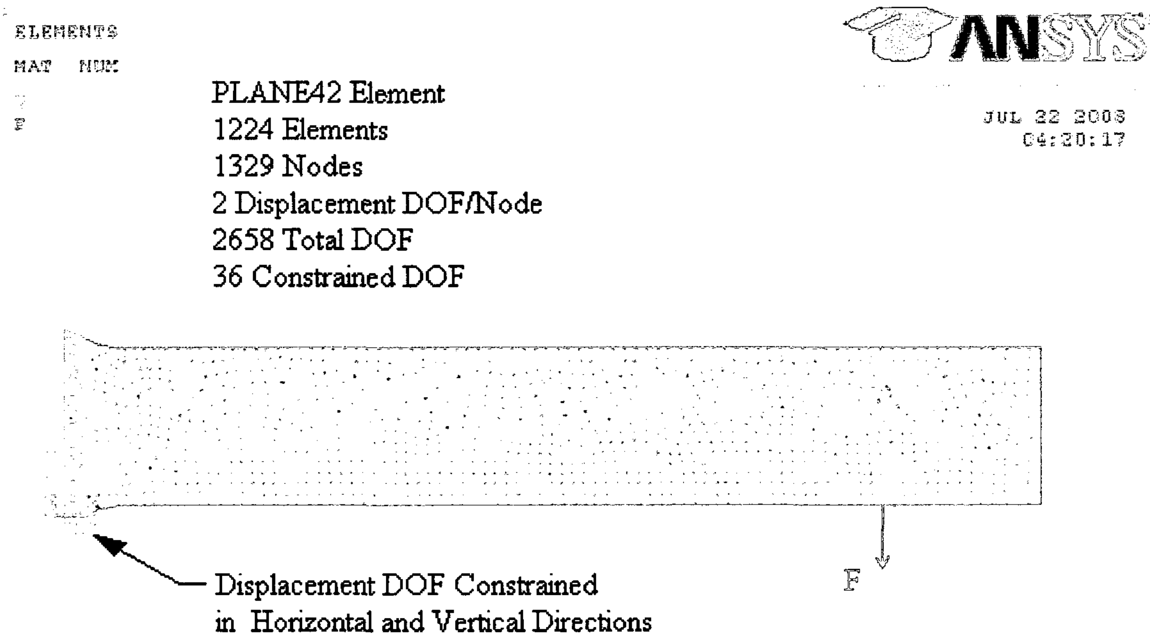


Figure 2.2 Plane stress FE mesh of cantilever beam.

2.7 Frequency/Modal Analysis

A modal analysis was carried out since a major contributor of high cycle fatigue loading is due to vibration. If the frequency of the loading reaches a resonance condition, large amplitudes of vibration will occur in a machine component. If the component is subjected to large vibrational amplitudes, the applied cyclic stresses may cause fatigue failure depending on geometry, material, loading type, and number of cycles.[24] The modal analysis can provide insight on where to locate a larger mass and/or where to increase component stiffness. The modal analysis was not carried out in the machine design textbook by Norton.[6,7]

The cantilever beam has a fixed boundary on the left-hand side and all other DOFs in the FE mesh are free throughout the beam in Figure 2.2. A hand solution to determine the frequencies (eigenvalues) and mode shapes (eigenvectors) are well documented in vibrations and structural dynamics textbooks for the long cantilever beams.[27] However, the geometry of the cantilever beam in Figure 2.1 classifies the beam as short due to the length to depth ratio (ten to one or less). The frequency of a short beam is obtained by multiplying the long beam frequency by a correction factor found in the handbook by Harris.[27] When a beam is short then the effects of rotary motion and shearing forces must be taken into account in the long beam hand frequency analysis.[27] These effects are based on Timoshenko beam theory and are not commonly found in undergraduate machine design textbooks or most vibrations and structural dynamics textbooks. The frequencies for the first five modes based on the hand analysis are shown in the third column of Table 2.1.

The commercial FEM code ANSYS® was used to calculate the natural frequencies and mode shapes of the beam. The FE model is shown in Figure 2.2. The FE results for the first five frequencies are shown in fourth column of Table 2.1. There is very good agreement between the hand and FE analyses. One should note that since the ANSYS® model was formulated based on theory of elasticity, therefore, the effects of rotary motion and shearing forces are included.

Table 2.1 Natural frequencies of the cantilever beam for hand and ANSYS® analyses.

Mode	Mode Type	Frequency (Hz) Short Beam Hand Analysis*	Frequency (Hz) ANSYS® Analysis (PLANE42 Elements)	% Difference of Solutions
1	Bending	898.92	898	0.10%
2	Bending	5008	5051	0.86 %
3	Axial	8426	8457	0.36 %
4	Bending	12270	12442	1.40%
5	Bending	20923	21234	1.49%

*Hand analysis frequencies are shown as corrected using short beam correction factors for modes 1 through 5, 0.99, 0.88, 1.0, 0.77, and 0.67, respectively.[27]

The FE model was verified with a hand analysis to ensure that the total mass and mass center is correct. If the total mass and mass center of the FE mesh is incorrect, then the frequencies and mode shapes will be incorrect. Based on past experience the authors have found that students, and even practitioners, do not carry out these two simple checks. The mass and the mass center for the cantilever beam are shown for the hand and ANSYS® analyses in Table 2.2. The hand analysis was based on the theory in statics textbooks.[28-30]

Table 2.2 Total mass and mass center locations for hand and ANSYS® analyses.

Analysis Method	Total Mass lbm.	% Difference in Total Mass	Center of Mass Location (X, Y) in.	% Difference in Center of Mass Locations X	% Difference in Center of Mass Locations Y
Hand	3.4094	0.08%	(2.9931, 0.5)	0.07%	0.0%
ANSYS®	3.4065		(2.9952, 0.5)		

2.8 Deflection Analysis

The design requirement is that the vertical deflection of the beam is less than 0.02 in. A maximum load of 1,100 lbs ($F = F_{max} = 1,100\ lbs$) was applied at the right end of the cantilever beam as shown in Figure 2.1. A hand analysis using mechanics of materials principles in Norton[6,7] yielded a vertical deflection at the end of the cantilever beam of 0.0119 in. ≈ 0.012 in. as displayed in the textbook. The actual magnitude of this value is important when considering the accuracy of the solution. This calculation ignores the effects of transverse shear deflection since it assumed a long uniform beam. If the transverse shear deflection is considered using Castigliano's energy method for a short beam (not considered in Norton), the maximum vertical deflection increases to 0.01226 in., a 3.03% increase.

The maximum vertical deflection, shown in Figure 2.3, was determined by ANSYS® to be 0.011975 in., a 0.63% difference in the hand (long uniform beam) and FEM solutions. When compared to Castigliano's method for short beams, the ANSYS® solution is 2.32% different. The hand and ANSYS® analyses show that the design requirement for the vertical deflection is satisfied since it is less than 0.02 in at the free end.

You might be asking why is there a difference between the long beam hand solution, short beam hand solution, and ANSYS® solution. First, both hand solutions are based on a uniform cross-section, i.e., no fillet radii. A long or short beam containing two fillet radii has a greater stiffness than a uniform beam and the result is a smaller vertical deflection. Carrying out an ANSYS® analysis using PLANE42 elements for a uniform beam (no fillet radii) yields a vertical deflection that corresponds to short beam theory, not long beam theory considered in Norton.[6,7] Since the PLANE42 ANSYS® element was formulated based on theory of elasticity, shear deformations are accounted, therefore, the vertical deflection corresponds to short beam theory. Second, another reason for a difference between the hand solutions and ANSYS® solution is due to how the force is applied. Applying the concentrated force in Figure 2.1 as a parabolic shear stress distribution throughout the beam depth will result in an ANSYS® deflection that corresponds to the short beam hand solution.

2.9 Static Stress Analysis

A hand stress analysis for the maximum loading case of 1,100 lbs ($F = F_{max} = 1,100$ *lbs*) ensures that the maximum bending stresses are far below the nominal value required for yielding on the first loading cycle. Two static stress analyses are required to carry out a fatigue analysis. The first static analysis is where the mean load of $F = F_m = 600$ *lbs* is applied one in. from the right end as shown in Figure 2.1. The second static analysis is where the alternating load of $F = F_a = 500$ *lbs* is applied one in. from the right end as shown in Figure 2.1.

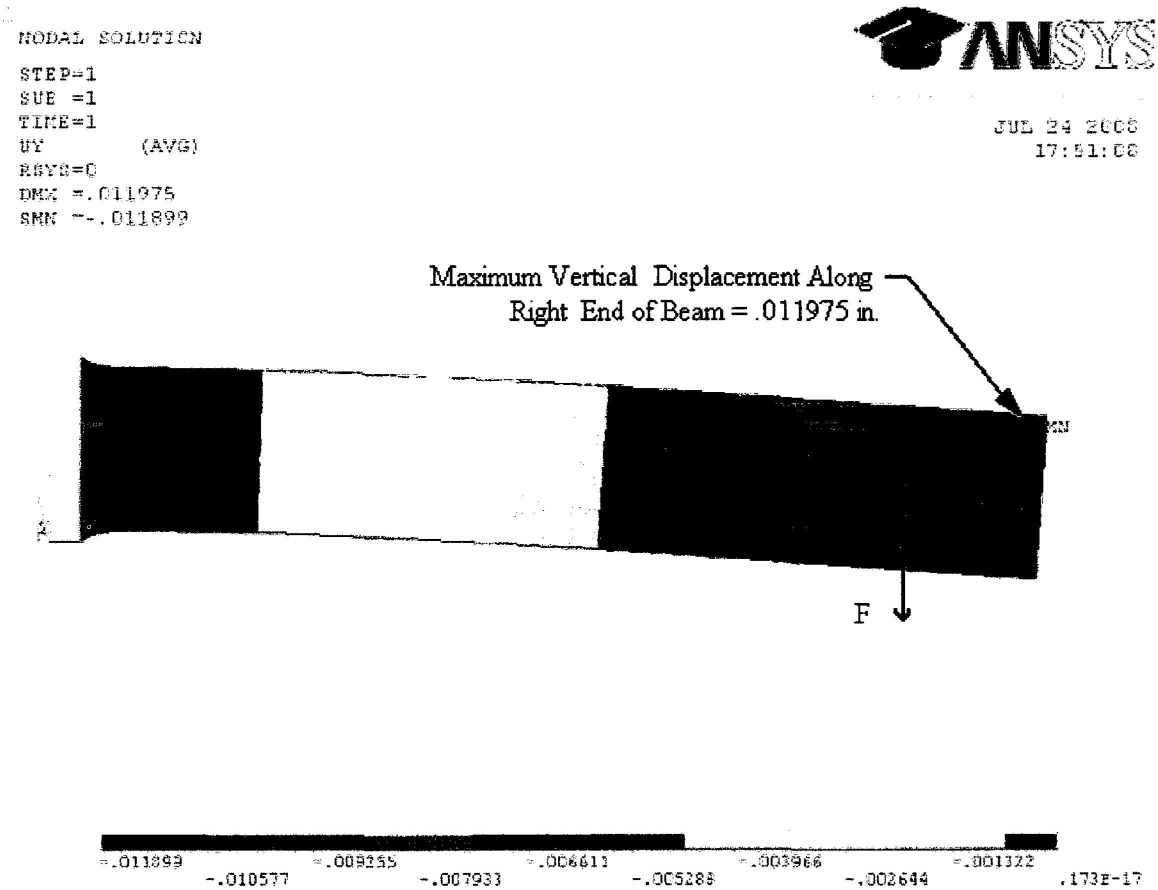


Figure 2.3 Maximum vertical deflection (in.) and deflected shape of the beam due to a maximum applied load of $F = F_{max} = 1,100$ *lbs.*

Mean Load Case

A mean load of $F = F_m = 600$ *lbs* is applied on the right side of the cantilever beam as shown in Figure 2.1. A hand static stress analysis determined that the maximum bending stresses at the top and bottom fibers of the cantilever beam wall[6,7] is 9,000 psi. By knowing that the fillet radii at the left end is the location of the highest localized bending stresses, the geometric stress concentration factor, K_t shown in Figure 2.1, is used to determine the maximum stress at the fillet. Using the figure for geometric stress concentration factors and functions for a stepped beam in pure bending and the modifications for the ultimate strength and notch sensitivity from Chapter 4 of Norton[6,7], the corrected geometric stress concentration factor is 1.16. The actual bending stress at the fillet radius is 10,454 psi. The shear stresses near the outer fibers of the cantilever beam at the left end are very small in magnitude such that Norton[6,7] neglected their contribution when determining the von-Mises stress.

The ANSYS® using the PLANE42 four node quadrilateral element includes the stress concentration effect since the element was formulated based on theory of elasticity. The shear stresses are included in the von-Mises stress since the element was formulated based on the theory of elasticity. This is why the von-Mises stress is slightly lower for FEM compared to the hand analysis. The FEM approach calculates the von-Mises stress to be 9,865 psi as shown in Figure 2.4. This value is slightly lower and is why there is a 5.63% difference in hand and FEM solutions.

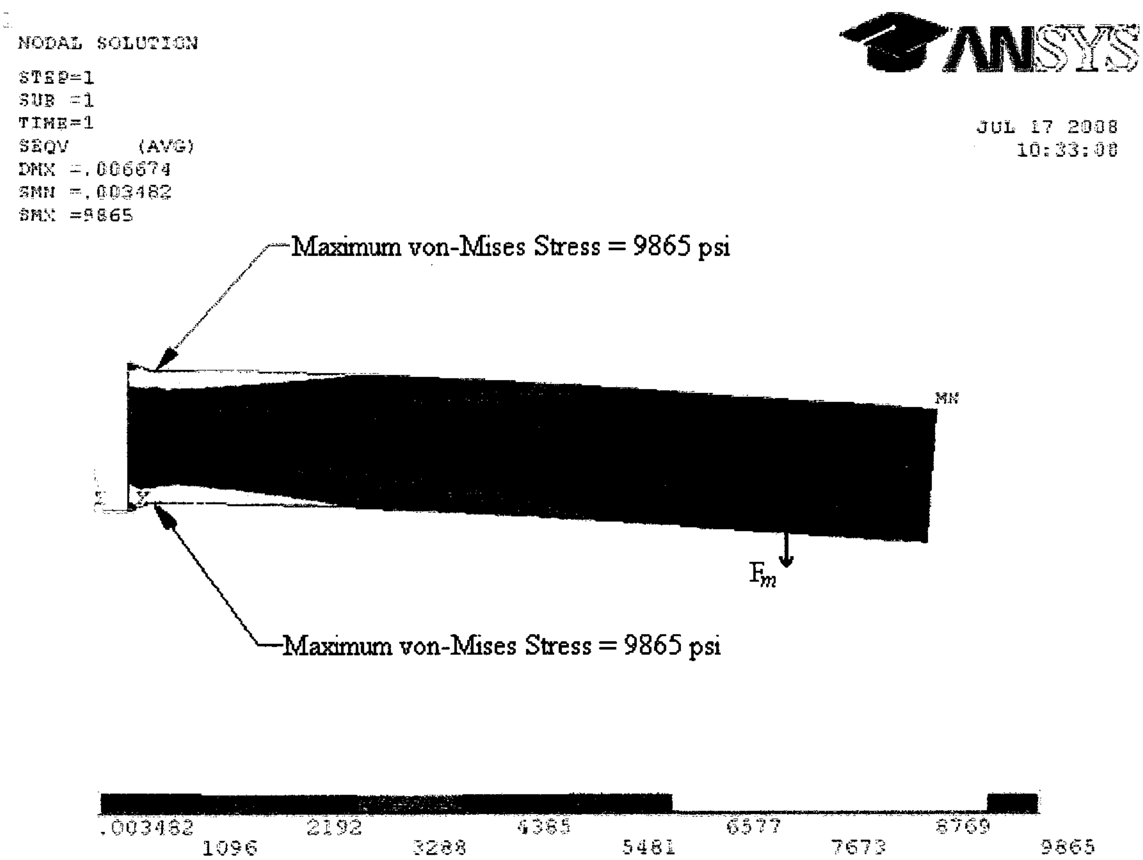
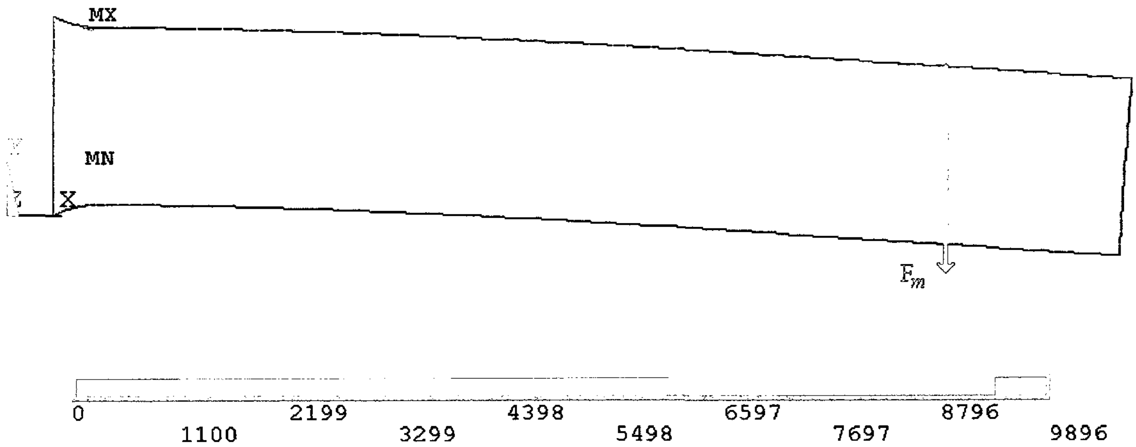
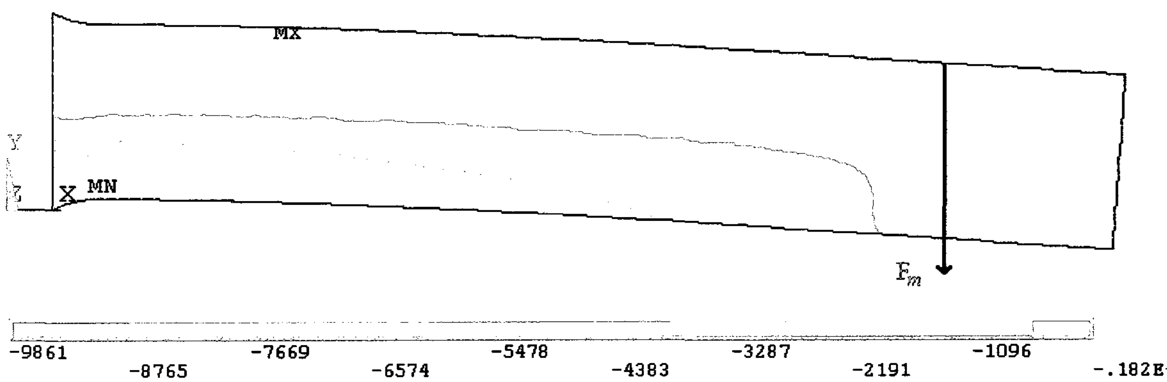


Figure 2.4 von-Mises stress (psi) distribution for a mean load of $F = F_m = 600\ lbs.$

Apart from von-Mises stresses, a closer look at the maximum and minimum principal stresses is taken. An advantage of the principal stresses over von-Mises stresses is the ability to describe the nature of the load. The maximum and minimum principal stresses are shown in Figure 2.5a.) and 2.5b.), respectively, for the mean loading case ($F = F_m = 600\ lbs$). The maximum principal stresses shown in Figure 2.5 a.) are all tensile. The maximum tensile stress of 9,896 psi is located at the fillet radius on the top left-hand side of the beam. The location of maximum tensile stress will be located at the fillet radius on the bottom as the applied direction of the cyclic load changes. Knowing the location of highest areas of tensile stresses will allow an engineer to predict the possible location of crack intiation, the main cause of fatigue failure. Figure 2.5 b.) displays the areas of compressive stresses located in the bottom half of the beam. The maximum compressive stress is -9,861 psi. The presence of compressive stresses is assumed to only increase the fatigue strength. As previously discussed, as the cyclic load changes direction the location of tensile and compressive stresses will switch. One should note that the magnitudes of the maximum principal stresses are slightly more conservative than the von-Mises stresses, while the minimum principal stresses are slightly reduced when compared to the von-Mises stresses. Norton[6,7] did not consider maximum and minimum principal stresses.



a.) Maximum principal stress (psi).



b.) Minimum principal stress (psi).

Figure 2.5 Principal stresses for the mean loading case F_m = *600 lbs.*

Alternating Load Case

An alternating load of $F = F_a$ = *500 lbs* is applied at the right-hand side of the cantilever beam as shown in Figure 2.1. The bending stress at the top and bottom fibers at the left end of the beam was determined by hand as 7,500 psi. The geometric stress concentration must be accounted for at the fillet locations as discussed for the mean load case. The corrected geometric stress concentration factor is the same one used for the mean load case, a value of 1.16. The value for the maximum bending stress using the stress concentration factor was 8,711 psi at the top and bottom fillets. The shear stresses were once again neglected due to their low magnitude and for hand calculation simplicity. The von-Mises stress is 8,711 psi, and is the same value as the bending stress. The FEM approach calculated the von-Mises stress to be 8,239 psi, as shown in Figure 2.6, a difference of 5.42% in solution types.

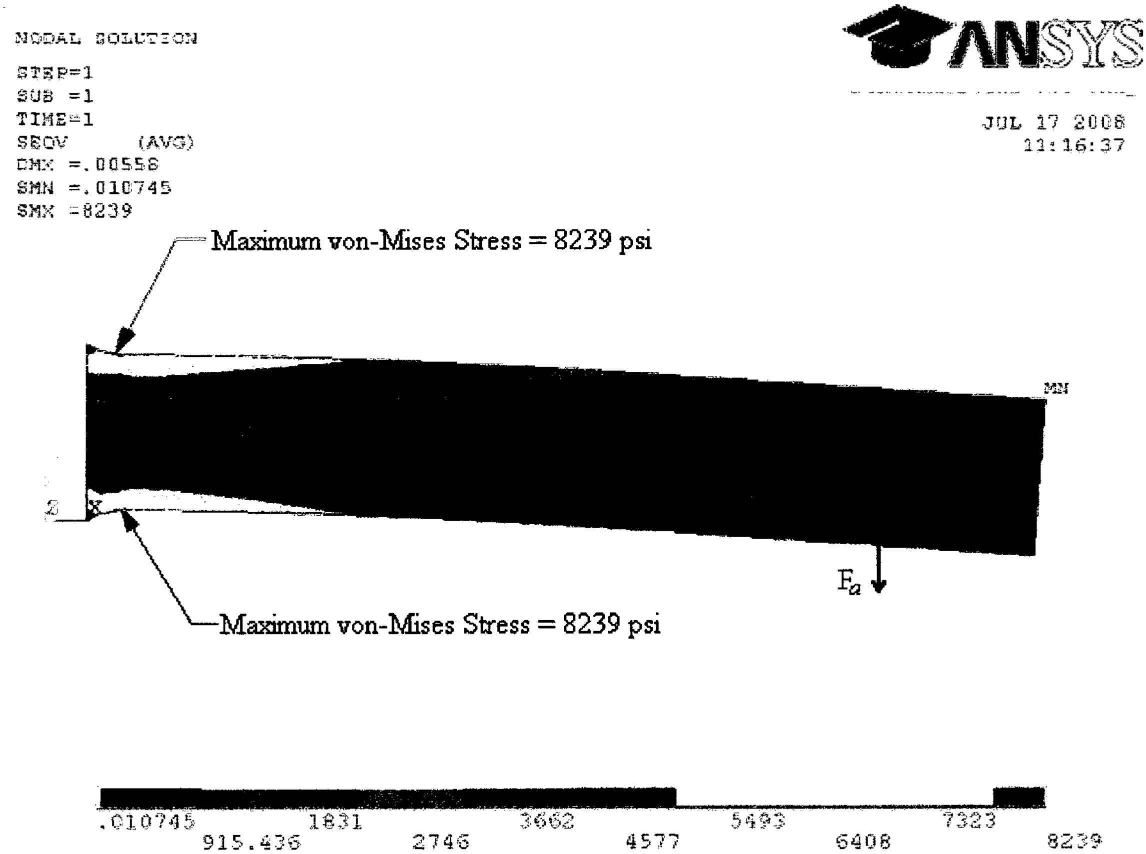
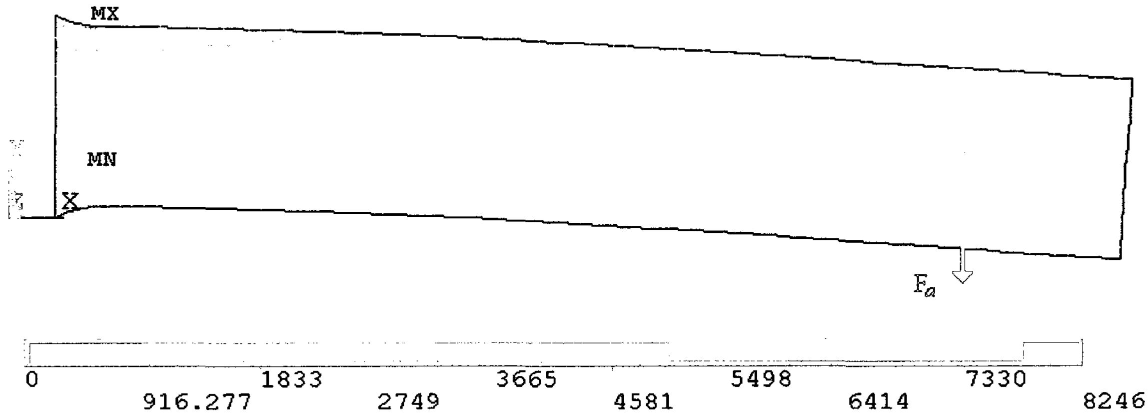
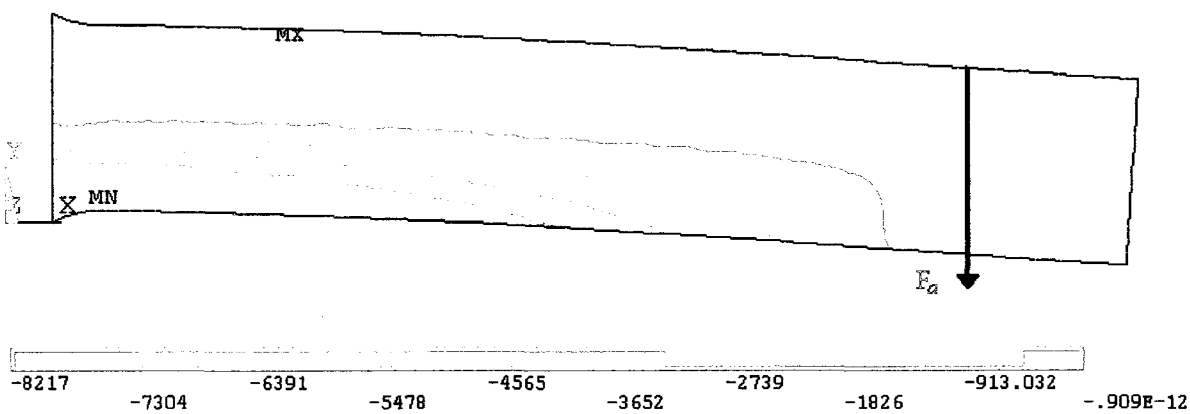


Figure 2.6. von-Mises stress (psi) distribution for an alternating load of $F = F_a = 500\ lbs.$

The maximum and minimum principal stresses for the alternating loading case ($F = F_a = 500\ lbs$) are shown in Figure 2.7 a.) and 2.7 b.), respectively. The maximum principal stresses shown in Figure 2.7 a.) are all tensile. The maximum tensile stress is 8,246 psi. Figure 2.7 b.) shows the variation of compressive stress throughout the beam. The maximum compressive stress is -8,217 psi. As mentioned in the previous discussion, the maximum and minimum principal stresses can be used to predict areas of the highest tensile stresses. The tensile stresses are of importance because these areas tend to be locations of crack initiation and growth over cyclic stresses.



a.) Maximum principal stress (psi).



b.) Minimum principal stress (psi).

Figure 2.7. Principal stresses for the alternating loading case F_a = *500 lbs.*

2.10 Fatigue Analysis

The beam is designed to withstand 10^9 loading cycles, which is considered high cycle fatigue. A stress-life approach was used as for this example to carry out the fatigue analysis since it is valid for high cycle fatigue, and it is commonly found in undergraduate and graduate machine design courses.

Knowing the ultimate tensile strength of the SAE 1040 normalized carbon steel to be

S_{ut} = 80 kpsi (Figure 2.1), the estimated endurance limit is 40 kpsi.[6,7] This estimated endurance limit must be corrected for the following factors: loading type, surface finish, temperature of operating environment, component size compared to test samples, and desired reliability. The corrected endurance limit is 21.833 kpsi. This means that for SAE 1040 normalized carbon steel the stress values are well below the limit that is required for an infinite fatigue life or 10^9 loading cycles. This corrected endurance limit is also required to find the safety factors.

Figure 2.8 shows the safety factors based from a hand analysis based on the Modified-Goodman diagram. There are four methods described in Norton[6,7] to determine the lowest safety factor. Each safety factor is calculated by varying the mean and alternating stresses. The first safety factor (N_{f1}) is based on assuming that the alternating stress value is held constant. For this loading configuration the value of the first safety factor is relatively large compared to the other three safety factors shown in Figure 2.8. The second safety factor (N_{f2}) assumes a constant mean stress value. The third safety factor (N_{f3}) is calculated using a proportional amount of both alternating and mean stress values. The fourth safety factor (N_{f4}) is a random set of values for the mean and alternating stresses. This is the most conservative safety factor. Depending on the state of loading, any of the four mentioned cases could become the minimum calculated value for the safety factor. The fourth case provides the minimum safety factor for the fatigue design as shown in Figure 2.8, i.e., $N_{f14} = 1.7$.

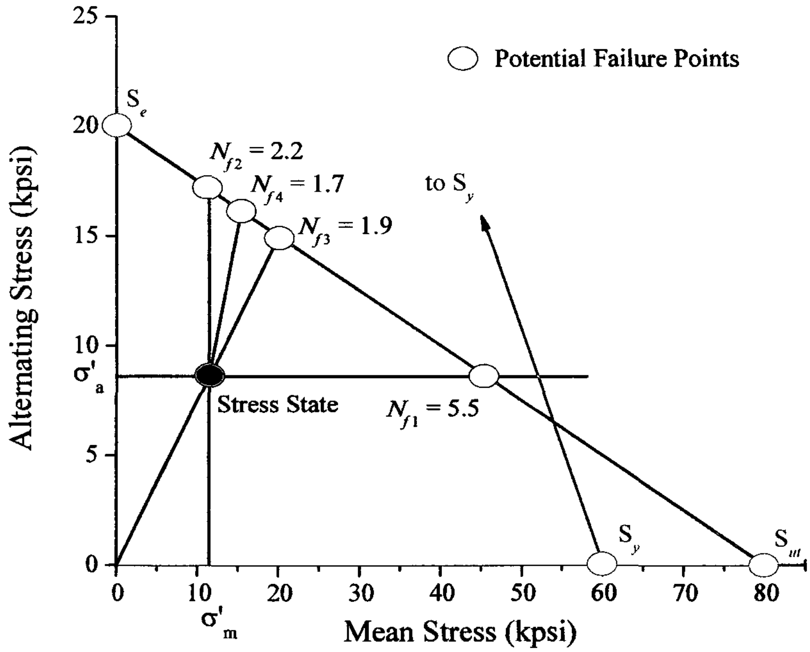


Figure 2.8 Modified-Goodman diagram displaying fatigue design safety factors for hand static stress analysis.

The safety factors are calculated by using the von-Mises stress values from ANSYS® as shown in Figure 2.9. The safety factors are calculated using the same four methods as previously described for the hand analysis. The values shown in Figure 2.9 indicate that the safety factors slightly increased. The inclusion of shear stresses in the FE analysis reduces the von-Mises stresses by approximately 5% in the beam. The minimum safety factor for the ANSYS® stress analysis is 1.8. The increased safety factor provides a difference in the two solution methods of only 5.88%. The hand analysis is found to be more conservative than the FE analysis.

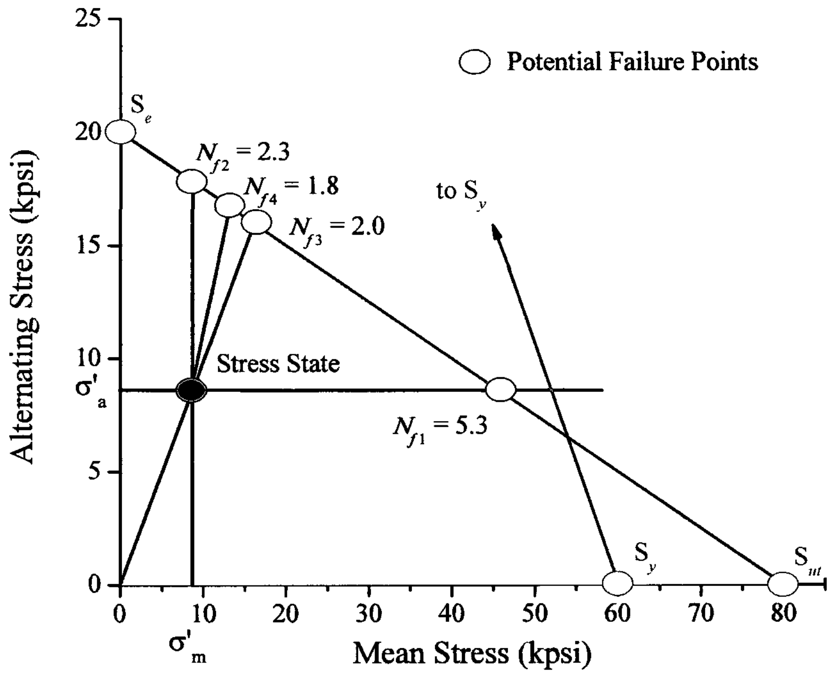


Figure 2.9. Modified-Goodman diagram displaying fatigue design safety factors for ANSYS® static stress analysis.

2.11 Conclusion

The use of commercial FE codes in the workplace is rapidly impacting the field of fatigue analysis and design. Engineering students and practitioners must have a basic understanding of the fatigue theory before being able to carry out a fatigue FE analysis. Based on a literature review by the authors, the integration of fatigue into a finite element course or finite elements into a machine design course has not been done in the past. This paper considered a simple example of a cantilever beam that is analyzed by hand and using the commercial FE code ANSYS®. This paper is a resource for both instructors and practitioners who want to consider both fatigue and FEM.

2.12 Future Work

This work is part of a larger scale project to develop FE learning modules for undergraduate engineering courses[8] that will be available 24/7 to the world-wide community on the Internet. The project goals are as follows:

1. *Developmental.* Develop FE Learning Modules in different engineering areas that are easily accessible and require minimal instructor effort.
2. *Educational.* Provide undergraduate engineering students with an understanding of a specific engineering topic and FE theory, along with an ability to apply commercial FE software to typical engineering problems.
3. *Assessment.* Accurately and comprehensively assess each educational objective and the effectiveness of the FE Learning Modules.

This module will be integrated into an undergraduate machine design course or undergraduate finite element course at one of the six participating universities associated with this project. An assessment program will be carried out for the fatigue FE learning module that will include the following four assessment tools: post student survey, pre-course and post-course quizzes, learning styles (Felder-Soloman), and personality types (Myer-Briggs). The student survey and quizzes will indicate what the student liked and disliked about the FE fatigue learning module and if the student has improved learning using the module when compared to a traditional classroom approach. The learning styles and personality types of each student are identified through a survey and are used to determine whether the fatigue FE learning module is biased towards a particular learning style or personality type. The goal is to have a FE learning module that does not have a bias towards particular learning styles and personality types. The assessment results will be used for continuous improvement of the fatigue FE learning module over the next year. An in-depth discussion of the assessment program that will be carried out for this module can be found in Brown.[8]

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Chapter 3

FINITE ELEMENT LEARNING MODULE FOR IMPROVING KNOWLEDGE OF FATIGUE USING COMMERCIAL SOFTWARE

3.1 Abstract

Finite element (FE) active learning modules have been developed for various undergraduate engineering courses. These FE learning modules are used to introduce basic and complex engineering problems to enhance student learning of the theory and fundamentals of the finite element method. A review of educational literature reveals that fatigue and finite elements are not addressed together. The fatigue FE learning modules were designed based on the Kolb Cycle of learning experience progression. The educational value of the fatigue FE learning module is assessed by short quizzes administered before and after students use the module. The results of the pre-quiz and post-quiz are used to identify any Felder-Soloman learning style and/or Myers-Briggs personality type bias in the module. Statistical study of these assessment results will allow the content and presentation of the module to be improved to better suit engineering students. Post-survey will be used as part of the module assessment process to include students' opinion.

3.2 Introduction

Fatigue is a material based phenomenon that causes failure in machine parts at stress values much lowers than static yield strength of the material. Fatigue failure is due to repeated or cyclic loading and unloading or fluctuating reversal in loading after a large number of cycles. Fatigue failures are estimated to occur in 80-90% of all machine component failures. Fatigue is a major topic that is addressed in undergraduate and graduate machine design courses and textbooks. A machine design course is required in most undergraduate mechanical engineering programs. In academia or industry fatigue problems have traditionally been solved by hand or an in-house computer program specialized for a particular type of fatigue application.

The finite element method (FEM) is a computational tool that has been used extensively the past thirty years in industry and is now a standard engineering tool for both analysis and design. When FEM first appeared in the 1960's it was introduced into the engineering curriculum at the graduate level. As the method and computer technology matured, FEM was introduced at the undergraduate level in engineering and engineering technology programs, even in some two-year engineering technology programs. Today, FEM is primarily offered as an elective undergraduate course in mechanical, civil, and aeronautical engineering programs.

Fatigue analysis that in the past was carried out by hand and/or in-house computer programs is now done using commercial FEM software. Fatigue design modules have recently been integrated into commercial FEM codes that include ABAQUS®, ALGOR®, ANSYS®, COMSOL®, COSMOSWorks ®, and Pro/ENGINEER®. The usage of FEM in fatigue analysis does have some limitations. An absence of actual loading data throughout components life limits the accuracy of life prediction results. A second limitation is the random variance in material performance even in materials of the same type.

Finite element (FE) learning modules have been developed for various undergraduate engineering courses. Modules have been developed for the following topics: curved beam, bolt and plate stiffness, lateral frequency of a cantilever beam, lateral vibration of a tapered cantilever beam, steady state heat transfer in a bar, transient heat transfer in a l-bar, cylindrical drag, friction flow in a pipe, probe feed patch antenna, specific absorption rate, transmission parameters of an infinitely long co-axial cable, and human head.[1,2] These FE learning modules are used to introduce basic and complex engineering problems to enhance student learning of the theory and fundamentals of the finite element method (FEM). Students are also introduced to best practices in modeling and problem solving through the use of commercial FE software. In the development of an earlier ANSYS® based fatigue FE learning module[3], a review of educational literature revealed that fatigue and finite elements are not addressed together. The intended usage of this fatigue FE learning module is to integrate fatigue design theory into a FEM course or fatigue FE in a machine design course. The fatigue FE learning module will serve as an online resource for students and a tool for effectively presenting the lecture material for instructors.

The FE learning module considered in this paper is the fatigue loading of a stepped shaft. COSMOSWorks®[4] was selected as the commercial FE software. The design of the fatigue FE learning module is based on student learning experience progressions using the Kolb Cycle. The different experiences found in the module will require students to think in ways not typically found in a traditional classroom lecture. Student assessment data will be used to evaluate and make improvements to the FE learning module. The students' opinion of the FE learning module will also be evaluated using a post survey upon completion of the module. The educational value of the FE learning module will be monitored using pre- and post-quizzes. Additional assessment tools will be used to identify any bias in the FE learning module towards any Felder-Soloman learning style and/or Myers-Briggs personality type. Statistical study of these assessment results will allow the content and presentation of the module to be continuously changed to better suit engineering students.

3.3 Learning Experience Progression

3.3.1 History & Overview

Experiential learning has been valued as early as the teachings of Confucius or Aristotle. At the start of the 20th century, John Dewey[5] first identified experiential education as a fundamental foundation in formal educational. During the decades following John Dewey, many psychologists and educators began to believe that experiential education was valuable and could be incorporated in addition to traditional instruction methods rather than replace them.[5] Building upon earlier works by John Dewey, Jean Piaget, William James, and Kurt Lewin, David A. Kolb determined that learning is an experienced based process.[6] From this work, Kolb[6] determined that "learning is the process whereby knowledge is created through the transformation of experience." The theory presents a cyclical model of learning that consists of four stages.

In developing the fatigue FE learning modules, the Kolb Cycle has been selected for its ability to reach students of all learning styles. The importance of the Kolb Cycle as a guide for engineering education is stated in a journal paper, "The use of that model (Kolb Cycle) in the engineering teaching assists to three main objectives: to reach all the students through the teaching to each learning style; to stimulate the students to use all the four learning types; and, to teach the students to complete the cycle for themselves so that they think and learn in an independent way."[7] Learning styles will be discussed later in this paper.

3.3.2 Kolb Cycle

The Kolb Cycle has been proven to be an excellent technique to improve student retention of complex numerical methods used to analyze engineering problems.[6-9] The Kolb Cycle describes a cycle through which learning is achieved by various experiences. The Kolb Cycle, shown in Figure 3.1, displays four distinct stages used in the development of knowledge within an individual through the experiences found in a stage.

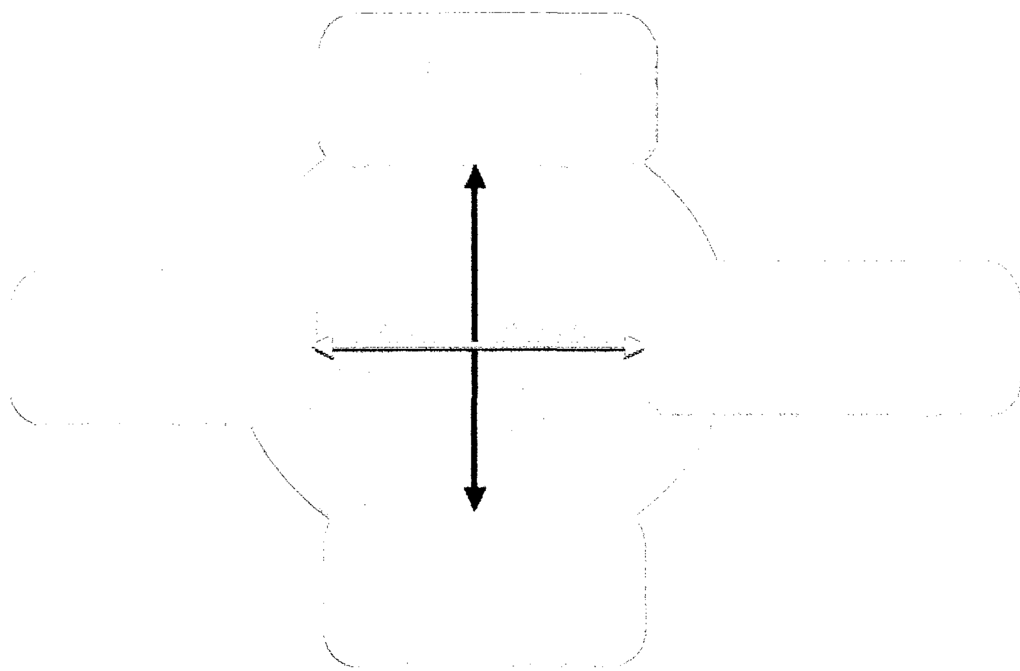


Figure 3.1. Kolb Cycle for learning experience progression.[6-9]

An individual will have strengths or preferences in both vertical and horizontal dimensions shown in Figure 3.1. The way this newly presented information is perceived correlates to an individual's learning styles and personality type.[6] The Kolb Cycle creates learning independent of how the information is perceived. Rather, the Kolb Cycle accommodates for all. Depending on the nature of the information, presentation method, learning styles, and personality types, new information may be difficult or easy to understand for a given individual. Within the stages of ***Concrete Experience*** and ***Abstract Hypothesis and Conceptualization*** learning takes place through the presentation of new factual or new theoretical information. These two vertical stages, as shown in Figure 3.1, are where an individual will "*Take-In Information.*" The vertical dimension within the Kolb Cycle describes how an individual will perceive this new information.[6]

In the stages of ***Active Experimentation*** and ***Reflective Observation*** knowledge is gained through the activities found in these stages of the Kolb Cycle.[6] The horizontal dimension of the Kolb Cycle describes the way an individual tries to "*Process Information*" previously perceived in the vertical dimension.[6] The activities found in the stage ***Active Experimentation*** are used to investigate the validity of new information by experimental methods. This stage may or may not match with the learning styles and personality types of an individual. Once again the Kolb Cycle contains a contingency. ***Reflective Observation*** uses much more passive and reflective activities, as shown in Figure 3.1, to verify the newly perceived information. Using the Kolb Cycle as a guide, classroom instruction may be developed to include all stages and encompass individuals of all types.

The inner loop of the Kolb Cycle shown in Figure 3.1, describes a pattern of possible thoughts that lead to a progression from one set of experiences to new experiences. Each of the following four questions are seen as transitional phases: "*Why?*", "*What?*", "*How?*", and "*What If?*".[7] These transitional questions will tend to arise, as a natural curiosity develops in the minds of a student.

3.3.3 Application of Kolb Cycle to Fatigue FE Learning Module

In a paper written by Brown[8], *Teaching Finite Elements using the Kolb Learning Cycle*, a global analysis of a FE course is made in regard to stages of the Kolb Cycle that are experienced in that course. Brown states that, " Students are provided ***Abstract Hypothesis/Conceptual*** Modules that begin with the background of the FE method, fundamental mathematics of FE, move through the concept of "stiffness-analysis", one-dimensional direct stiffness analysis of various structures, the topology of the various finite elements, error analysis of FE results, and concludes with how to model engineering problems using this technique."[8] The ***Abstract Hypothesis/ Conceptual*** stage in Figure 3.1 can have experiences encompassed in the following three areas: the modeling, analysis, and theory. One or more of these experiences may be used to engage students in the ***Abstract Hypothesis/Conceptual*** stage. Brown then goes on to say that experiences found in homework assignments, course projects, and the FE learning modules apply to the ***Active Experimentation*** portion of the cycle. Additional types of ***Active Experimentation*** classroom activities are stated in Figure 3.1. These activities include laboratory experiments, product teardowns, testing using engineering tools and methods, and performing simulations. The fatigue FE learning module focuses mainly on the simulation activity, but these other activities could certainly be used to connect new ideas and get students involved in the learning cycle. The problems considered in the FE course are often related to a "real-world" problem and are an example of a ***Concrete Experience.***[8] Activities within the ***Concrete Experience*** stage shown in Figure 3.1 can be used to reinforce or provide a ***Concrete Experience.*** These activities can include dissection, reverse engineering, and case studies. In the fatigue FE learning module the activity experienced most like a case study. After the student performs fatigue FE learning module, they are asked to compare the FE results with the analytical solution. Most importantly, they are asked to attempt to explain the differences between the FE and analytical results. This requires that they engage in ***Reflective Observation*** portion of Kolb's Cycle. Activities, shown in Figure 3.1, that are found to provide a ***Reflective Observation*** type experience include: having open discussions, keeping a journal or notebook collection, and perturbation by a course instructor. Individual activities require inner thought and reflection which require a student to engage in a ***Reflective Observation*** of activities or experiences recently completed. Designing around Kolb Cycle will reach more if not all students. Brown also describes a micro learning cycle for his FE learning modules that engages all areas of the Kolb Cycle.[8] It is in this same manner that that the fatigue FE learning module has been developed.

The fatigue FE learning module has been designed and interlaced within the four stages of the Kolb Cycle. Prior to the introduction of the module, the students will have partially covered the fundamentals of machine design theory. A brief introduction to FE theory may also be provided, but will be covered as well in the fatigue FE learning module. This prior knowledge starts the Kolb Cycle for the FE learning module at the ***Abstract Hypothesis and Conceptualization*** stage of the cycle. In this area some of the students may begin to develop ideas as to "*How?*" the theory may be applied to "real world" problems. This develops a progression towards applying theory as is done in the ***Active Experimentation*** stage of the Kolb Cycle.

The fatigue FE learning module is largely a listing of a step-by-step user's guide on how to carry out a FE analysis of a fatigue based machine design problem. In the stage of ***Active Experimentation*** the students will be asked to perform the required steps for the FE analysis. Later they will be asked to perform manipulations that will include changing physical geometries and/or loading conditions. This will lead the students to form opinions as to how these changes will affect the results, as well as reinforce guiding principles. These changes may lead the student to draw the conclusion "*What If?*" while making modifications. The problem selected for the fatigue FE learning module is a circular stepped shaft subjected to fully reversed fatigue loading. This problem presents a simple case study that is present in many everyday applications, such as power transmission shafts in automobiles. The example problem selected is from Shigley[9] and provides the student with a ***Concrete Experience*** as well as a reference to applicable fatigue theory.

Reflective Observation can be achieved by asking the students to compare the results from the FE analysis to the analytic solution from fatigue theory and compare the results match. If the FE solution results do not match the analytical solution, the students should be asked "*Why?*" the solutions are different. The instructor may prompt students with diagnostic questions to reveal errors in steps where mistakes are commonly made. Other possible ways to invoke ***Reflective Observation*** include group discussions and report writing. These types of assignments require the students to reanalyze what they have done and reflect "*Why?*" they have done these things in the three previous stages. Finally to complete the cycle, students will take what they have learned from the module and want to know "*What?*" other problems can be modeled and solved with FE methods. The students now have used commercial tools and developed skills to analyze more complex problems with further practice. It is in this manner they will be able to begin providing solutions to new problems using self conceived ideas in new areas.

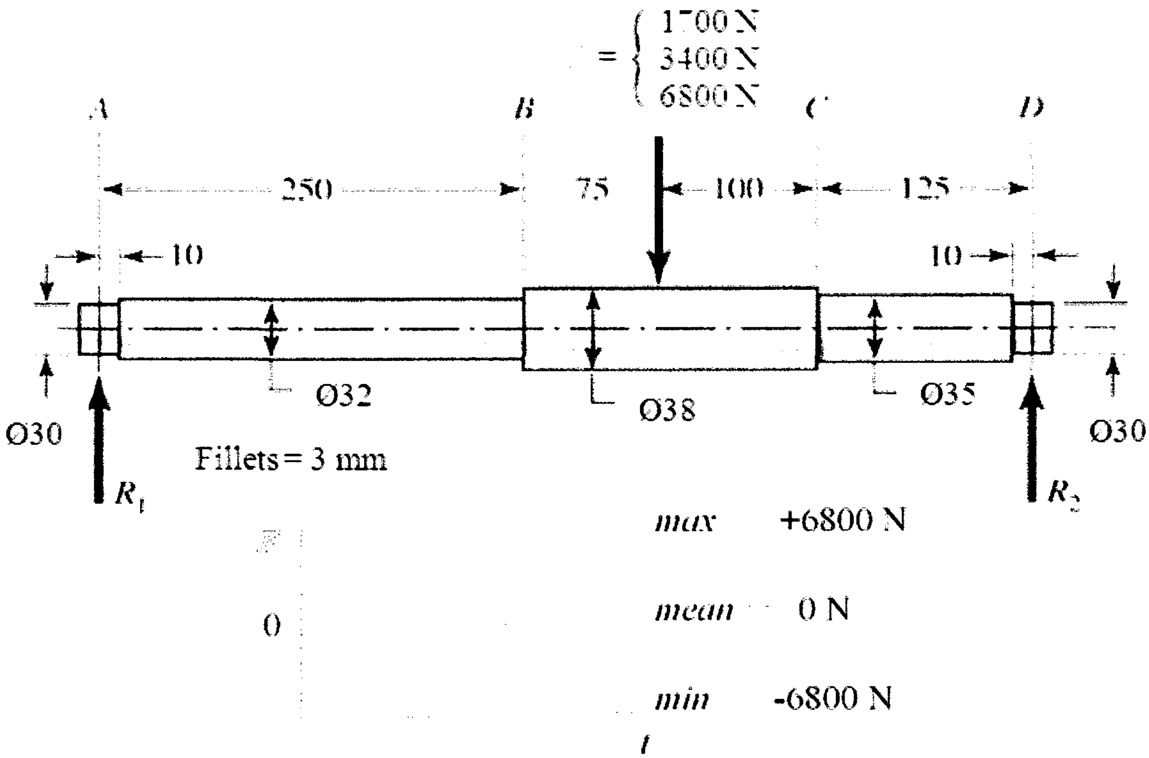
3.4 Fatigue FE Learning Module

3.4.1 Overview

This module was integrated into the senior level MECH 125 Machine Design II course at the University of the Pacific by Prof. Jiancheng Liu in the spring semester of 2009. The fatigue FE learning module is designed to be used as a classroom learning tool within an undergraduate machine design course or FE course. Very little knowledge of FE theory is required to complete the module. However, some introductory undergraduate machine design theory is required to understand the terminology and principles applied in the creation of the FE model. The background required before using the module are the fatigue equations for fully reversed loading. The fatigue problem selected is simple, so that the students may connect the solution to the pertinent machine design theory within the FE analysis. The fatigue FE learning module will be available in two file formats, Microsoft® Office PowerPoint® and Adobe Acrobat®. These file formats ensure ease of use and the ability to go back and review steps in the solution development process. An instructor can also change the PowerPoint® slides to meet his/her needs. As mentioned in a previous paper[1], certain aspects of the module will be included to create overall uniformity. These items include module title, author, author contact information, expected module completion time, table of contents, and references. Educational objectives based upon Bloom's Taxonomy[10] and ABET Criteria 3 for Engineering Programs[11] are stated at the beginning of the module. A detailed problem description and relevance is included along with the analysis objectives. A large majority of the module content will be the step-by-step process to create a FE model and carry out a FE analysis. Portions of this guide will be directed at properly viewing the FE results. A comparison of FE results to the analytic solution is included to emphasize the importance of solution verification. Finally, an overall summary and discussion section is included to review what the user has accomplished and the techniques and underlying FE theory involved.[1]

3.4.2 Example Problem

Choices of fatigue problems that are appropriate for both introductory undergraduate machine design and FE courses are quite limited in nature. Example 7-10 from Chapter 7 of Shigley's *Mechanical Engineering Design* was used.[9] The problem selected is a circular stepped shaft with ball bearing supports at points A and D. At each diameter change a fillet with a radius of 3 mm is present. The shaft is subjected to a fully reversed concentrated loading. The applied load is a non-rotational force (F) with a magnitude of 6.9 kN as shown in Figure 3.2. The shaft is machined from AISI 1050 cold drawn steel with a tensile yield, S_y, of 580 MPa. The ultimate tensile strength, S_{ut}, is 690 MPa. The shaft is to operate at room temperature. The reliability factor is 1.0 and the fatigue endurance limit, S_e is 345 MPa. The problem requires that the shaft life be estimated for loads (**F**) of 1.7 kN, 3.4 kN, and 6.8 kN. Additional material properties for AISI 1050 cold drawn steel not provided by Shigley[9] are required for the three-dimensional FE analysis and they include Young's Modulus, $E = 207$ GPa, Poisson's ratio, $\nu = 0.29$, and shear modulus $G = 80$ GPa



AISI 1050 Cold Drawn Steel:
S_y = 580 MPa; S_{ut} = 690 MPa; S_e = 345 MPa; E = 205 GPa; ν = 0.29; G = 80 GPa.

Figure 3.2 Stepped circular shaft (dimensions in mm.) subjected to a fully reversed loading.[9]

3.4.3 Finite Element Model

The commercial software COSMOSWorks®[4] is used for this fatigue FE learning module. COSMOSWorks® is widely used in industry and undergraduate engineering programs, and with the SolidWorks® three-dimensional solid modeling software. Within COSMOSWorks® there are several analyses that can be performed. This problem requires both static and fatigue analyses. COSMOSWorks® uses the static analysis to formulate the fatigue analysis. Essentially the loading is considered the same as the static analysis and an event is defined for the application of the fully reversing cyclic load with the loading ratio of (R = -1) for the defined static load for a specified amount of cycles.

The failure analysis compares the applied alternating stresses against a fatigue strength curve (S-N curve) for the given material on the interval of the applied cycles.

The stepped shaft was modeled in SolidWorks® as a three-dimensional solid. The solid model is meshed with ten node quadratic tetrahedral elements by the high quality automatic mesh generator in COSMOSWorks®. The geometry, material properties, and loading are shown in Figure 3.2. The FE mesh consists of 12,873 nodes and 7,940 tetrahedral elements as stated in Figure 3.3. Each node has three degrees of freedom (DOF) and the mesh has a total of 38,619 DOF. The ball bearing end supports are shown in Figure 3.3. All DOFs were constrained on the cylindrical surfaces of the shaft that make contact with the bearings. These constraints resemble fixed-fixed boundary conditions. The concentrated load was defined as a normal force over a 5 mm radius circle on the top surface of the shaft in as Figure 3.3. This was done to eliminate stress concentrations in the vicinity of the concentrated load.

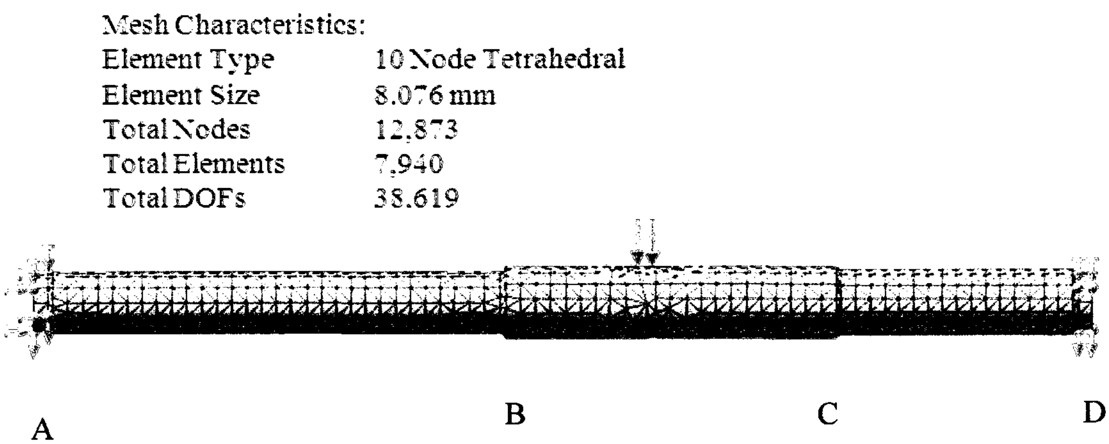


Figure 3.3. COSMOSWorks® FE mesh of the stepped circular shaft.

3.4.4Static Deflection Analysis

A static deflection analysis of the shaft with a 6.8 kN load was carried out using COSMOSWorks®. The maximum vertical deflection occurs 298 mm from the left end of the beam with a magnitude of 0.3706 mm as shown in Figure 3.4. The maximum deflection is to the left of the applied load.

This result was verified with mechanics of materials principles considering a fixed-fixed uniform circular shaft of 38 mm, 35 mm, and 32 mm in diameter. The deflection value is -0.258 mm for a uniform 38 mm shaft, -0.359 mm for a uniform 35 mm shaft, and -0.513 mm for a 32 mm uniform shaft. The FE solution of 0.3706 mm for the stepped shaft is bounded between these values for the uniform shafts. The deflection may seem small, but it is actually too large if the shaft included gears. The recommended maximum deflection for a shaft with gears is 0.127 mm.[12]

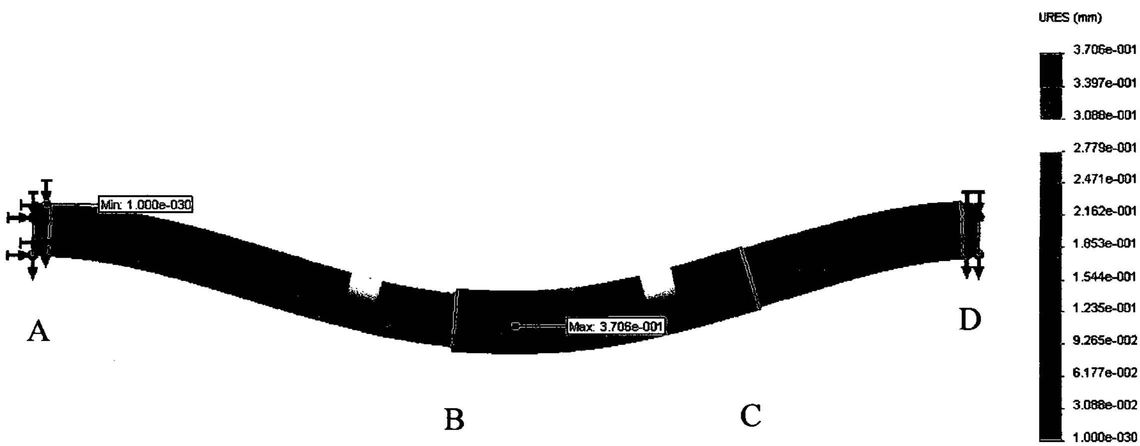


Figure 3.4 Resultant deflection (mm) analysis for the 6.8 kN load.

3.4.5 Static Stress Analysis

A static stress analysis was carried out in COSMOSWorks® as shown in Figure 3.5. The highest stress was found at the bottom surface of the right bearing support (point D) in the fillet radius. The magnitude of the von-Mises stress at that location is 296 MPa as shown in Figure 3.6. This value is approximately 56% of the tensile yield strength, S_y = 530 MPa on the first loading cycle.

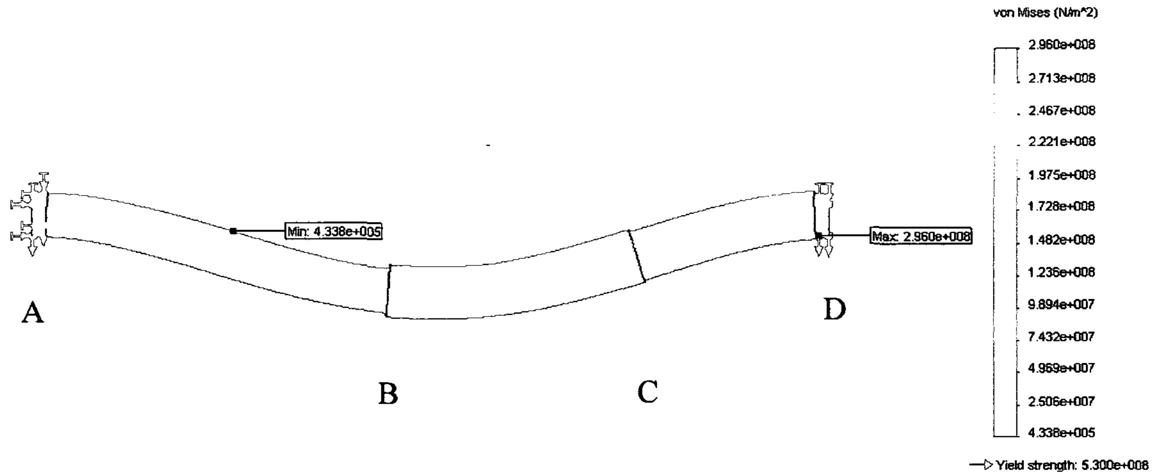


Figure 3.5 Static von-Mises stress (Pa) analysis for the 6.8 kN load.

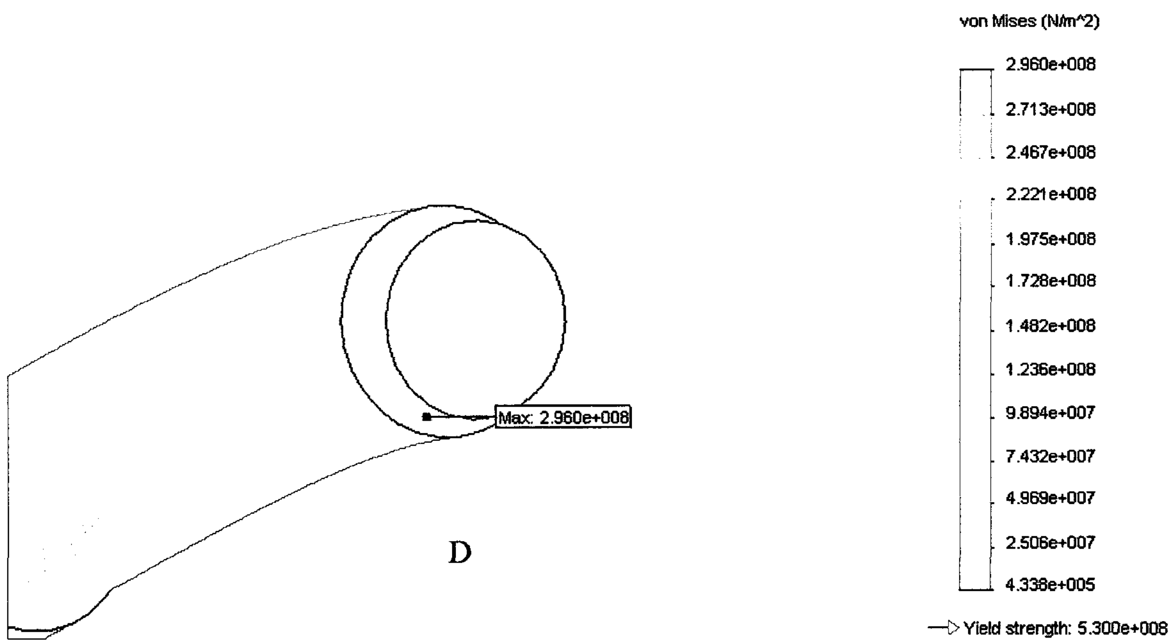


Figure 3.6 Highest von-Mises stress (Pa) location at the bottom right bearing support (point D).

Bending stresses were verified at the right bearing support (point D) using the mechanics of materials solution for a fixed-fixed beam. The stress concentration values at the fillet radii were determined from Shigley.[9] The bending stress at the fillet radius of the bearing support location was 312.30 MPa using mechanics of materials. There is a

5.2% difference in the two solutions types for the maximum static stress. Since the educational version of COSMOSWorks® was used, there was a limitation in obtaining a more accurate FE solution at the fillet locations, therefore, 5% is considered acceptable in this work.

3.4.6 Fatigue Analysis

COSMOSWorks®[4] was used to estimate the number of life cycles the shaft would survive subjected to reapplications of the 6.8 kN load as shown in the F-t curve of Figure 3.2. The shaft should be designed to withstand 10^6 loading cycles; however, the corrected endurance limit is 236 MPa and the highest applied static stress is 296 MPa which means that the shaft will have a finite number of life cycles.

In COSMOSWorks® a stress-life approach is used to carry out the fatigue analysis. Stress-life methods are commonly found in undergraduate machine design courses and textbooks. As previously discussed in the section on the finite element model, COSMOSWorks® uses the results from the static stress analysis to compute an alternating von-Mises stress for the defined fatigue event. This alternating von-Mises stress is compared to the material S-N curve. The ASME austenitic fatigue S-N curve for AISI 1045 cold drawn steel is shown in Figure 3.7. This material was selected since it most closely matches AISI 1050 in the COSMOSWorks® material library. AISI 1050 is not available in the COSMOSWorks® material library.

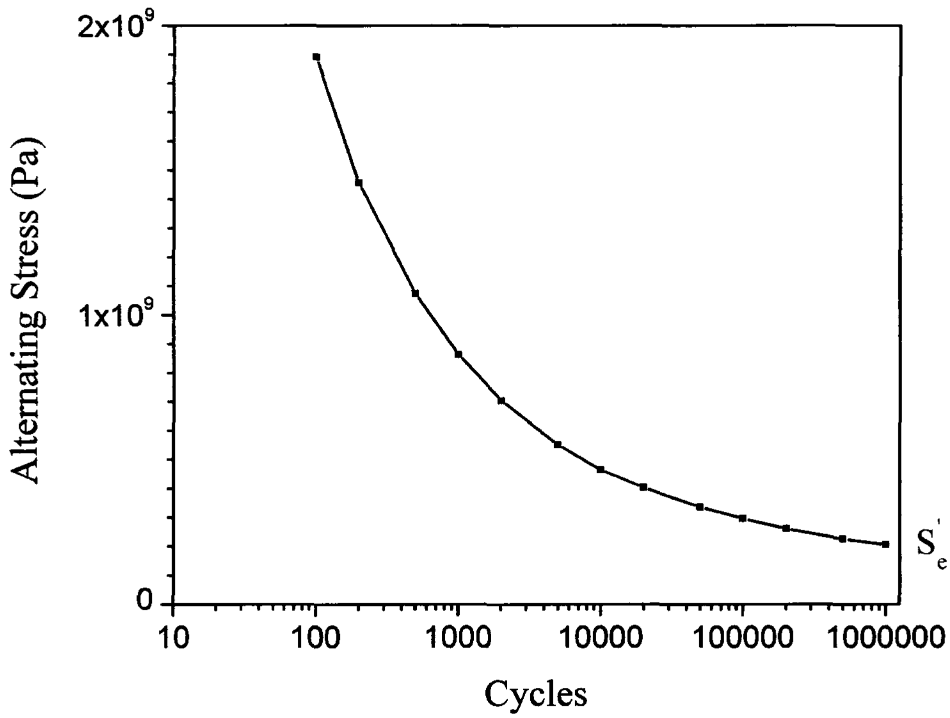


Figure 3.7 Semi-log scale S-N plot of AISI 1045 cold drawn steel from COSMOSWorks® material library.[4]

The life plot in Figure 3.8 shows the lowest number of cycles until failure at all locations of the shaft. The most probable location for failure is at the bottom right bearing support of the shaft (point D) as shown in Figures 3.8 and 3.9. The minimum number of cycles for the shaft is 99,280 until failure. The life plots in Figures 3.8 and 3.9 show a range of 99,280 to 339,500 cycles at the bearing support. This compares well with the analytic solution of 112,000 cycles stated in Shigley.[9] Therefore, COSMOSWorks® is more conservative than the analytic solution.

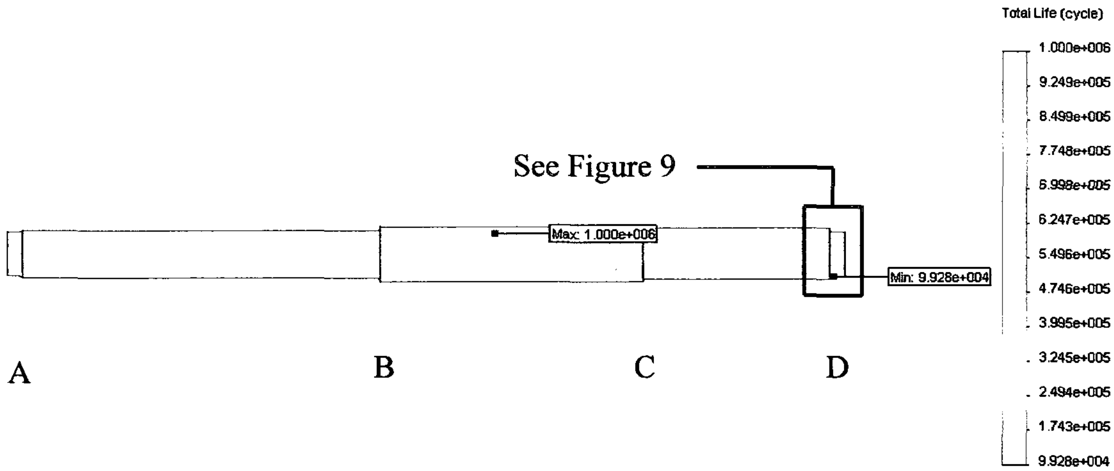


Figure 3.8 Life plot of shaft.

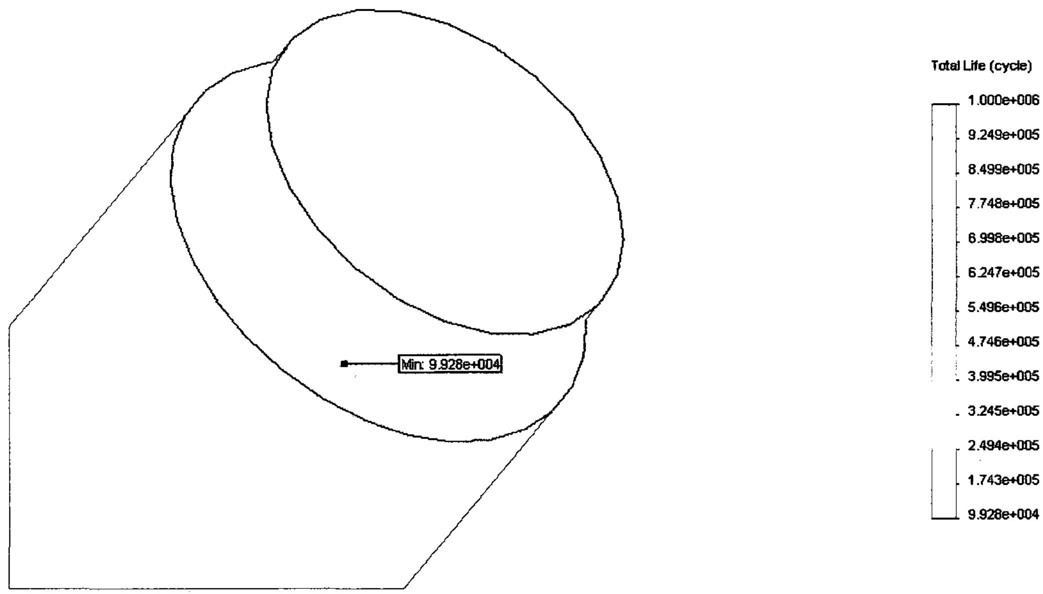


Figure 3.9 Enlarged view reveals fillet radii at the bottom right bearing support is the most probable failure location.

It is important to compare these results with applicable fatigue theory found in the textbook. This verification provides a secondary check to the FE analysis. Table 3.1 displays the life cycle predictions through the analytical and FE solution. It can be observed that the values for the 6.8 kN load are within a reasonable range of values. As one can see from the Table 1, the loading cases of 1.7 kN and 3.4 kN have an infinite life.

The discussion of these loadings was not covered in this paper; however, it discussed in the module as a modification to the FE model. The solution from COSMOSWorks®[3] by its nature is slightly on the conservative side. If the results are not within a similar range with the analytical solution it is quite possible that an error has been made. Stepping through the portions of the analysis and checking the results will allow the student to develop skills on how to identify potential errors in future FE analyses.

Table 3.1 Comparison of solution methods for the fatigue analysis.

Loading Case (F)	**Solution Type**	
	Analytic[9]	**COSMOSWorks®**
1.7 kN	Infinite Life	Infinite Life
3.4 kN	Infinite Life	Infinite Life
6.8 kN	112,000 Cycles	99,280 Cycles

3.5 Learning Styles: Felder-Soloman

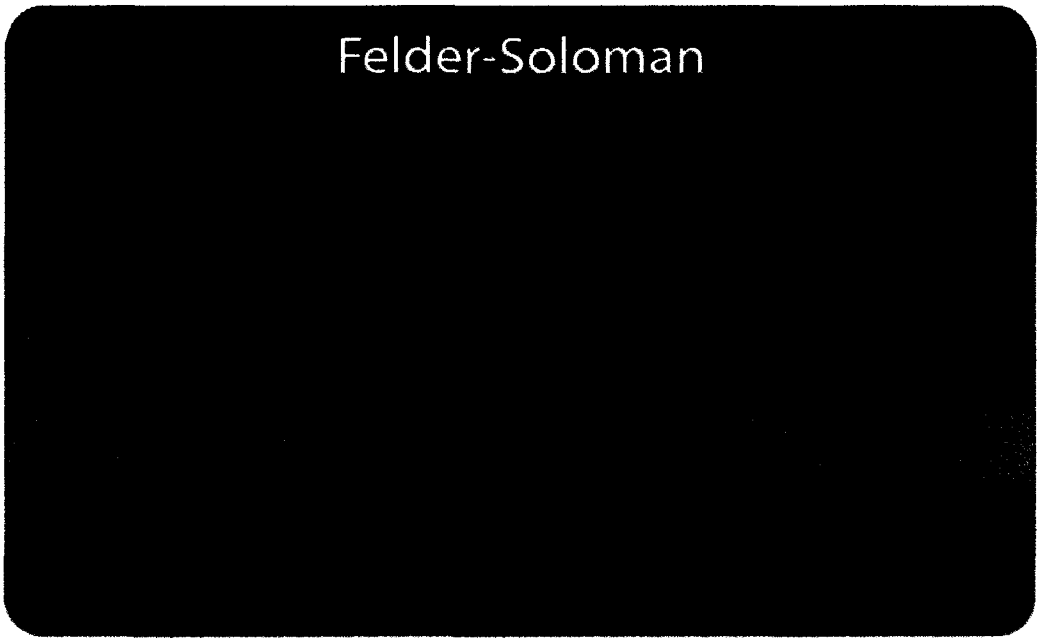
3.5.1 History & Overview

Learning styles have only been used as an important learning tool in formal education since the start of the 20th century. The Felder-Soloman learning style model is based on initial psychological theory of Carl Jung[13], the learning style work of David Kolb[6], and the Myers-Briggs Personality Types Indicator. In some cases, learning styles and personality types are discussed in unison. The Myers-Briggs personality types will be discussed in-depth later in the next sections of this paper. A large number of learning style models have been established for various fields. A few to be mentioned are models developed by Anthony F. Gregorc[14], David Kolb[6], and the Herrmann Brain Dominance.[15] These learning styles may have applications in certain educational programs; however, the work of Richard M. Felder and his associates have focused almost entirely on engineering students. This is the reason why this learning style model is used in this work to aide in the development and improvement of the fatigue FE learning module.

3.5.2 Felder-Soloman Model

Richard M. Felder Linda K. Silverman addressed a mismatch of learning styles reached by traditional classroom techniques and engineering student learning styles.[16] This paper was based on the prior psychological theory by Carl Jung[13] and included additional learning style information written by Kolb[6], discussed earlier, for his work in the development of the experiential learning cycle. Felder and Silverman proposed that identifying common learning styles in engineering students would allow for the creation of new styles for presenting lecture material that would more effectively educate students of all learning styles. Felder continued this work and with the help of Barbara Soloman created the Felder-Soloman *Index of Learning Styles*.[16-18] The Felder-Soloman Index of Learning Styles is shown in Table 3.2 and is used to identify the fixed learning styles present in an individual.

Table 3.2 Felder-Soloman Index of Learning Styles.[16-18]



The Felder-Soloman Index of Learning Styles is composed of four pairs **Active/Reflective**, **Sensing/Intuitive**, **Visual/Verbal**, and **Sequential/Global** as shown in Table 3.2. Felder notes that engineering students are typically, "...**Visual**, **Sensing**, Inductive (now omitted), and **Active**, and some of the most creative students are **Global**."[16] Felder identifies a discrepancy of engineering student learning styles and traditional instructional methods. Felder states that traditional instruction methods appeal to the following learning styles: "most engineering education is auditory (**Verbal**), abstract (**Intuitive**), Deductive (now omitted), passive (**Reflective**), and **Sequential**." [16] In 2002 a republication of the original learning styles paper by Richard M. Felder removed the Inductive/Deductive categories. These categories were removed since a sampling of Felder's students indicated that most students actually preferred the Deductive instruction type, contrary to his personal belief that Induction methods should be used in education until graduate school.[16]

Since Felder has focused specifically on engineering students, the Felder-Soloman model is used to develop and design the FE learning module. The initial goal of our fatigue FE learning module is to focus on designing the module to include the four typical engineering learning styles stated above. The FE learning module will accommodate **Active** learners since involvement or participation is required to complete the module during lecture/lab time periods. Students with a preference for **Sensing**, "prefer concrete information such as descriptions of physical phenomena, results from real and simulated experiments, demonstrations, and problem-solving algorithms".[19] The concrete nature of the example problem selected for analysis will appeal to students of the **Sensing** type. By knowing most engineering students have a **Visual** learning preference, we created a large amount of **Visual** instruction through computer screen captures of step-by-step instructions that are used to complete the FE learning module. **Visual** learners will also be captivated by the presentation of FE results that include deflection, stress, and life plots from the commercial software. Also, **Visual** learners will be taught how to model the problem in SolidWorks®, which is a visually stimulating and intensive process. Furthermore, the fatigue FE learning module is by its nature very sequential. Each step is clearly covered and builds towards the final goal of an accurate simulation of the problem, which will make it easier for the **Sequential** learner to grasp the content. **Global** learners may find it very easy to go through the module once the overall problem has been solved. **Global** learners may be able to avoid the step-by-step instruction methodology and can move faster through the module than their **Sequential** counterparts if the overall process is quickly learned.

3.5.3 Index of Learning Styles On-line Assessment

The Index of Learning Styles (ILS) is available online from Richard Felder's website at North Carolina State University.[18] The ILS provides instant results after completion of the 44 item questionnaire. This questionnaire measures the four classifications of the Felder-Soloman Model shown in Table 3.2. Each learning style classification has 11 questions. The responses of the 11 questions for each classification are used to compute the magnitude of a preference for a particular learning style. The magnitudes of each learning style preference will be presented as part of the assessment process for the FE learning module. The Felder-Soloman ILS may be found at the website http://www.engr.ncsu.edu/learningstyles/ilsweb.html.[18] The results of the learning style assessments are discussed later in this paper.

3.6 Personality Types: Myers-Briggs

3.6.1 History & Overview

Based heavily on the psychological types of Carl Jung[13], I.B. Myers and K.C. Briggs developed their personality type paper for twenty years before releasing it in 1962. The Myers-Briggs Type Indicator (MBTI) assessment is a psychometric questionnaire designed to measure psychological preferences in how people perceive the world and make decisions in their life. The personality type indicator assessment tool helped identify what kind of roles women, who were entering the industrial workforce of war-time production jobs, would be best suited for during World War II.[20] In a related way the MBTI may be used to analyze the best instructional methods for a range of personality types. Though the work of Carl Jung and the MBTI has no true scientific basis, it has been one of the most popular and widely used methods to classify personality types for the past half century.

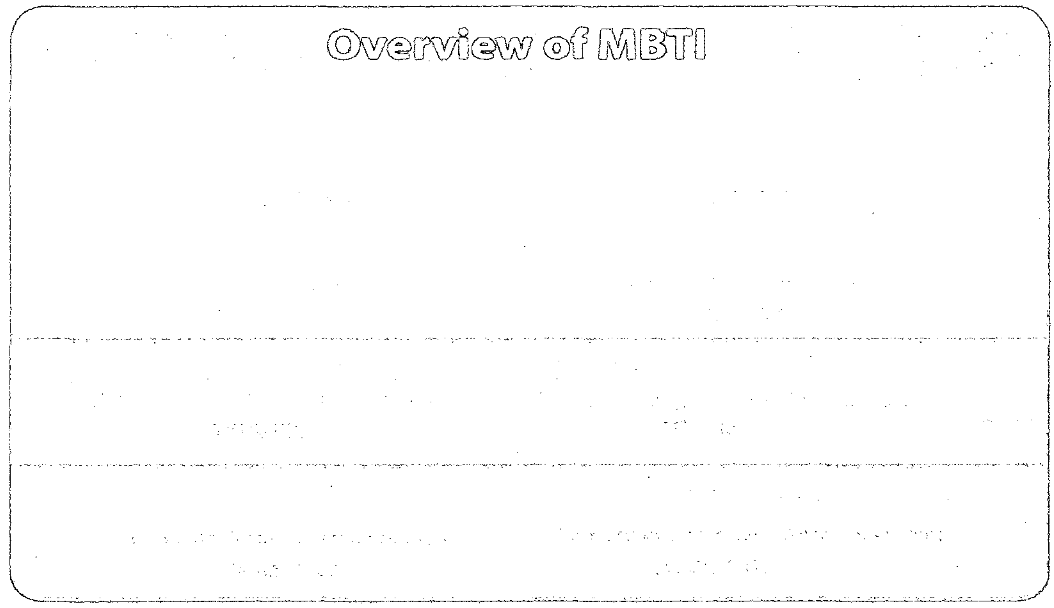
3.6.2 Myers-Briggs Type Indicator

The MBTI shown in Table 3.2 includes four categories of personality type preferences: **Extroversion/Introversion, Sensing/Intuition, Thinking/Feeling,** and **Judgment/Perception**. The first pair of **Extroversion** vs. **Introversion** regards the way an individual interacts with their environment. In the FE learning module **Extroverts** may find it easier to be involved and participate if the module is completed as a group or class, whereas **Introverts** would prefer to complete the module on an individual basis. The second of the four categories **Sensing** vs. **Intuition** provides insight into how a person processes information. People who tend to process and learn through their senses are referred to **Sensors**, versus people who process data based on the view that the information is of future use are referred to as **Intuitor**. The **Sensor** vs. **Intuitor** pair is seen by most researchers to be the most important of the four categories in terms of education. A major goal of this project is to design, use, and improve the FE learning module in ways that will be effective for students with different MBTI personality types. For example, the module proceeds in a deductive manner. First, the FE and machine design theory is presented, and then module is completed. **Intuitor** types prefer to contemplate theory and then quickly implement the use of the theory in an application. The modules also have content explicitly addressed to the **Sensor** types. In particular, the tremendous visual aspects of the FE analysis results appeal to the **Sensors.**[19] A number of researchers have used the knowledge of MBTI types to enhance engineering education. The third pair, **Thinking** vs. **Feeling**, for MBTI preference attempts to describe the manner in which a person evaluates information. Those who tend to use a logical "cause and effect" strategy **Thinkers** versus those who use a hierarchy based on values or on the manner in which an idea is communicated **Feelers**. The final MBTI type pair indicates how a person makes decisions or comes to conclusions. **Judgers** are people that tend to back up their decisions based on evidence. Those who tend to wait to be sure that all data has been thoroughly considered are known to be **Perceivers.**[20]

3.6.3 Personality Types On-line Assessment

The assessment of the personality types will be completed using the Jung Typology Test™. A 72 item questionnaire is completed to determine the MBTI types and their relative strengths. The MBTI on-line survey provides students with four letters (either **E** = **Extrovert** or **I** = **Introvert**; either **N**= **Intuitor** or **S** = **Sensor**; either **T** = **Thinker** or **F** = **Feeler**; either **P** = **Perceiver** or **J** = **Judger**) that indicate their personality component types. In addition, weights or strength values for each preference are provided to the students as well. From these strengths the personality type of a student may be analyzed and used further in the assessment process to identify any biases towards any one personality type. The location of the Jung Typology Test™ may be found at the website http://www.humanmetrics.com/cgi-win/JTypes2.asp.[21] The results of the personality type assessments are discussed in the next section of this paper.

Table 3.3 Myers-Briggs Type Indicator (MBTI) categories of personality types.[19,20]



3.7 Assessment Tools and Results

3.7.1 Overview

An assessment program is carried out for the fatigue FE learning module. The results from these assessment tools are used for continuous improvement of the module. The four assessment tools used are as follows:

- *Post-survey.* The post-survey is administered following the completion of the fatigue FE learning module. The post-survey can be used to indicate what the students liked and disliked about the module. The post-survey will also ask the students how much they learned using the module in comparison to a traditional classroom approach.
- *Pre- and Post-quizzes.* A short quiz is administered before and after the implementation of the fatigue FE learning module.

- *Learning Styles.* The Felder-Soloman learning styles of each student are identified through an on-line questionnaire to determine whether the fatigue FE learning module is biased towards a particular learning style based on the pre- and post-quiz results.
- *Personality Types.* The Myers-Briggs personality types of each student are identified through an on-line questionnaire to determine whether the fatigue FE learning module is biased towards a particular personality type based on the pre- and post-quiz results.

Each assessment tool above will now be discussed in-depth.

3.7.2 Post-survey

One assessment tool used to assess the fatigue FE learning module was the post-survey, administered after using the module. The post-survey questions and format were developed to follow a common template for all FE learning modules.[1] This ensures present and future FE learning modules are evaluated in a common manner to analyze the educational and analysis objectives.[1] The post-survey questions were based on the module educational objectives and analysis objectives. The post-survey responses used a five point Likert scale. The Likert scale used has the following five point scale: "Disagree", "Partly Disagree", "Neither Agree or Disagree", "Partly Agree", and "Agree". The post-survey for the fatigue FE learning module is shown in Figure 3.10. Multiple questions for each educational objective and each analytical objective were asked.

The post-survey results shown in Figure 3.10 were overall very positive. The results show that over 78% of the student responses were "Partly Agree" and "Agree" and including the "Neither Agree or Disagree" the positive response rate increased to

97%. We will now discuss the questions with shaded rows in Figure 3.10. A total of eleven students responded to the post-survey. Analyzing the 1st question of the post-survey, nine of the eleven students found that the module helped them to better understand "fully reversed fatigue loading." The 4th question reveals that ten of the eleven students felt that the module improved their understanding of static and fatigue FE analysis, as well as increased their confidence about carrying out machine component analyses. The responses of these two questions indicate that the students feel more confident in understanding both fatigue and FE analysis. In the 5th question all eleven students selected either "Partly Agree" or "Agree" with a simple conceptual question about the fatigue FE solution. The only fully negative feedback regarding the module was in the 10th question, a student felt that the module was not helpful in learning how to select a suitable finite element type. In the 17th question, seven of the eleven students thought the self-learning in the module was more beneficial than an instructor led classroom demonstration. Additionally, seven out of eleven students found the module to be very clear in its purpose and intentions as according to the 18th question. The 19th question is of particular importance because it indicates whether students enjoyed the module and found it to be a more effective method than traditional instruction. Only two students were found to "Partly Disagree" that was not an effective method for presenting FE and fatigue when compared to the traditional approach. The 20th question indicates that eight of the eleven students would like to learn more about the FE method and how to apply it to other mechanical engineering problems. The post-survey confirmed the perception by the students that this module helped them understand the concept of fatigue and assisted them in understanding FE theory.

Figure 3.10 Post-survey results for the fatigue FE learning module administered at the University of the Pacific in Spring 2009.

This survey will be used to evaluate and improve active learning activities in this class. Your student ID is used only to match up the results of this survey with others used in the course. Your opinions will be used to improve course learning activities. We will not correlate your survey response with your name or the assessment of any individual. Thank you in advance for your cooperation in our research efforts to improve learning here at the University of the Pacific under this NSF Grant. Prof. Jiancheng Liu

Student ID:____________________

Please put an X in the box below that corresponds to your answer.

#	Question	Disagree	Partly Disagree	Neither Agree nor Disagree	Partly Agree	Agree
1.	This activity helped me understand "fully reversed fatigue loading" in a conceptual manner?			2	9	
2.	This activity helped me to understand the assumptions of "fatigue theory?"		1	2	7	1
3.	This activity helped me understand the limitations of "finite elements and usage for fatigue theory?"			4	7	
4.	This activity helped me understand the topic of "static and fatigue finite element analysis," so that I have the ability to carry out finite element analysis of other machine components?"			1	8	2
5.	This activity showed me that the finite element method determines an approximate solution for the "life cycles of a rotating shaft fatigue" problem?				9	2
6.	Activities like this one, and similar ones done by commercial finite element software vendors, are only required to understand finite element theory?		2	7	2	
7.	This activity showed me that an understanding of "fatigue" theory can be reinforced with finite elements?			1	8	2
8.	This activity helped me create the correct geometry to model a "three-dimensional stepped shaft?"			2	5	4
9.	This activity helped me identify the material properties required to model the "static and fatigue finite element analysis?"			2	5	4
10.	This activity helped me to select suitable finite element type to model "the static and fatigue analysis of the rotating stepped shaft?"	1			6	4

Figure 3.10 'Continued' Post-survey results for the fatigue FE learning module administered at the University of the Pacific in Spring 2009.

Student ID:____________________

Please put an X in the box below that corresponds to your answer.

#	Question	Disagree	Partly Disagree	Neither Agree nor Disagree	Partly Agree	Agree
11.	This activity helped me understand that accuracy (not the correctness) of the solution is dependent on the quality of the mesh?			1	6	4
12.	This activity helped me to the correct boundary conditions (loads and constraints) to model the "rotating shaft"?			1	8	2
13.	After completing this activity, I was able to implement a suitable finite element type and construct a correct finite element model using commercial software?			2	8	1
14.	This activity helped me understand why it is important to check if the "applied loads" are specified correctly?			1	6	4
15.	This activity helped me to understand why it is important to check if the "constraints" were specified correctly?			1	6	4
16.	This activity helped me to understand why it is important to verify a finite element solution "i.e., deflections, stresses, and loading cycles" through an independent method, e.g., hand and/ or experiment?			3	6	2
17.	Personally seeing and developing the finite element model on my own was better than a classroom demonstration?			4	5	2
18.	This activity was very clear?			4	3	4
19.	This activity was more effective than using class time for lectures or board-work?		2	1	7	1
20.	I would like to learn more on using the finite element method to solve other mechanical engineering problems?			4	5	3
	Totals	1	5	42	126	46
	Percentage of Students Selecting Response	0.4%	2.3%	19.1%	57.3%	20.9%

3.7.3 Pre- and Post-quizzes

A pre-quiz and post-quiz shown in Figure 3.11 was administered to the students before and after using the fatigue FE learning module. The quiz should take no more than fifteen minutes to complete. Table 3.4 presents the results of the students' scores on the pre- and post-quizzes.

The average scores for the pre- and post-quiz is approximately 61 percent as shown in Table 3.4. Table 3.5 summarizes the statistical analysis of Table 3.4. Analysis reveals that the statistics of the data was not significant. This was due to the average of the pre-quiz and post-quiz being equal. The pre-quiz and post-quiz scores indicate that there was no overall improvement in student learning for the course. Furthermore, some students saw individual improvement while other students did not. This could be attributed to the quiz administered. The quiz may not be a good assessment tool since some of the students already understood the material better than before using the module. The authors plan to develop a new quiz that has multiple choice and true/false question to eliminate any subjectivity in grading by the instructor. Furthermore, the quizzes did not count as part of the course grade, therefore, the instructor will be suggested to count the post-quiz grade as part of the course grade. The module will be evaluated and modified before it is introduced in a future course.

Table 3.4 Individual student performance on the pre- and post-quiz.

Student ID	Pre-quiz Results	Post-quiz Results
1	70%	60%
2	60%	40%
3	50%	40%
4	55%	50%
5	65%	60%
6	45%	55%
7	50%	90%
8	85%	70%
9	85%	85%
10	40%	50%
11	65%	70%
Average Scores	**60.9%**	**60.9%**
	0% Improvement	

Table 3.5 Statistical analysis of the pre- and post-quiz results.

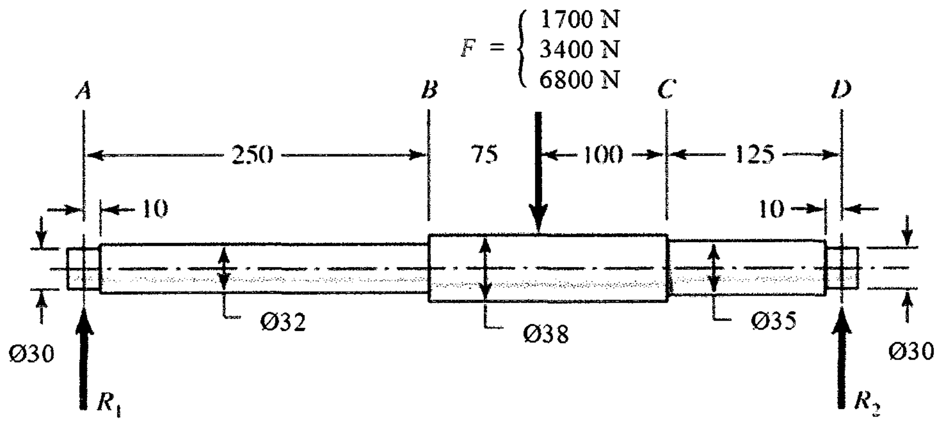
Quiz	Mean	Standard Deviation	Standard Error of the Mean
Pre-quiz	60.91%	14.97%	4.51%
Post-quiz	60.91%	16.55%	4.99%
95% Lower Bound For Mean Difference = 5.71		t-value = 0	p-value = 1.0

Figure 3.11 Pre- and post-quiz administered at the University of the Pacific in Spring 2009.

MECH 125 Machine Design II
Spring 2009

Your Student ID:____________________
Your Name:__________________________

Your responses will not be used for assessing your grade in MECH 125.



1.) The fatigue may first occur at which cross section location?
a) A b) B c) C d) D e) The cross section where the load is applied.

Answer: Prior to FE analysis: 2) Point B.
After FE analysis: 1) and 4) Points A and D.

2.) With a decrease of the external load, the shaft's life will increase. This statement is
1) True 2) False3) Both have no relation.

Answer: 1) True

3.) What is the difference between a static analysis and a fatigue analysis?

Answer: Static analysis estimates the stress level and compares the stress level to its yielding or ultimate strength. Fatigue analysis has to simultaneously take the stress level and operation time into account. The analysis procedures are also different when using FE analysis tool.

4.) The discrepancy between the analytical results and FE analysis results is large. Explain why?

Answer: For both methods, it is hard to get a real accurate result since there are many assumptions when conducting hand calculations or FE analysis using computer. But, it is clear from FE analysis results the life decreases with the increase of the load level.

One goal of this research is to create FE learning modules that span the spectrum of learning styles and personality types. As previously noted, we have chosen to measure learning styles using the Felder-Solomon model and measure personality preferences using the Myers-Briggs Type Indicator (MBTI). In order to gain insight into the effectiveness of the modules across different learning styles and personality types, the pre-quiz and post-quiz results will be separated based on these demographic data. Statistical analysis of these correlations will allow us to determine if the modules are more effective for certain demographic groups than others. This data will be used to change the modules in a closed-loop feedback manner where the goal is serving the learning needs of students with diverse learning styles and personality types.

Table 3.6 shows the average pre- and post-quiz scores for each learning style pair based on Felder-Soloman. The learning styles in Table 3.6 denoted by capital letters are common for engineering students.[16] The learning styles for each student was determined using the Felder-Soloman ILS.[18] The third learning style pair in Table 3.6 has eleven **VISUAL** students (N = 11) and zero **Verbal** students (N = 0). Most engineering students are typically **VISUAL** learners; this can be seen in Table 3.6. No students of the **Verbal** learning style are present in this course.

Table 3.6 Felder-Soloman learning style pairs with pre- and post-quiz percentage results.

Learning Style Pairs	N	Pre-quiz	Post-quiz	Delta*	Standard Deviation	Weighted Pre-quiz	Weighted Post-quiz	Weighted Delta
ACTIVE**	7	56.43	61.43	5.00	18.93	56.49	60.21	3.72
Reflective	4	68.75	60.00	-8.75	4.79	77.08	65.00	-12.08
SENSING**	4	53.75	60.00	6.25	25.62	52.88	60.00	7.12
Intuitive	7	65.00	62.14	-2.86	8.09	76.72	71.90	-4.83
VISUAL**	11	60.91	60.91	0.00	16.43	60.11	59.89	-0.21
Verbal	0							
SEQUENTIAL**	7	52.14	55.00	2.86	19.55	53.29	57.14	3.85
Global	4	76.25	71.25	-5.00	9.13	75.36	67.50	-7.86

*Delta = (Post-quiz – Pre-quiz)
**Common engineering student Felder-Soloman learning styles.[16]

We are interested in determining if the "Deltas" [(post-quiz score) – (pre-quiz score)] are statistically different between the pairs of learning styles. In order to determine this, the data is treated as a sample of a theoretical larger population. "Student-t" distributions are used for the statistical analysis as the sample sizes are relatively small. Note that the last three columns in Table 3.6 refer to "weighted" data. The on-line learning styles survey[18] returns results indicating learning style for the individual in each of the four learning style pairs and also includes a weight or strength for that learning style. This allows one to differentiate, for example, between someone who is only slightly **ACTIVE** over **Reflective** in their learning style and someone who very strongly prefers an **ACTIVE** over **Reflective** learning environment. The data in these last three columns were weighted (using a linear interpolation) according to the weights reported from the learning style survey for each student.

Standard statistical "t-student" analysis is used to determine the confidence intervals that are used that determine the likelihood that the "Deltas" for different learning styles are actually different (in a statistically meaningful manner). Table 3.7 shows the confidence intervals and the **VISUAL** vs. **Verbal** pair is missing. This is because all of the students in this data set were determined to be all **VISUAL** learners as shown in Table 3.6. So, for example, the unweighted confidence interval of 88.9% for **ACTIVE** vs. **Reflective** learners indicates that there is an 88.9% likelihood that there is a real (statistically speaking) difference between the Deltas for these two opposing learning styles. It is somewhat common to set the threshold of "statistical significance" at a confidence interval of 95%. As can be seen from Table 3.7, if this standard is used, there is no statistically significant differences between effectiveness of the fatigue FE learning module for the different learning styles for either weighted or the unweighted cases. This would indicate that the fatigue FE learning module has relatively equal effectiveness across the different learning styles. This is a very positive result as one goal is to avoid significant bias toward one learning style over another.

Although the confidence interval threshold of 95% is commonly used to indicate statistical significance, it may be informative to consider any occurrences where the confidence interval is greater than 50%. This would indicate that there was greater than 50% likelihood that one learning style benefited more than another from the fatigue FE learning module. If this criterion is used, noting from Table 3.8 that the **ACTIVE** learners had a higher positive Delta than the **Reflective** learners and noting from the first row of Table 3.7 that the confidence intervals were 88.9% and 92.6%, respectively, for the unweighted and weighted values the implication is that the module was more helpful for **ACTIVE** learners than for **Reflective** learners. This result is not surprising as the FE learning modules are, by nature, a very active process where the students participate in each step of building and analyzing the computational model. This being the case, the statistical analysis provides us with an opportunity to refine the FE learning module process in an "active feedback loop" manner. Perhaps the **Reflective** learners would be more effectively engaged in the process if, along with the step-by-step FE learning modules, reflective oriented questions were part of the process. This will be considered before the module is integrated the next time in the course.

Table 3.7 Confidence interval percentage for differences between Felder-Solomon learning style pairs.

Learning Style Pair Differences	Unweighted Confidence Interval	Weighted Confidence Interval
ACTIVE* vs. **Reflective**	88.9	92.6
SENSING* vs. **Intuitive**	46.1	56.9
SEQUENTIAL* vs. **Global**	60.8	78.6

*Common engineering student Felder-Soloman learning styles.[16]

In a manner very similar to what was done for the learning styles, Myers-Briggs Type Indicator (MBTI) personality type data is correlated with pre- and post-quiz scores. The goal is the same as with the learning styles data; to determine if certain student groups (in this case certain personality types) benefit differently from the fatigue FE learning module. Table 3.8 has the pre- and post-quiz average scores as well as the Deltas (difference between the pre- and post-quiz score) and standard deviations all separated based on MBTI pairs. In the same manner as was done for the learning styles, Table 3.8 includes weighted data as well as unweighted data. The personality types in Table 3.8 denoted by capital letters are common for engineering students.[20] The learning style for each student was determined using the on-line MBTI survey.[21]

Table 3.8 Myers-Briggs personality type pairs pre- and post-quiz percentage results.

Personality Type Pairs	N	Pre-quiz	Post-quiz	Delta*	Standard Deviation	Weighted Pre-quiz	Weighted Post-quiz	Weighted Delta
Extrovert	6	58.33	58.33	0.00	11.40	57.50	57.30	-0.20
INTROVERT**	5	64.00	64.00	0.00	22.64	69.38	65.00	-4.38
SENSOR**	6	61.67	57.50	-4.17	9.70	63.06	58.33	-4.73
Intuitor	5	60.00	65.00	5.00	22.36	53.74	59.17	5.43
THINKER**	6	59.17	65.83	6.67	17.68	62.01	63.32	1.31
Feeler	5	63.00	55.00	-8.00	11.51	62.79	50.45	-12.34
JUDGER**	8	65.00	59.38	-5.62	10.16	64.20	62.60	-1.59
Perceiver	3	50.00	65.00	15.00	22.91	50.00	68.85	18.85

*Delta = (Post-quiz – Pre-quiz)
**Common percentage of engineering students' Myers-Briggs personality type.[20]

Standard statistical "t-student" analysis is again used to determine the confidence intervals for the four relevant Myers-Briggs personality type pairs. Table 3.9 displays this data. Recall that the confidence interval is the statistical likelihood that there is a difference between the Deltas for the different personality type pairs. For example, as can be seen in the Table 3.9, the likelihood (weighted) that the **Extrovert** students have a statistically significant Delta than do the **INTROVERT** is 27.70%. As previously mentioned, the threshold for statistical significance is set at a confidence interval of 95%. Using this criterion there is no statistical differences, weighted or unweighted, between the different personality type pairs. This indicates that, at least for this fatigue FE learning module, different personality type pairs do not have significantly more or less benefit from the module. In other words, the fatigue FE learning module is not biased toward one student group based on a personality type. This is a very desirable result!

Table 3.9 Confidence interval percentages for differences between Myers-Briggs personality type pairs.

Personality Type Pair Differences	Unweighted Confidence Interval	Weighted Confidence Interval
Extrovert vs. **INTROVERT***	0	27.70
SENSOR* vs. **Intuitor**	49.95	56.72
THINKER* vs. **Feeler**	86.34	83.78
JUDGER* . **Perciever**	72.86	72.56

* Common percentage of engineering students' Myers-Briggs personality type.[20]

3.8 Conclusion

The fatigue FE learning module did not show any improvement of student learning based on no change in the pre-quiz and post-quiz scores. Past FE learning modules[1,2] have shown improvement of student learning. The fatigue FE learning module will be modified and the quiz will be improved before the module is implemented again into the classroom. It has been statistically shown that the fatigue FE learning module is not biased towards a particular learning style or personality type. Ultimately, the goal is to refine the FE learning modules and overall modeling experience in order to remove any bias toward specific student groups and to maximize the effectiveness of all the FE learning modules developed in this project.

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Chapter 4

STRUCTURED PROCESS FOR WRITING, REVISING, AND ASSESSING MULTIPLE-CHOICE QUIZZES

4.1 Abstract

A structured process is presented for developing or revising a multiple-choice quiz. A multiple-choice checklist form was created based on the best practices found in educational measurement books. The multiple-choice checklist form serves as a guide for an instructor to revise an old quiz or develop a new quiz. The effectiveness of the multiple-choice quiz checklist form is determined based on an assessment and evaluation process. This paper considers the development a 'new' quiz for bending stress in a sophomore level fundamentals of mechanics course. Four instructors used the multiple-choice checklist form to develop a new quiz and five instructors developed a new multiple-choice quiz without the checklist form. Independent reviewers are used to carry out a quantitative evaluation of the new quizzes developed with and without the multiple-choice checklist form. The assessment form is based on the multiple-choice checklist form. The results of the assessment process show that the proposed multiple-choice quiz checklist form is a valuable tool for instructors to develop more effective quizzes.

4.2 Introduction

Finite element (FE) learning modules have been developed for fifteen required undergraduate engineering courses.[1,2,3] Some modules have been developed for the following topics: curved beam, bolt and plate stiffness, lateral frequency of a cantilever beam, lateral vibration of a tapered cantilever beam, steady state heat transfer in a bar, transient heat transfer in a l-bar, cylindrical drag, friction flow in a pipe, probe feed patch antenna, specific absorption rate, transmission parameters of an infinitely long co-axial cable, and human head. These FE learning modules are used to introduce basic and complex engineering problems to enhance student learning of the theory and fundamentals of the finite element method (FEM).

After the implementation of a new fatigue FE learning module in the spring of 2009, the pre- and post-quiz assessment results showed no improvement in student learning.[3] This was the first time a FE learning module did not show significant improvement in student learning. After closer examination, we realized the quiz for the fatigue FE learning module used different question formats. The fatigue FE learning module quiz used half multiple-choice and half open-ended questions. Previous FE learning modules used entirely multiple-choice questions. Since open-ended questions are more challenging to assess student learning, future FE learning modules will use only multiple-choice questions. Whether a multiple-choice quiz should be used as opposed to a different format of a quiz (short answer, etc.) is a completely separate question. We have chosen to use a multiple-choice quiz as part of the assessment strategy for our learning modules.

This paper presents a multiple-choice checklist form that was developed based on a review of educational measurement books. The checklist provides a list of best practices divided into domains for an instructor to develop a new quiz or revise an old quiz. The proposed checklist form is easy to use and requires minimal time to complete. The checklist was validated using an assessment and evaluation process.

First, the paper reviews the educational literature for multiple-choice and discusses how the multiple-choice checklist form was developed. A supplemental instructor guide for developing/revising quizzes is discussed. The quiz development/revision process used in this work is described. The paper addresses the assessment process used to evaluate the effectiveness of the checklist form. Instructor groups used to develop new quizzes are defined. Assessment results are presented for the two instructor groups that did and did not use the checklist to write their quizzes. Finally, the paper discusses the conclusions drawn and scope of future work.

4.3 Multiple-Choice Quiz Checklist Form Literature Review

The literature review for the quiz development/revision process first considered engineering educational journals and conference proceedings. This review yielded widely varying results and very little guidance in developing quizzes. Most of the engineering educational literature focused on developing web based quizzes so that an instructor can easily grade and change questions for large enrollment courses.[4,5,6] A review of multiple-choice and educational measurement literature[7-29] provided insights into a process of developing new quizzes or revising old quizzes. Multiple-choice revision checklists were found in several books and contained very similar information.[7,10-12, 14, 27,28]

The checklist developed in this work is a derivative of checklists found in the educational measurement and multiple-choice exam writing books by Bloom[7], Gronlund[10], Haladyna[11], Hambleton[12], McDonald[14], Reynolds[27], and Linn[28]. Only these texts presented organized checklists. A majority of other texts contain long lists of guidelines followed by additional reading. These lengthy readings are impractical due to instructor time constraints. Checklists provide a direct means to evaluate quiz quality in a timely manner. Based on the literature review carried out by the authors, this is the first checklist that has been used in an engineering education environment.

4.4 Multiple-Choice Quiz Checklist Form

The ***Multiple-Choice Quiz Question Checklist Form*** developed in this work is shown in Figure 1. This checklist has been revised to meet the needs of our quizzes. The number of questions have been condensed and the questions rewritten to remove much of the jargon.

Multiple-Choice Quiz Question Checklist Form

Instructions: Review your new or old quiz using this checklist. The "perfect" quiz answers 'YES' to all questions. The pages that follow will provide guidance in filling out this checklist, and references are included if an in-depth explanation is required. Any question from the checklist that is answered 'NO' must be addressed in revising the quiz.

Quiz Name:____

Instructor:______________________________ Date:____________________

	YES	NO
Content		
1. Is each question designed to measure a *single learning objective*?	____	____
• If no, what *learning objectives* are not addressed (check appropriately)? #1____ #2____ #3____ #4____		
• How many questions are on the quiz? ______		
• State the number of quiz questions that address each *learning objective*. #1____ #2____ #3____ #4____		
Note: Sum total above must equal total number of quiz questions.		
2. Has new material, not introduced to students, been avoided in formulating problems measuring understanding and applications?	____	____
3. Has an appropriate number of questions been selected?	____	____
Format Suggestions		
1. Have numbers and letters been used to denote questions and options, respectively?	____	____
2. Are all options grammatically consistent with the question and parallel in form?	____	____
3. Are options listed vertically on separate lines?	____	____
Writing the Question		
1. Is the problem defined clearly in the question?	____	____
2. Is as much information in the question as possible?	____	____
3. Has no irrelevant information been included in the question?	____	____
4. Have grammatical cues or clues been avoided in the question?	____	____
5. Has a minimum number of negatively stated questions been used?	____	____
6. If a negative statement is used, has it been clearly emphasized?	____	____
Writing the Multiple-Choice Options		
1. Do all distractors represent plausible alternatives to examinees that do <u>not</u> possess the skill measured by the test question?	____	____
2. Are all the options as homogeneous as possible?	____	____
3. Are all options of the same length and complexity?	____	____
4. Have two options that mean the same been avoided, such that both can be rejected?	____	____

Figure 4.1. ***Multiple-Choice Quiz Question Checklist Form.***[7,10-12,14,27,28]

Multiple-Choice Quiz Question Checklist Form **'Continued'**

Instructions: Review your new or old quiz using this checklist. The "perfect" quiz answers '**YES**' to all questions. The pages that follow will provide guidance in filling out this checklist, and references are included if an in-depth explanation is required. Any question from the checklist that is answered '**NO**' must be addressed in revising the quiz.

Quiz Name:____

Instructor:______________________________ Date:____________________

Writing the Multiple-Choice Options **'Continued'**	**YES**	**NO**
5. Have modifiers like "usually" and "sometimes" been avoided in the options?	_____	_____
6. Are there important, detailed, or technical sounding words in the distractors?	_____	_____
7. Has the correct answer not been described in more detail than other options?	_____	_____
8. Has the length of the correct answer been varied, thereby eliminating a potential clue?	_____	_____
9. Is there one correct or clearly best answer?	_____	_____
10. Have the use of options such as "All-of-the-above" or "None-of-the-above" been avoided or minimized?	_____	_____

Figure 4.1. ***Multiple-Choice Quiz Question Checklist Form.***[7,10-12,14,27,28] 'Continued'

The ***Multiple-Choice Quiz Question Checklist Form*** was divided into four domains based on the guidelines described in Haladyna.[11] Almost all other books were not categorized into domains. The four checklist domains used in this paper are as follows:

- *Content.* This domain is used to evaluate the content of the entire quiz.
- *Format Suggestions.* This domain provides guidelines to format a quiz question and options.
- *Writing the Question.* This domain provides guidelines on writing the stem for a question.
- *Writing the Multiple-Choice Options.* This domain presents guidelines to develop the responses for correct and incorrect options for a given question.

Dividing the checklist into four domains could be very beneficial in future work. After the checklist has been used many times to develop or revise quizzes, the assessment results may show that there are common trends in certain domains. This may be beneficial in identifying problems and improving the quality of future quizzes. Completion of the ***Multiple-Choice Quiz Question Checklist Form*** by the instructor verifies that items within the specified domains are addressed. Any checklist item that is answered 'NO' by the instructor suggests that the quiz questions be reevaluated. For example, consider the first checklist item 'Is each question designed to measure a single learning objective?'. This checklist item requires the instructor to examine each quiz question to determine if each learning objectives is addressed by the quiz. The instructor is also required to determine the number of quiz questions that address each learning objective. The subcategories were added by the authors of this paper for an in-depth analysis of the overall content of the quiz.

4.5 Supplemental Guidelines for Writing or Revising Multiple-Choice Quizzes

The ***Multiple-Choice Quiz Question Checklist Form*** was designed to be concise. Therefore, the authors developed ***Supplemental Guidelines for Writing or Revising a Multiple-Choice Quizzes*** as shown in Appendix A. This supplement provides vocabulary and formatting guidelines for an instructor in the quiz development/revision process. Furthermore, this supplement could be a valuable resource for faculty members and graduate students who are new or inexperienced in developing multiple-choice quizzes. The supplement contains additional guidelines and best practices based on the knowledge-base in multiple-choice educational literature.[7-29] Textbook references are also included in the supplement for instructors who desire additional in-depth knowledge about multiple-choice quiz development/revision. The supplement is divided into the following four sections:

- *Definitions for Multiple-Choice Questions.* The definitions of the stem and options that form a multiple-choice question are discussed.
- *Multiple-Choice Question Formats.* This section defines the two types of multiple-choice question formats that should be used and they include direct questions and completion or incomplete statements.
- *Items from the Multiple-Choice Quiz Question Checklist Form.* This section provides additional guidelines for each domain, i.e., content, format suggestions, writing the question, and writing the multiple-choice options.
- *Proofreading the Quiz.* This section provides guidelines in proofreading the quiz.

The usage of the supplement by the instructor was optional in this work.

4.6 Quiz Development/Revision Process by Instructors

The multiple-choice quiz development/revision and assessment process used in the work is shown in Figure 2. This process was developed based on examples described in multiple-choice educational literature.[11] This section will only discuss the instructor's role in the quiz development/revision process. The multiple-choice quiz development/revision process begins with an instructor developing the quiz based on the learning objectives. Two groups of instructors defined as the control group and experimental group are used to assess the effectiveness of the multiple-choice quiz development/revision process. These groups are defined as follows:

- *Control Group.* The control group is shown on the left-hand side of Figure 2. The control group consists of instructors who each write the quiz based on their professional experience. The control group does not use the ***Multiple-Choice Quiz Question Checklist Form***.

- *Experimental Group.* The experimental group is shown on the right-hand side of Figure 2. The experimental group consists of instructors who each write independently a new quiz using the ***Multiple-Choice Quiz Question Checklist Form*** in Figure 1. All instructors in the experimental group are required to use the checklist form. The form will provide guidance for an instructor to identify any deficiencies in the quiz. An instructor can obtain additional guidance in writing a new quiz using the ***Supplemental Guidelines for Writing or Revising a Multiple-Choice Quiz*** in Appendix A. This guide is not required (optional) to be used by the instructor. After the quiz is written the instructor is required to fill out the checklist form.

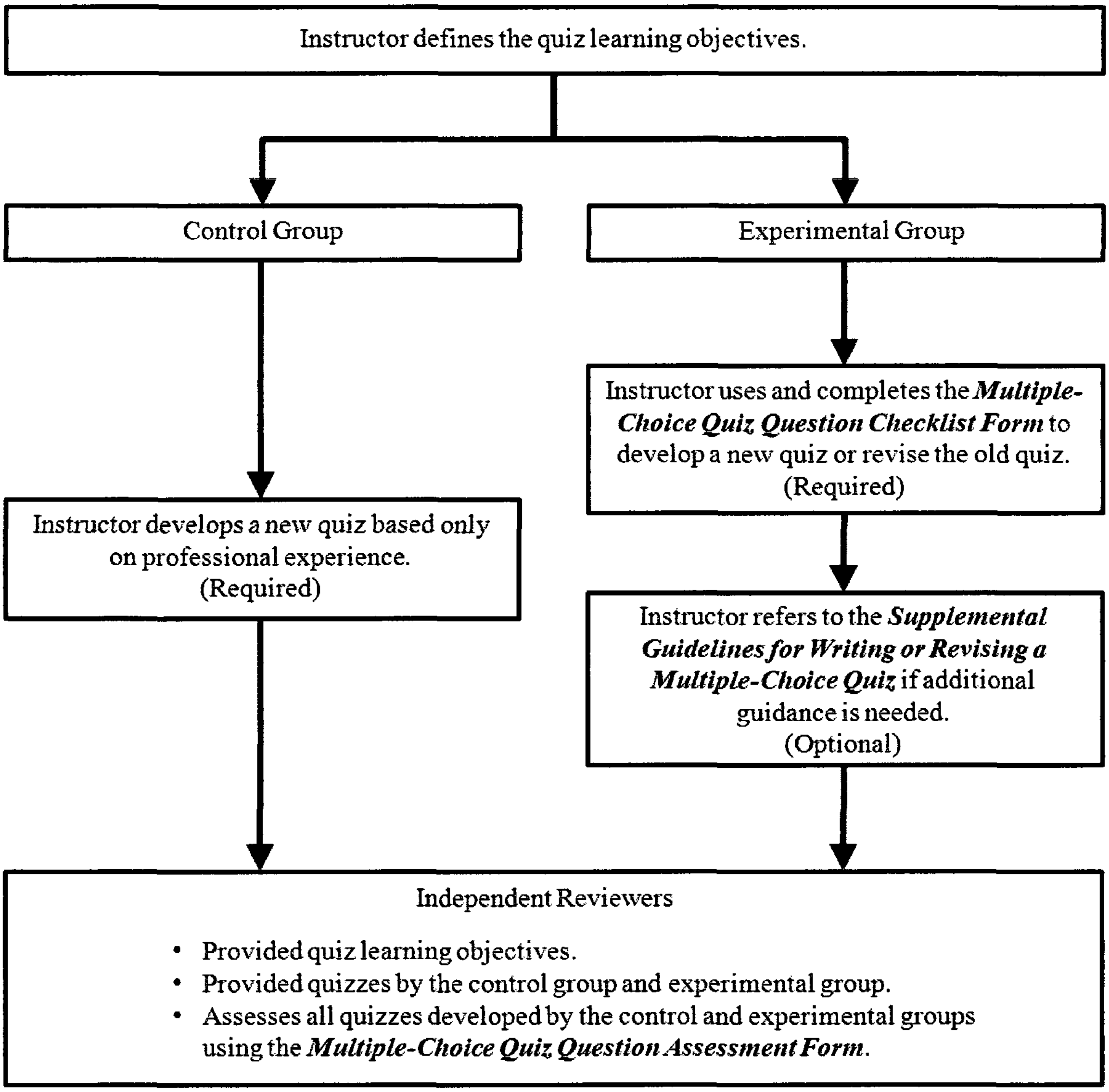

Figure 4.2. Multiple-choice quiz development/revision and assessment process.

Once all instructors from the control and experimental groups write their quiz, the assessment process is carried out by independent reviewers. The section to follow will discuss the assessment process used in this work.

4.7 Assessment Process by Independent Reviewers

The reader should note that this paper only assesses the usage of the ***Multiple-Choice Quiz Question Checklist Form*** (Figure 1) to improve quiz quality. This paper does not consider the impact of the checklist on student performance based on a quiz developed by the proposed multiple-choice development/revision process. This will be done in future work.

Figure 2 shows that after the quizzes are completed by instructors in the control and experimental groups an assessment is performed by independent reviewers. The following provides addresses the types of individuals that should be used as independent reviewers:

> "The persons asked for comment might be content-area experts, editorial specialists, or even examinees. Judgmental reviews have two guiding principles: each reviewer must be qualified for the task, and the task itself must be a systematic process. Both numerical analysis and judgmental review are important ways for writers to learn about the items they have written."[7]

Based on this information, the authors 'ideally' would like the following types of independent reviewers:

- *Engineering Faculty Members.* Engineering faculty members have the background to prove the validity of the quiz content related to the quiz learning objectives.
- *Non-engineering Faculty Members.* The non-engineering faculty members would have scientific and educational backgrounds. Their knowledge and experience of test construction and student learning will be a factor in identifying weaknesses within quizzes.
- *Cognitive Psychologists.* Cognitive psychologists provide further validation that the desired cognitive processes to be measured are addressed.

- *Educational/Testing Experts.* Individuals well versed in educational measurement, more specifically associated with multiple-choice testing formats.

The distribution of reviewers described above was difficult to achieve due time commitment (typically 2-3 hours) required to assess the quizzes. Also, no funding was available to compensate reviewers; therefore, all independent reviewers were volunteers. Due to the technical content of the quizzes, efforts to include an educational specialist were unsuccessful. However, the authors feel that the independent reviewers selected met the criteria as stated in the quote above.

The independent review is similar to content reviews suggested by educational measurement text; however, it has been extended to cover the other domains from the checklist form.[11,16] The requirements of an independent reviewer are shown in Figure 2. Each independent reviewer was first given the quiz learning objectives. The reviewers were also provided the quizzes from the control and experimental groups. The group associated with each quiz was not identified to the independent reviewers. Each reviewer independently evaluated each quiz. Independent reviewers were provided the ***Independent Reviewer Multiple-Choice Quiz Question Assessment Form***, in Appendix B, to record their evaluation. This assessment form is almost identical to the ***Multiple-Choice Quiz Question Checklist Form*** in Figure 1. One difference between the two forms is that the checklist form items are written as questions and the assessment form items are written as statements. A second difference is that each item in the checklist form is evaluated on a 1 to 5 Likert Scale. The independent reviewer uses the Likert Scale to evaluate how well the quiz satisfies each assessment form statement. The scale used was as follows: (1) not at all, (2) needs improvement, (3) marginal, (4) satisfactory, and (5) exceptional. This assessment process is used to determine if the checklist is a valuable tool to develop/revise more effective quizzes.

4.8 Control and Experimental Groups for Developing New Quizzes

A sophomore level fundamentals of mechanics course is required for all students at The United States Air-Force Academy (USAFA). The course is three semester hours (no lab) and topics included statics and mechanics of materials. This course was offered in the fall of 2009 and has 24 sections, 1 lead instructor, 10 instructors, and 650 students. The factors of a single university, single course, same quiz topic, same quiz learning objectives, and short timeline allowed for a controlled setting for the development of a new quiz and assessment of the multiple-choice quiz development process proposed in this work.

The authors Josh Coffman and Dan Jensen first held a meeting at USAFA with the lead instructor to discuss the process and the requirements of the participating instructors. The lead course instructor suggested that a new quiz be developed for the bending stress lessons. This lesson was selected by the course instructors since the lesson learning objectives could be evaluated by a multiple-choice quiz. The lead instructor provided demographic data for each instructor that included age, teaching experience, number of times the instructor taught the course, and the instructor's engineering discipline. The control and experimental groups were established based on the demographic being approximately equal to one another. The control group consisted of five instructors and each instructor developed a new quiz based on their professional experience. The experimental group consisted of four instructors (actually five, but one instructor declined to participate later) and each instructor developed a new quiz using the multiple-choice quiz development/revision process as shown in Figure 1. The lead instructor was a member of the experimental group.

The lead instructor, Josh Coffman, and Dan Jensen met with the ten instructors from the control and experimental groups to discuss the project. In this meeting the instructors were asked to develop a new quiz with five to ten multiple-choice questions that were based on the learning objectives for bending stress lessons. The quiz learning objectives are as follows:

1. Explain how to find the distance, y, in the elastic flexure formula.
2. Calculate moments of inertia for symmetric cross-sections.
3. Analyze a beam using the flexural (normal stress due to bending) stress formula to calculate the stress at any point in the beam's cross-section.
4. Explain how the magnitudes of M, y, and I influence the magnitude of the flexure stress and where flexural stress will be a maximum.
5. Draw the flexural stress distribution on the cross-section of a beam.
6. Look around you—identify construction techniques (in bridges, flooring, bookcases, aircraft, etc.) that use concepts discussed in lessons 24.

Each instructor was required to develop the quiz independently. The usage of the quiz in the course was not mandatory. The instructors were told that their names would not be associated with the quizzes in any publication or saved in any manner. This was done to ensure that the instructors were not being evaluated on their quiz writing skills. The meeting provided enough information about the development of a new quiz without discussing the ***Multiple-Choice Quiz Question Checklist Form*** and ***Supplemental Guidelines for Writing or Revising a Multiple-Choice Quiz***. The instructors were allowed to only ask questions that did not reveal the goals of this work. At the end of this meeting the control group instructors were asked to leave.

A five minute meeting was held with the experimental group instructors. The ***Multiple-Choice Quiz Question Checklist Form*** (Figure 1), and ***Supplemental Guidelines for Writing or Revising a Multiple-Choice Quiz*** (Appendix B) were distributed and discussed. The instructors were told how to use these documents to develop a new quiz. The instructors were also allowed to ask any type of question.

The quizzes were returned to Dan Jensen within one week by the instructors in the control and experimental groups. The quizzes were then distributed to the independent assessment reviewers. The independent review process was discussed in the previous section entitled 'Assessment Process by Independent Reviewers.' The assessment results of the independent reviewers are presented in the next section.

4.9 Independent Reviewer Assessment Results

Six independent reviewers carried out assessment of quizzes from the control and experimental groups. The independent reviewers consisted of three engineering faculty members, one engineering Ph.D. candidate, one engineering M.S. student with an educational background, and one humanitarian engineering education Ph.D. candidate with a background in education. Recall, each reviewer evaluated all the quizzes using the ***Independent Reviewer Multiple-Choice Quiz Question Assessment Form*** in Appendix B. Tables 1 and 2 show the assessment results of the independent reviewers.

Table 1 shows the five control group quizzes and the four experimental group quizzes (in the second column). Averages and standard deviations are shown for each assessment form domain (columns four to seven), each overall quiz (last column), and for the control and experimental groups (rows seven and twelve). Analyzing these rows (seven and twelve) containing the group averages, the experimental group shows significantly higher averages in the Content, Format, and Writing the Question assessment form domains. This is also shown to a lesser extent for the Writing the Options domain (column six). The last column shows the experimental group overall quiz averages tend to be higher than control group. A further analysis of Table 1 shows, in general, the high to low average ranking of each domain is the same in the control and experimental groups as follows: Format domain, Writing the Question domain, Content domain, and Writing the Options domain. Overall, Table 1shows that for an instructor that uses the quiz development guidelines (***Multiple-Choice Quiz Question Checklist Form*** in Figure 1 and ***Supplemental Guidelines for Writing or Revising a Multiple-Choice Quizzes*** in Appendix B) may effectively improve the overall quiz quality.

The first two columns of Table 2 show the assessment form domains and the associated assessment form statement numbers from the ***Independent Reviewer Multiple-Choice Quiz Question Assessment Form*** (Appendix B). The average independent reviewer scores for the control group and experimental group are shown for each assessment form statement number in the third and fourth columns, respectively. The fifth column shows for each assessment form statement number a difference between the average experimental and control groups based on the independent reviewers' scores. The second to last column shows the confidence interval for each assessment form statement number of the control and experimental groups. Negative difference values imply that the control group received higher average assessment form statement scores compared to the experimental group. Four negative difference values occur in the

Writing the Options domain and are associated with assessment statement numbers four, five, seven, and ten (shown as shaded rows). The four assessment form statements (Appendix B) are as follows: 4. No two options that mean the same are used such that both can be rejected. 5. The use of modifiers like 'usually' and 'sometimes' has been avoided in the options.; 7. The correct answer has not been described in more detail. 10. The use of options such as 'All-of-the-above' or 'None-of-the-above' have been avoided or minimized.

A review of the checklist forms from the experimental group instructors revealed that one or more instructors did not follow the checklist form guidelines explicitly, i.e., they answered NO to these questions (in Figure 1). The challenge for the experimental group instructors in addressing statement four could be due to the difficulty of creating suitable discriminating options that are also homogenous in nature. Reviewing the quizzes for the experimental group we found that statement five was not addressed by the instructors. The usage of 'usually' and 'sometimes' make certain quiz options vaguely described. Statement seven prevents students from recognizing familiar terms as seen in a lecture and/or textbooks. Usage of 'All-of-the-above' and 'None-of-the-above' in statement ten is understandable, since it has been done by the authors and our own college instructors in quizzes and tests. Haladyna[29] has found that for the 'All-of-the-above' option type that 70% of educational measurement textbook authors feel that it can be used if done properly. Furthermore, Haladyna[29] comments that the 'None-of-the-above' option is more controversial based on a study of educational measurement textbooks. His research suggests that 48% of educational measurement textbook authors do not support the use of 'None-of-the-above' while only 40% support the use. After careful review of the checklist and assessment forms, assessment form statement ten should be separated into two statements to reflect the common opinions of educational measurement textbook authors.

A closer look at the confidence intervals shows a very low value for the following assessment form statement: 9. One correct or clearly best answer has been keyed. This may arise in statement nine since the correct and incorrect options may be too closely related. This difficultly in writing the options to satisfy both statements four and nine may be due to the focused topic (bending stress) addressed by the quiz learning objectives. The fact that these two similar statements are shown to be problematic identifies a positive characteristic of consistency and quality of the assessment process. Educational measurement literature states that the "most critical part of writing multiple choice items is the selection of the response alternatives - the correct answer and incorrect choices".[20] One way for an instructor to improve quiz quality in the Writing the Options domain is to initiate the development or use established multiple-choice question item banks.[7-10,14,16,28] Item banks have been created for many courses including statics.[30] These item banks contain multiple-choice questions that have be validated in practice. This allows the quiz developers to pick and choose from existing quiz questions. This will completely eliminate problems developing options or aid in the creation of new options based on existing examples.

Analyzing the last column of Table 2 shows confidence intervals for the first three assessment form domains are approximately 99%. This means that the instructors who developed new quizzes using the ***Multiple-Choice Quiz Question Checklist Form*** (Figure 1) showed statistically significant improvement in creating better quality quiz questions for these three domains. The Writing the Options domain confidence interval is approximately 91%. However, the bottom right-hand corner of Table 2 reveals that the confidence interval based on the overall average of the quizzes for the experimental group versus the control group 77%. Even though a 77% confidence interval value is not considered statistically significant, however, there is a 77% chance that the experimental group developed a more effective quiz than the control group. Since the overall number of independent reviews was small, a t-test was used. The t-test assumes a normal distribution and provides the probability of the null hypothesis that the means of data points are statistically equivalent. The two-sided t-test p-value in Table 2 suggests there is greater than an 80% chance that the data measured could be significant.

Table 4.1 Independent reviewers' assessment results for assessment form domain and each quiz in the control and experimental groups.

Group	Quiz Number		Assessment Form Domains				Overall Quiz
			Content	Format	Writing the Question	Writing the Options	
Control	1	Average	3.58	3.72	4.08	4.20	3.90
		Standard Deviation	1.44	1.36	0.84	1.01	1.16
	2	Average	4.67	4.94	4.40	4.36	4.59
		Standard Deviation	0.65	0.24	0.88	0.77	0.63
	3	Average	4.58	4.89	4.37	4.34	4.54
		Standard Deviation	0.67	0.32	0.84	0.95	0.70
	4	Average	4.08	4.06	4.37	3.80	4.08
		Standard Deviation.	1.16	1.00	0.77	1.20	1.03
	5	Average	2.42	3.28	3.27	3.00	2.99
		Standard Deviation	1.24	1.27	1.21	1.25	1.24
	1-5	*Group Average*	3.87	4.18	4.10	3.94	4.02
		Group Standard Deviation	1.03	0.84	0.91	1.03	0.93
Experimental	6	Average	4.58	4.94	4.47	4.20	4.55
		Standard Deviation	0.51	0.24	0.77	1.24	0.69
	7	Average	4.08	4.61	4.30	4.28	4.32
		Standard Deviation	1.08	0.85	1.08	0.92	0.98
	8	Average	4.20	4.80	4.46	3.94	4.35
		Standard Deviation	1.03	0.41	0.97	1.13	0.89
	9	Average	4.80	4.73	4.83	4.30	4.67
		Standard Deviation	0.42	0.46	0.35	0.99	0.55
	6-9	*Group Average*	4.42	4.77	4.51	4.18	4.47
		Group Standard Deviation	0.76	0.49	0.79	1.07	0.78

Table 4.2 Average assessment scores for assessment form statements and domains.

Assessment Form Domain	Assessment Form Statement Number	Average Independent Reviewer Score		Group Difference (Experimental – Control)	Experimental Group vs. Control Group	
		Control Group	Experimental Group		Confidence Intervals for Assessment Form Statement	Confidence Intervals for Assessment Form Domain
Content	1	3.93	4.36	0.43	82.3%	99.4%
	2	3.80	4.32	0.52	89.4%	
Format	1	4.40	4.91	0.51	98.5%	99.9%
	2	4.17	4.50	0.33	80.7%	
	3	3.97	4.95	0.98	99.9%	
Writing the Question	1	3.77	4.36	0.59	97.0%	99.9%
	2	4.07	4.27	0.20	55.5%	
	3	4.10	4.36	0.26	64.0%	
	4	4.27	4.82	0.55	99.6%	
	5	4.43	4.86	0.43	98.6%	
	6	3.97	4.32	0.35	63.1%	
Writing the Options	1	3.70	4.21	0.51	90.5%	90.6%
	2	3.67	4.25	0.58	95.7%	
	3	3.93	4.17	0.24	63.3%	
	4	4.27	4.21	-0.06	0%	
	5	4.67	4.46	-0.21	0%	
	6	3.77	4.08	0.31	59.8%	
	7	4.17	4.04	-0.13	0%	
	8	4.27	4.42	0.15	48.4%	
	9	3.53	3.71	0.18	32.3%	
	10	4.10	4.00	-0.10	0%	
					Confidence Interval for Experimental Group vs. Control Group Quizzes	77.4%
					Two Sided t-test p-value	0.255

4.10 Conclusion

This paper presented a checklist form for instructors to develop/revise a multiple-choice quiz using guidelines found in educational measurement literature. The checklist form is easy to use and requires minimal time to complete. The checklist form was used by a group of instructors and assessment results showed that there was a seventy-seven percent chance that the quiz is more effective than quizzes developed without the checklist form. The checklist form is a valuable resource for new and inexperienced instructors and can be used by engineers and non-engineers.

4.11 Future Work

- *Checklist Form Improvement.* The ***Multiple-Choice Quiz Question Checklist Form*** can be improved with the suggestions found in the results section of this work.
- *Software Introduction.* To streamline the overall process in the future, on-line programs or other electronic quiz writing software may be used. As part of this future work item banks, as discussed earlier, should be developed and maintained in electronic format.
- *Finite Element Learning Modules.* This process will be adapted for use in revising the quizzes for existing finite element learning modules. Also, this process will be used to create quizzes for new finite element learning modules.
- *Item Analysis.* As suggested by educational measurement and multiple-choice literature a traditional item analysis should be conducted to further examine the validity and reliability each finite element learning module quiz.

4.12 Acknowledgment

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4.14 Appendix A

Supplemental Guidelines for Writing or Revising a Multiple-Choice Quiz

Instructions

This optional supplement is included for the instructor if you desire more guidance in developing a new multiple-choice quiz or revising an old multiple-choice quiz. The supplement is a collection of best practices from educational literature for writing a new or revising a multiple-choice quiz. The first two sections list multiple-choice definitions and quiz formats which are described in detail. Following this are guidelines for writing different portions of a multiple-choice questions for a quiz. The guidelines are broken down into sections based on ***Content***, ***Format Suggestions***, ***Writing the Question***, and ***Writing the Multiple-Choice Options*** found in the **Multiple-Choice Quiz Question Checklist Form** on the previous two pages. These guidelines will help address problems found in the development or revision of quiz questions using the **Multiple-Choice Quiz Question Checklist Form**. References with page numbers are provided for more in-depth discussion at the end of this document.

Definitions for Multiple-Choice Questions

In a multiple-choice quiz question there are two parts:

1. *Stem*. Poses a problem/question through clear, simple language.
2. *Options*. Includes the correct answer (one, except for all-of-the-above) and distractors.
   Distractors present plausible options that can mislead a student who has not mastered the quiz content.[2,4,5,8-15]

Multiple-Choice Question Formats

The following two formats are strongly recommended in literature for effective multiple-choice quiz items:

1. *Direct Question*: A simple question is stated within the stem of the item.[1,3,9,10,16,21]
2. *Completion/Incomplete Statement*. Essentially fill-in-the-blank style, however, with multiple options. The stem provides an incomplete statement with possible options to complete the statement provided in the stem.[1,3,9,10,16,21]

It should be noted that there are other formats available; however, they are not as strongly recommended in literature as the formats above. The other formats, if desired, can be found in the references at the end of this document.

Items from the Multiple-Choice Quiz Question Checklist Form

Content

1. Each question measures a single educational objective or outcome.[4,5,7-20]

2. The reading level is appropriate for the examinees and not an excessive amount.[1,2,5-9,11,12,14-16,19,21]
3. Avoid trick questions[5,7-9], opinion based questions[5,9,12], and having correct answers fall into a pattern.[1,4,5,10,11,14,16,18,21,22]
4. Give careful consideration to the number of questions on the quiz.[21]
5. As a rule of thumb, most multiple-choice items take approximately one minute to complete, unless complex calculations or reading are required.[8]
6. Break any rule or guideline if it improves the effectiveness of a question.[4,21]

Format Suggestions

1. Directions are made as clear as possible.[5,7,21]
2. The question and options should appear entirely on one page.[21]
3. The stem and options should be grammatically consistent.[2-5,7-22]
4. Format options vertically instead of horizontally for each question.[5,21]
5. Use an efficient or recommended question format.[3,4,13]
6. Never use a "best-answer" solution when a correct answer is available.[3]
7. Questions should be carefully proofread.[5]
8. Each question should be numbered as to be easily identified with indented options identified with capital letters.[21]
9. All questions and options should all be framed in third person.[7]
10. Avoid indefinite and absolute terms, "usually" or "generally", in the stem or options.[2,3,21]

Writing the Question

1. Simply, briefly, and clearly identify a single question or problem.[1,3-5,7-22]
2. Any words to be repeated in the options should be placed in the stem.[1,3-5,7-11,13,16-19.22]
3. Avoid negatively stated questions when possible.[1-5,7-13,15,16-22]
4. Questions should be independent of other questions.[2,4,5,8-15,18,19,21]
5. Use a direct question or incomplete statement.[9,10]
6. Narrow focused stems help measure understanding.[11]
7. Use the terms "why" and how" over "who", "when", and "where".[10]
8. Do not use the definition of a term as a stem.[11]

Writing the Multiple-Choice Options

1. Be sure to key the correct or clearly best answer within the options.[1-4,7-9,12,13,15,17,22]
2. Each distractor in the options should be plausible and attractive to students who have not mastered the material being examined.[1-5,7-13,15-22]
3. Difficulty can be controlled through homogeneity of distractors.[2,3,4,8,10-15,20,22]
4. Avoid giving clues to the correct answer.[1-5,7-15,21]
5. Complete opposites of the correct answer should be avoided because it allows the elimination of the remaining distractors.[8,16]
6. If the question is to define a term, then the distractor options should consist of alternate definitions of that term.[1]

7. Four- or five-option formats are more desirable than those with fewer options.[1,10,11,21]
8. Do not use textbook language or exact words from instructional material in the answer, but it is permissible to include in distractors.[11,12,17,21,22]
9. When possible arrange options in a logical order.[1,5,7-10,15,20,21]
10. Use the option of "None-of-the-Above" or "All-of-the-Above" sparingly.[1,2,4,5,8,9,11,13-22]
11. Options should be independent of one another.[1,8,10-12,15,18]
12. Options should be of the same length/word count.[2,3,5,8-22]
13. Options should all be of the same specificity and technicality.[8,10,11,15,16-22]
14. Use common misinformation and feasible erroneous conclusions for options.[11,12,14,16,22]

Proofread Quiz Questions

Review the quiz questions for clarity, grammar, spelling, punctuation, capitalization errors, and most importantly, for the accuracy of correct answers. In this review it should be ensured that there is only one right or most correct answer. Also, it is important to check for stereotyping of persons, insensitive uses of language, or any other biases towards groups of people.[5]

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4.15 Appendix B

Multiple-Choice Quiz Question Assessment Form

Assessment of Multiple-Choice Quizzes
Independent Reviewer Handout

QUIZ # 1

Multiple-Choice Quiz Question Assessment Form[1-3]

INDEPENDENT REVIEWER

Quiz Name: USAFA Fundamentals of Mechanics, Lesson 26 Bending Stress

Evaluator:______________________ Date: 12/01/2009

Instructions: **Analyze each question in the multiple-choice quiz and record how well the quiz questions fit the statements on the scale below. Please circle the appropriate number following each statement.**

1 = Not at All; 2 = Needs Improvement; 3 = Marginally; 4 = Satisfactory; 5 = Exceptionally

Content					
1. Each question designed to measure a single educational objective.	①	②	③	④	⑤
2. New material, not described in the learning objectives, has been avoided in formulating problems to measure understanding and applications.	①	②	③	④	⑤
Format Suggestions					
1. Letters have been used in front of the options.	①	②	③	④	⑤
2. All options are grammatically consistent with the question stem and parallel in form.	①	②	③	④	⑤
3. Listed options are on separate lines beneath each other.	①	②	③	④	⑤
Writing the Question					
1. The question clearly defines the problem.	①	②	③	④	⑤
2. As much of the information is in the question as possible.	①	②	③	④	⑤
3. No irrelevant information is in the question.	①	②	③	④	⑤
4. No grammatical cues are in the question.	①	②	③	④	⑤
5. A minimum number of negatively stated questions have been used.	①	②	③	④	⑤
6. Negative statements, used in the question, have been clearly emphasized.	①	②	③	④	⑤

QUIZ #1

Multiple-Choice Quiz Question Assessment Form 'Continued'

INDEPENDENT REVIEWER

Quiz Name: USAFA Fundamentals of Mechanics, Lesson 26 Bending Stress

Evaluator: ____________________ Date: 12/01/2009

Instructions: Analyze each question in the multiple-choice quiz and record how well the quiz questions fit the statements on the scale below. Please circle the appropriate number following each statement.

1 = Not at All; 2 = Needs Improvement; 3 = Marginally; 4 = Satisfactory; 5 = Exceptionally

Writing the Multiple-Choice Options					
1. All distractors represent plausible alternatives to examinees that do not possess the skill measured by the test question.	①	②	③	④	⑤
2. All the options are as homogeneous as possible.	①	②	③	④	⑤
3. All options are of the same length and complexity.	①	②	③	④	⑤
4. No two options that mean the same are used such that both can be rejected.	①	②	③	④	⑤
5. The use of modifiers like "usually" and "sometimes" has been avoided in the options.	①	②	③	④	⑤
6. There are important, detailed, or technical sounding words in the distractors.	①	②	③	④	⑤
7. The correct answer has not been described in more detail.	①	②	③	④	⑤
8. The length of the correct answer has been varied, thereby eliminating a potential clue.	①	②	③	④	⑤
9. One correct or clearly best answer has been keyed.	①	②	③	④	⑤
10. The use of options such as "All-of-the-above" or "None-of-the-above" have been avoided or minimized.	①	②	③	④	⑤

Chapter 5

CONLUSION

The *goal* of this engineering educational thesis was to develop a fatigue FE learning module that uses commercial FE software and can be integrated into an undergraduate machine design course. This goal was accomplished in full through the work conducted in each part of the *objectives* as defined in the introduction.

In an attempt to address the knowledge gap between FE educational instruction and the use of FE in industry practices, a FE learning module for the fatigue analysis of a cantilever beam using commercial FE software ANSYS® was developed. In the future, the fatigue FE module will be implemented into a machine design or FE course and assessed for student performance.

The fatigue FE learning module is innovative in the design and approach to use the commercial software and FEM to reinforce the fatigue principles found in an undergraduate machine design course. Special care was taken to design the fatigue module based on Kolb cycle as described in Chapter 3. Consideration for the learning styles and personality types for a 'typical' engineering student was also included in the design.

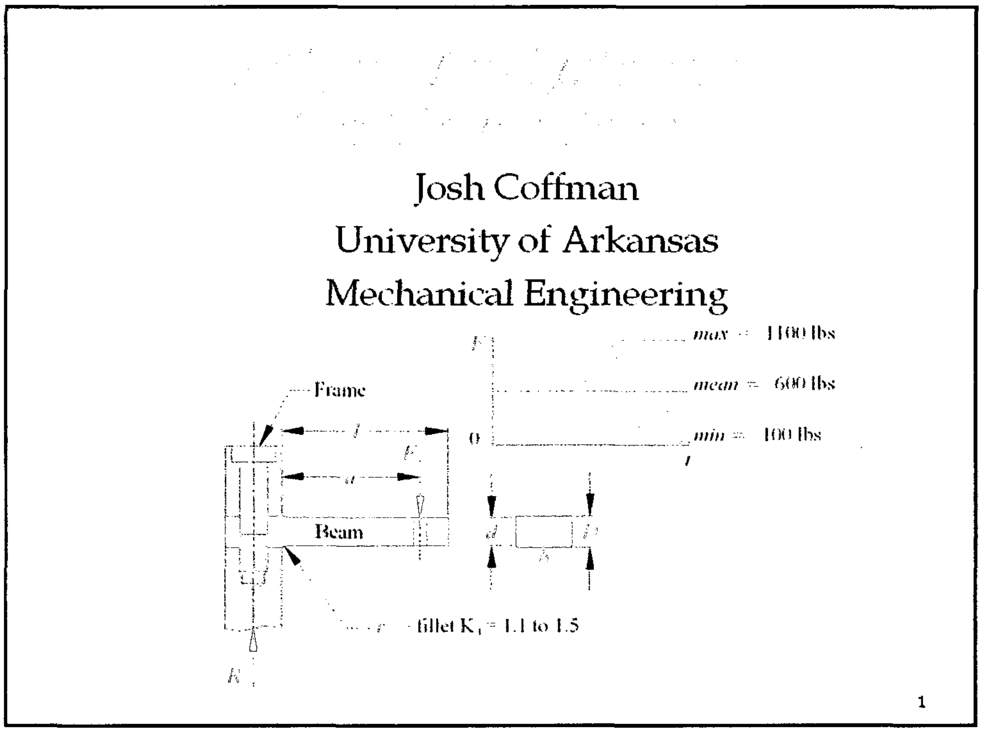
Working with colleagues, student performance was assessed following the implementation of another fatigue FE learning module for a rotating shaft. Unexpected results were observed for the student performance in the second fatigue FE learning module. The overall average of student performance did not increase. This was the first time that a FE learning module did not increase student performance. Assessment of the learning module performed in Chapter 3 revealed possible problems with some of the quiz questions. In this assessment two important things were learned. First, importance should be given to the quality of the quiz questions to measure student performance. And secondly, no bias was exhibited towards any particular learning style or personality type. Revisions were made to the content of the second fatigue FE learning module, and should be made continually to improve the module prior to future classroom implementation.

The work within Chapter 4 sought to remove any deficiencies in the quizzes that could affect the assessment data as observed in results of Chapter 3. A structured process for creating new or revising a multiple-choice quiz was developed. The methodology used to define this process in Chapter 4 is well grounded in traditional educational measurement literature. The process was assessed through the opinion of independent reviewers. The outcome from the reviews of this process revealed very strong possibilities that the process created higher quality quizzes than professional experience alone.

In closing, the work of this thesis has created innovative instructional tools designed to improve student knowledge of the FEM and provide experience working with various commercial FE software. Hopefully, the application of this work creates engineers better prepared for the early stages of their careers.

Appendix A. Fall 2007 Cantilever Beam Fatigue Finite Element Learning Module

The following Finite Element Learning Module was developed by Josh Coffman at the University of Arkansas. This module has not been used in the classroom. The design of this module can be observed in Chapter 2 of this work. An additional set of instructions to perform a modal analysis were created, but removed due complexity and length. Background finite element and fatigue discussions were removed from this module and can also be added as a supplement to this module as needed by the instructor.



Learning module uses ANSYS® Mechanical 12.0

Expected completion time for this tutorial is 50 to 90 minutes.

Companion tutorial for machine design or finite element course.

Referenced Text: 2nd and 3rd editions of
Machine Design: An Integrated Approach 2nd Ed. by R.L. Norton
Publisher Prentice Hall.

2

- Educational Objectives
- Problem Description
- General Steps
- Step-by-Step Process
- Viewing Finite Element Results
- Comparison of Fatigue Analytical Solution versus FEA
- Summary and Discussion
- Finite Element Theory

3

The *project educational goal* is to provide undergraduate engineering students with understanding of a specific engineering topic and FE theory, along with an ability to apply commercial FE software to typical engineering problems. The educational goal will be accomplished through four *project educational objectives* based on Bloom's Taxonomy and ABET Criterion 3 for Engineering Programs as follows:

1. *Engineering Topics (Comprehension; 3a, 3k).* Understand the fundamental basis of engineering topics through the use of finite element computer models.
2. *FE Theory (Comprehension; 3a).* Understand the fundamental basis of FE theory.
3. *FE Modeling Practice (Application; 3a, 3e, 3k).* Be able to implement a suitable finite element model and construct a correct computer model using commercial FE software – integrates objectives #1 and #2 above.
4. *FE Solution Interpretation and Verification (Comprehension and Evaluation; 3a, 3e).* Be able to interpret and evaluate finite element solution quality, including the importance of verification – integrates objectives #2 and #3 above.

4

- Determine the frequencies and mode shapes and compare to analytical solution.
- Carry out a deflection analysis based on cyclic maximum load and compare to analytic solution.
- Perform a static stress analysis using mean and alternating load cases and compare to analytic solution.
- Compare the FE fatigue prediction results with analytical results.

5

- The purpose of this tutorial is to provide visualization of the structural analysis concepts covered in your course and to introduce the concept of using finite element analysis (FEA) in analyzing a fatigue analysis problem. You begin with building a model of this problem using the ANSYS software. Once the 2-D model is constructed you then submit it to perform the FEA.
- FEA consists of two major steps: pre-processing and post-processing. Preprocessing involves preparing the 2-D model, meshing the model, and defining material properties along with placing boundary conditions on this model; the post-processing involves running the FEA analysis and then displaying the results. Two-dimensional elements
- Two dimensional (2-D) elements include plate and shell elements which are usually triangular or quadrilateral in appearance. These 2-D elements are usually thin and can be used to model very curved objects. In our mesh we will be using 2-D elements to model a beam subjected to a repeated bending load.

6

- **Create a geometric 2-D plane stress model of the cantilever beam in ANSYS.**
- **Create a finite element static structural analysis of this model in ANSYS.**
- **Create a hand fatigue analysis based on the results from the static finite element analysis in ANSYS.**
- **Determine appropriate fatigue safety factor for the three loads using ANSYS to determine the static stresses.**
- **Compare the Finite Element Fatigue Analysis (SF) with the text calculated Fatigue Analysis (SF).**

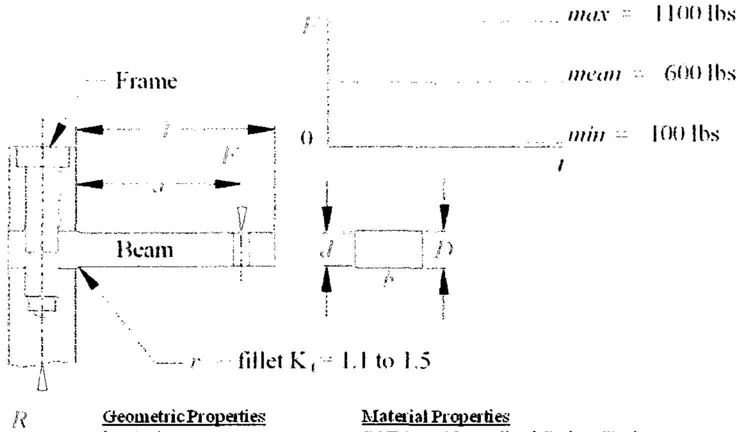
7

- Complete a static finite element analysis of the model using 2-D plane stress elements. The analysis will provide results for stress and displacements.
- Use the finite element analysis fatigue life for this beam model under the 6.8 kN load.
- Comparison of the analytical hand calculated life of the shaft with the finite element analysis expected life at these three loads.

8

A feed roll assembly is to be mounted at its ends on support brackets cantilevered from the machine frame as shown in Figure 6-47 (Norton 2nd Edition). The feed rolls experience a total fluctuating load that varies from a minimum of 200 lb to a maximum of 2,200 lb, split equally between the two support brackets. Design a cantilever bracket to support a fluctuating bending load of 100 to 1,100 lb amplitude for 10^9 cycles with no failure. The dynamic deflection cannot exceed 0.02 in.

9



Geometric Properties	Material Properties
$l = 6.0$ in	SAE 1040 Normalized Carbon Steel
$a = 5.0$ in	$E = 30 \times 10^6$ psi
$r = 0.5$ in	$\rho = 0.2834$ lb/in^3
$d = 1.0$ in	$\upsilon = 0.28$ (Poisson's Ratio)
$b = 2.0$ in	$S_{ut} = 80$ kpsi
$D = 1.125$ in	$S_y = 60$ kpsi

10

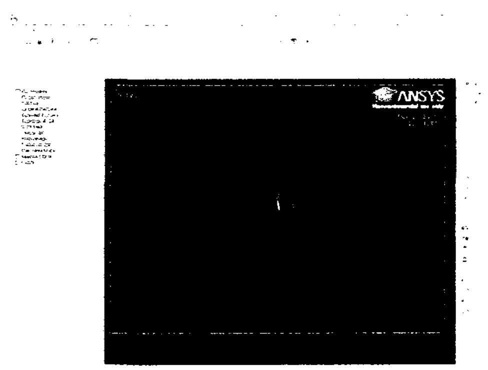
The load-time function shape is show in Figure 6-47. The operating environment is room air at a maximum temperature of 120°F. The available space allows a maximum cantilever length of 6 inches. Only ten of these parts are required.

11

The bracket can be clamped between essentially rigid plates bolted at its root. The normal load will be applied at the effective tip of the cantilever beam from a rod attached through a small hole in the beam. Since the bending moment is effectively zero, stress concentration from this hole can be ignored. Given the small quantity required, machining of stock mill-shapes is the preferred manufacturing method.

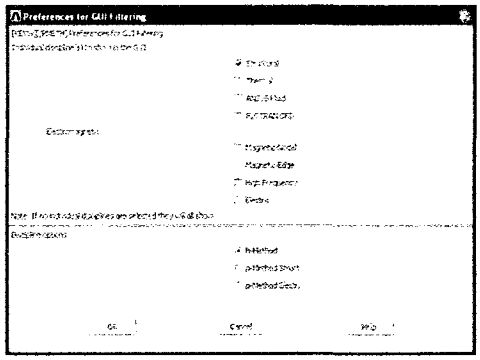
12

- Begin First by opening ANSYS 12.0 *Mechanical*



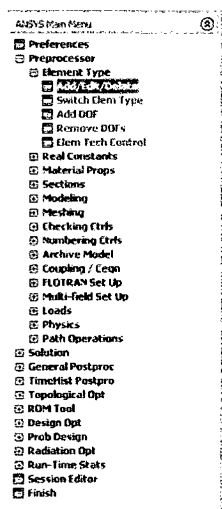
13

- In the left hand window, the ANSYS *Main Menu*, Select *Preferences.*
- Check the Box, *Structural*
- In Discipline Options Leave *h-method* marked and hit OK.



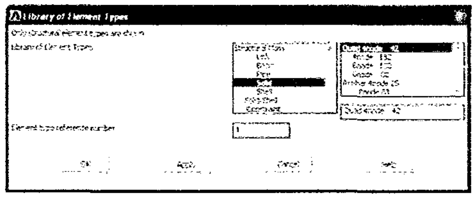
14

- Select *Preprocessor* in the ANSYS *Main Menu.*
- Then Select *Element Type*
- Select *Add/Edit/Delete*



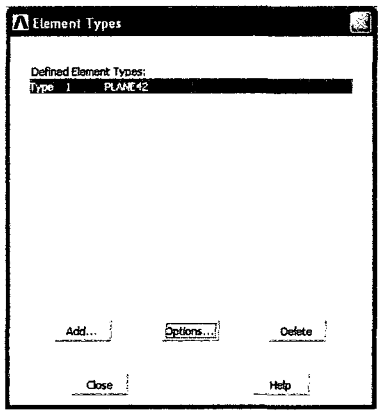
15

- Within this window all of the available element types within ANSYS are displayed.
- For our example we will use a 2-D element listed under *Solid* as the *Quad 4node 42 Element.*
- Leave the *Element type reference number* at 1
- And hit either Apply or OK.



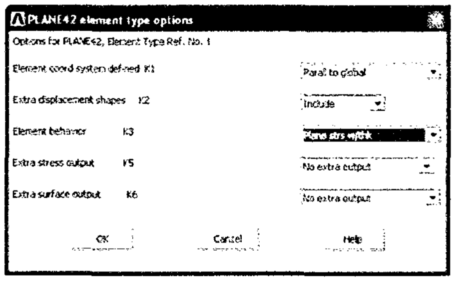
16

- We will only have one element type for this model.
- You are now returned to the previous screen with the element type selected shown as in the window to the right.
- Select the *Options...* for this element type.



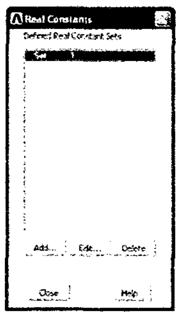
17

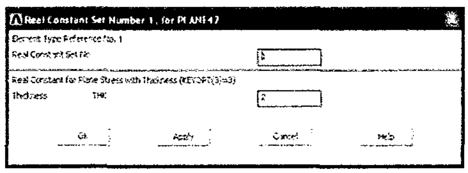
- The screen to the right displays the available options for this element.
- Change *Element behavior* to *Plane strs w/thk* and leave the rest as defined.
- We must now define the thickness for the model.



18

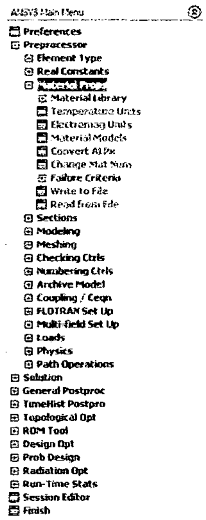
- In the *Preprocessor* menu select *Real Constants*.
- Select *Edit*, for *Set 1*.
- For this *Real Constant Set No.* 1 the *Thickness (THK)* is 2 inches as described in the problem.





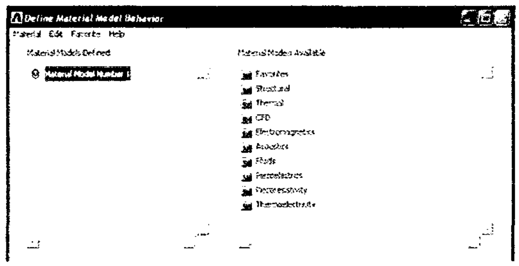
19

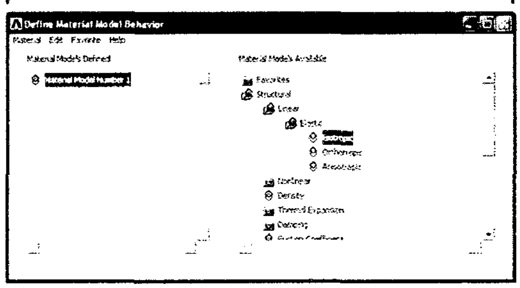
- Now we need to define the material models and material properties.
- Select *Material Props* under the *Preprocessor* Menu.
- Then Select *Material Models*.



20

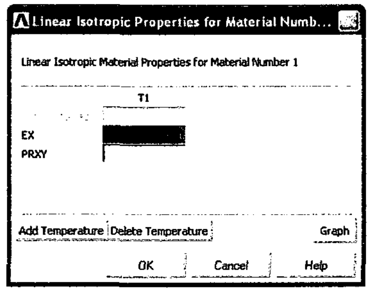
- Then the following prompt should appear.
- Select *Structural*
  - *Linear*
  - *Elastic*
  - *Isotropic*

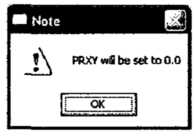




21

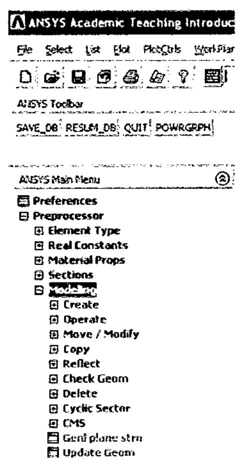
- We are then prompted for Young's Modulus and Poisson's Ratio.
- For this example enter (*EX*) Young's Modulus as 30e06.
- For this problem we can ignore Poisson effects. So leave (*PRXY*) Poisson's Ratio blank.
- Notice the Note It is a helpful reminder that we have defined Poisson's Ratio to be 0.0. Hit OK.





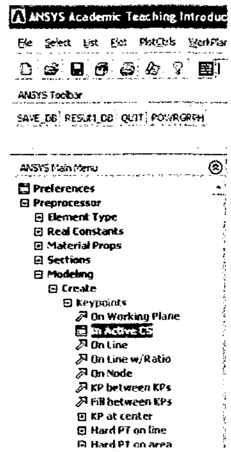
22

- Now that we have defined our material model and properties we can begin to build our model.
- First, select in the ANSYS *Main Menu*, under the *Preprocessor*, Select *Modeling* found on the left hand side of the GUI.



23

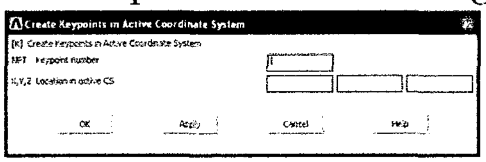
- Under *Modeling*, Select *Create*, *Keypoints*, Choose in *Active CS*.



- This will allow us to make use of the predefined X,Y,Z coordinate system.

24

- ANSYS will now provide the following prompt.

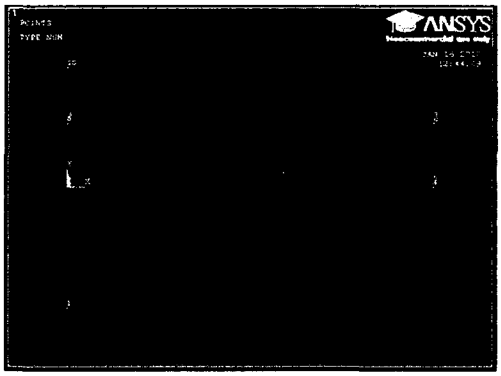


- Create the following keypoints in the Active Coordinate System:

Keypoint	X,Y,Z Coordinate
1	0,-2,0
2	0,0,0
3	0,0.0625,0
4	6,0,0
5	6,.0625,0
6	6,1.0625,0
7	6,1.125,0
8	0,1.0625,0
9	0,1.125,0
10	0,2,0

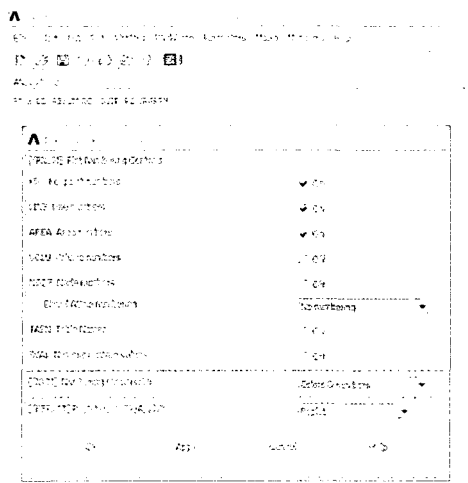
25

- After entering the keypoints the screen should appear like the screenshot to the right.



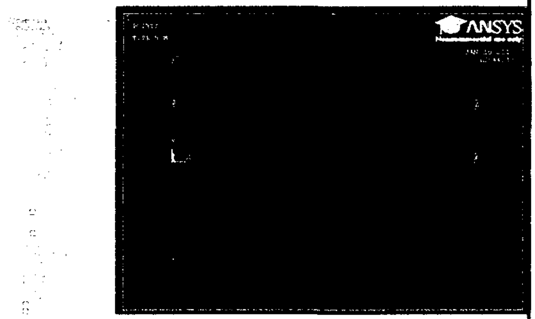
26

- To control whether keypoint and line numbers are visible use the *PlotCntrls* tab on the ANSYS *Toolbar*.
- Then Select *Numbering...*
- To View the *Keypoint numbers*, *Line numbers* and *Area numbers* should all be selected ON.



27

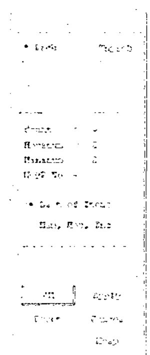
- Now we will create lines to connect keypoints.
- In *Modeling*, under *Create*, Select *Lines*, *Straight Line*.
- In ANSYS using this command requires the selection of keypoints, which we have just created.



28

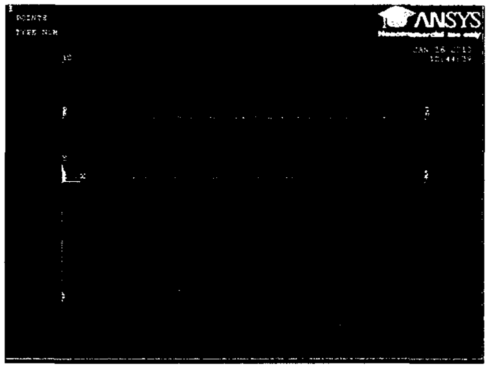
- Select the following keypoints, Leave *Pick* marked this will allow us to pick, in order, keypoints to create the straight lines:

1 and 3 Hit Apply
3 and 5 Hit Apply
5 and 6 Hit Apply
6 and 8 Hit Apply
8 and 10 Finally hit OK.



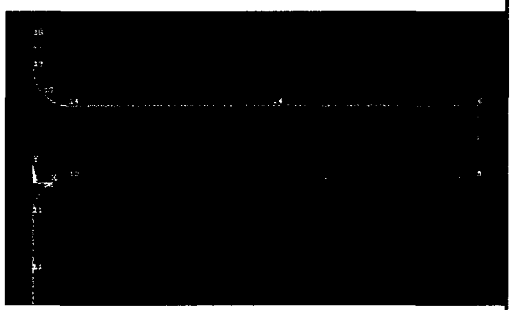
29

- The screen should now appear as shown to the right.
- We now wish to create the fillets on the left hand side of the beam.



30

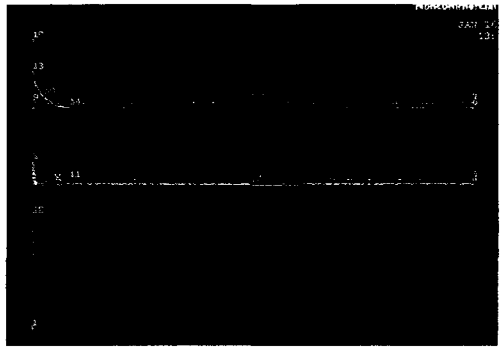
- Select *Modeling, Line Fillet* .
- Select the bottom vertical line and bottom horizontal line.
- The radius of the fillet is 0.5 in.
- Repeat this procedure for the top fillet radius.



31

- Now create two lines that run from keypoints #3 & 4 and # 7 & 9.

- We must now remove the excess lines and ensure the proper length for the beam.



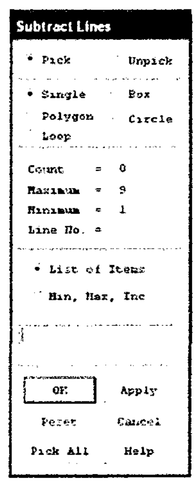
32

- Select *Operate, Booleans , Subtract, Lines*

- We will now be prompted to select lines to subtract.

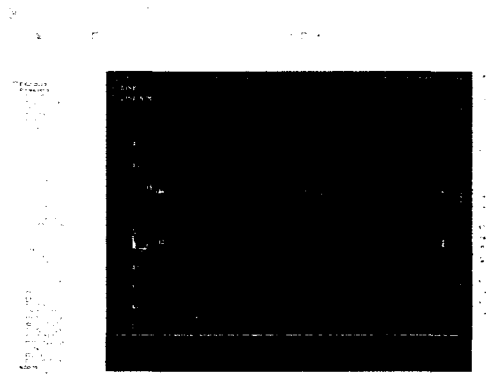
- First, *Pick* the top fillet, and then hit OK.

- Then Pick the top horizontal line intersecting the fillet and hit *Apply*.



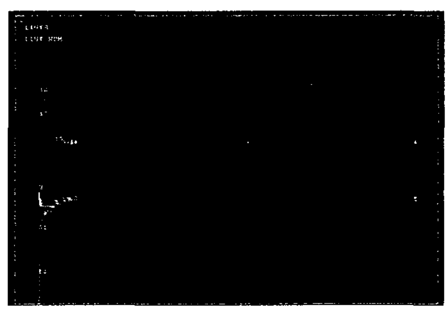
33

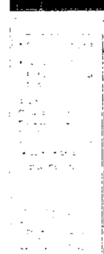
- The fillet is now divided into two segments.
- We only need the lower right segment from the fillet.
- Repeat this process for the bottom fillet.



34

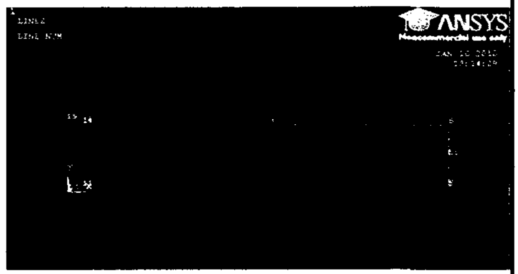
- Now we need to first remove unnecessary lines.
- Under *Modeling*, Select *Delete*, *Delete Lines Only*.
- Pick the second segment of the top fillet and the vertical line connected to this top fillet segment.
- Repeat for the bottom fillet segment and the attached vertical line.





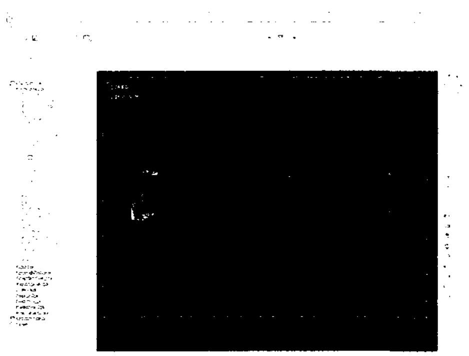
35

- Now create a vertical line to connect the top and bottom fillet segments.
- However our beam has gotten shorter, and we need to extend the beam back to the original length.
- Let's start by finding out how much further we need to extend the right end of the beam.



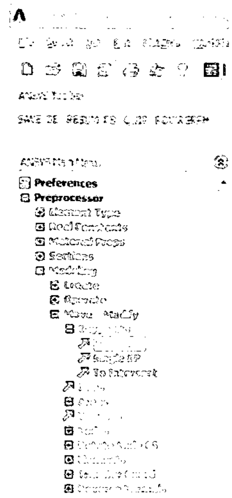
36

- Under *Modeling*, Select *Check Geometry, KP Distances.*
- Select the upper left corner keypoint and the upper right corner keypoint.
- It should currently measure 5.742401593; however we need the beam to be exactly 6" long.



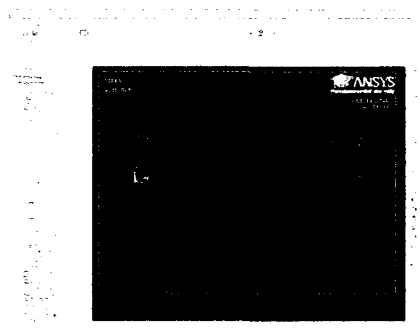
37

- To make the beam longer we will move the keypoints of the right hand side of the beam.
- Under *Modeling*, Select *Move*, *Set of KPs* (keypoints).
- Select the upper right corner and the bottom right corner of the beam.
- At the prompt, enter 6.257938541 for the *X-coord. In Active CS*.
- This means the left hand side of the beam is at the X = 0.25793854 inches.



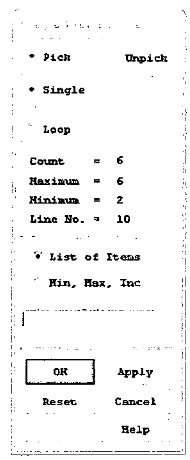
38

- Now check the keypoint distance as we have done earlier, to ensure the beam is at 6 inches in length.
- Now that we have a series of connected lines, it is time to create a solid area.



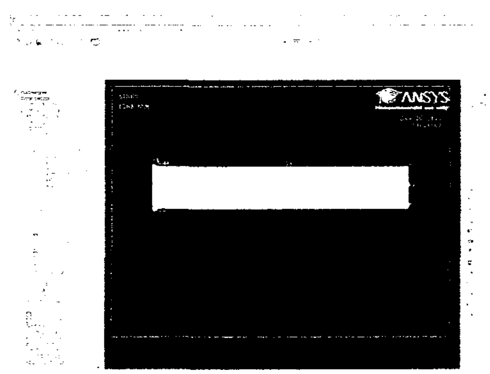
39

- You can create the area many different ways.
- For this example, we will be creating the area by the individual lines that compose the area.
- Begin by selecting *Create, Areas, Arbitrary, Lines*
- Select each line and hit OK.



40

- You have to be very careful not to make one than one area.
- We now have our beam as an area.
- The next step is to create the mesh for the area created.



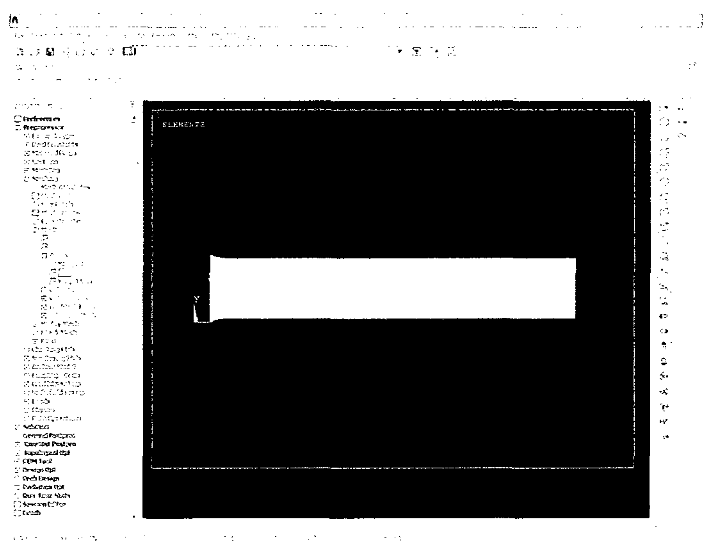
41

- To create the mesh
- In the *Preprocessor*, Select *Mesh, Areas, Free*
- Select the beam area and hit ok.

- The mesh we are given by this method is not very good for many reasons.

- We need to refine our mesh.

42

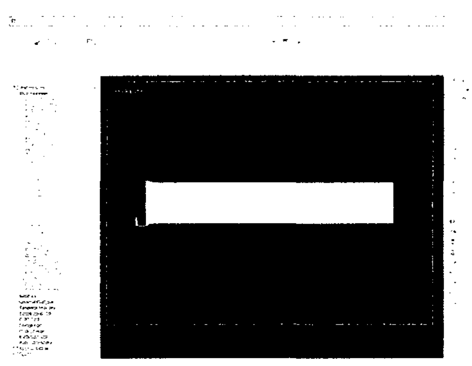


43

- The mesh we have created may not adequately capture stresses in the fillet radii of the beam.
- We will now decrease the size of the elements.
- Lets first start by making the element size for the area 0.10 inches in length and width.
- This may not be possible in some locations. So we may receive error messages informing us that the triangular element has been used.
- Later you will learn why this element can be problematic.

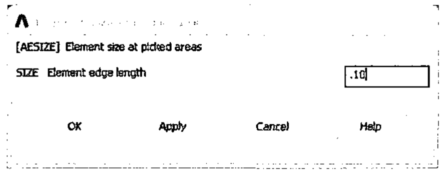
44

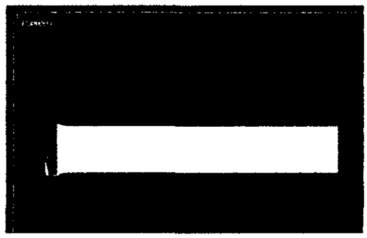
- The mesh we have created may not be adequate to capture the stresses in the fillet radii of the beam.
- We will now change the sizes of the elements by making the mesh size for the area 0.10 inches.



45

- Begin changing the size by going to *Size Cntrls* under *Meshing*.
- Then Select *ManualSize, Areas, Picked Areas,*
- Select the Area and hit OK.
- Now enter 0.10 for the Element edge length and Hit OK
- Now Select *Mesh, Areas, Free* again to create the new mesh.





46

- Now the right hand portion of the beam seems to be okay, but the left hand portion of the beam and the fillet radii are not meshed properly to extract the stresses.
- Now we need to use the mesh refinement tool in the Mesh Tool

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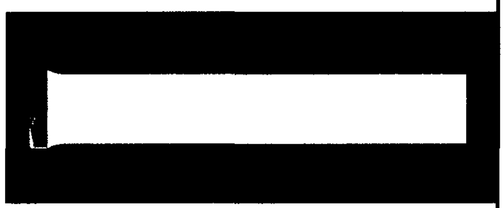
- Select *Modify Mesh, Lines*
- Select the two fillet radii and hit OK.
- Leave Refinement at 1 Minimal
- Leave *Advanced Options* unchecked
- It appears the mesh could still need more refinement so we will repeat this method.

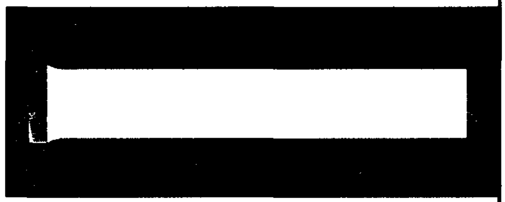
48

- However, this time select fillet radii and also the vertical line on the left hand side of the beam, and the two horizontal lines to the right of the fillet radii.
- Perform one more (Minimal) refinement on the entire area rather than just picked lines.
- Notice this mesh has a very high number of elements concentrated on the surface and on the fillet radii. This will be essential in capturing the stresses.



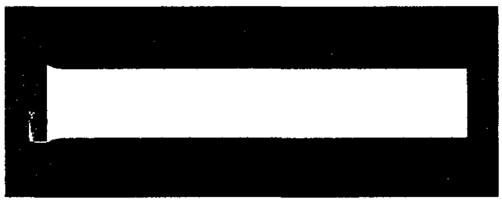
49

- Perform one more (Minimal) refinement on the entire area rather than just picked lines.
- Notice this mesh has a very high number of elements concentrated on the surface and on the fillet radii. This will be essential in capturing the stresses.



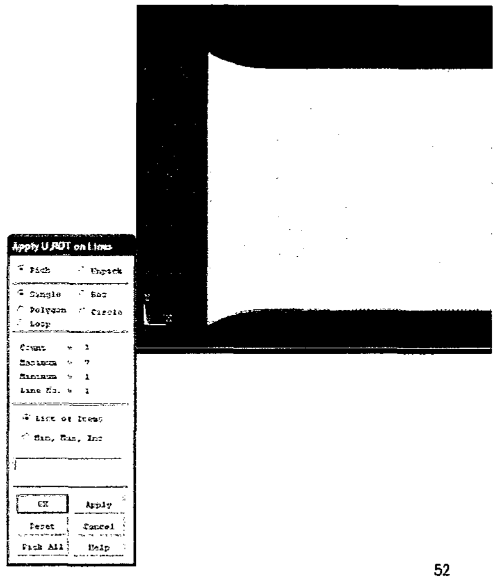
50

- Now that we have created the mesh, it is time to provide the boundary condition or restraints to this problem, along with the loading.
- List the statistics for the mesh.
  - # of Nodes
  - # of Elements
  - # DOF per Node
  - # Total DOF
  - # Constrained DOF (# of nodes where displacement was defined to be zero)
- **These can be found by viewing the list results.**



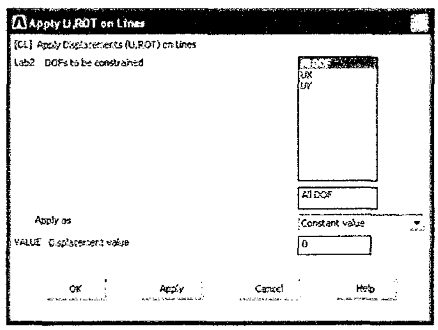
51

- Now that we have created an adequate mesh, it is time to provide the boundary condition or restraints to this problem, along with the loading.
- In the *Preprocessor*, Select *Analysis Type*, *New Analysis*, Click *Static Analysis*, Hit OK
- Now Select *Define Loads*, *Apply*, *Structural*, *Displacement*, *On Lines*
- Select the vertical line (highlighted in yellow) on the left end of the beam and hit OK.



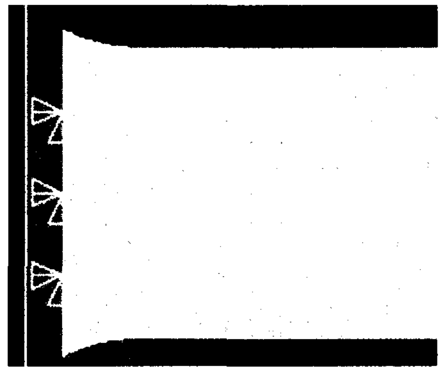
52

- Now with the clamped B.C. on the left end there is no displacement or rotation on the nodes in any degree of freedom (D.O.F.).
- So leave *ALL DOF* selected.
- Leave *Apply as A Constant Value* selected.
- Type in 0 as the *Displacement Value* and Hit OK.
- The beam is now fully restrained from any rigid body motion.



53

- Notice the beam now has cyan colored arrows on the line. These are the zero displacement B.C. we have just applied to this line on the beam.



54

- First we must create a line to know where to place the load.
- In the problem we are told the load is applied 1 inch from the right end in the x-direction.
- The coordinate of the right end in this problem is 6.257938541 in the x-direction.

55

- So we need to create two new keypoints
- #99 (5.257938541, 2)
- #100 (5.25793854,1 -2)
- Now create a straight line to connect these two points.
- Now go to PLOT and Select Multiplot.
- This will allow the mesh, area, lines, and keypoints to be visible in a single plot.

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- Now with the plot ready,
- Under the *Preprocessor,* Select *Loads, Define Loads, Apply, Structural, Force/Moment, On Nodes*
- Select the nodes that fall along the line, make note of the number of nodes selected and Hit OK.

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- On the prompt that follows:
- Change the *Direction of Force/Moment To FY*
- Leave *Apply As Constant Value*
- For *Value* type in the -1100 lbs. load divided by the number of nodes selected down the line(33 nodes selected). -33.3333 lbs/node
- We will use this load to determine the maximum deflection and maximum stress.

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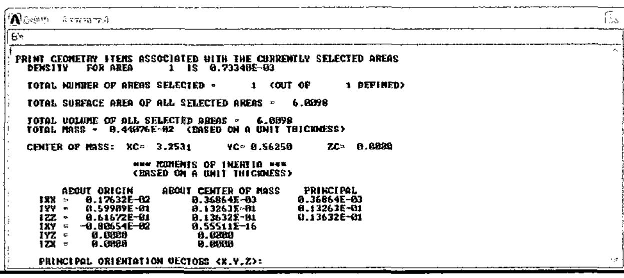
- This will provide a check that the problem being modeled has the proper mass and center of gravity.
- To check this begin in the *Preprocessor, Modeling, Operate, CALC GEOM ITEMS, OF AREAS.*
- The list results for the mass and center of gravity for this beam are shown below. Mass is in lbs force for 1" thick. Calculate the proper mass.



```
PRINT GEOMETRY ITEMS ASSOCIATED WITH THE CURRENTLY SELECTED AREAS
  DENSITY   FOR AREA      1  IS  0.73340E-03

  TOTAL NUMBER OF AREAS SELECTED =      1  (OUT OF      1 DEFINED)

  TOTAL SURFACE AREA OF ALL SELECTED AREAS =   6.0098

  TOTAL VOLUME OF ALL SELECTED AREAS =   6.0098
  TOTAL MASS =  0.44076E-02  (BASED ON A UNIT THICKNESS)

  CENTER OF MASS:  XC=  3.2531     YC= 0.56250     ZC=  0.0000

                  *** MOMENTS OF INERTIA ***
                  (BASED ON A UNIT THICKNESS)

       ABOUT ORIGIN      ABOUT CENTER OF MASS    PRINCIPAL
   IXX =   0.17632E-02      0.36864E-03        0.36864E-03
   IYY =   0.59989E-01      0.13263E-01        0.13263E-01
   IZZ =   0.61672E-01      0.13632E-01        0.13632E-01
   IXY =  -0.80654E-02      0.55511E-16
   IYZ =    0.0000           0.0000
   IZX =    0.0000           0.0000

   PRINCIPAL ORIENTATION VECTORS (X,Y,Z):
```

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Now the mass, center of gravity and moments of inertia for the beam can be viewed and checked against the hand calculations for these values.

Do you expect the center of gravity to be left or right of the center of the beam?

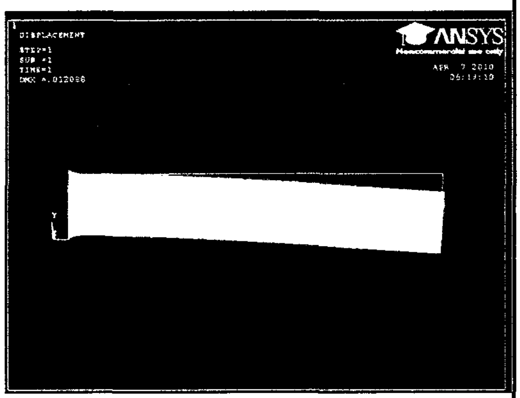
What is your percent error between the hand calculation and the values calculated by ANSYS?

Table 2. Total mass and mass center locations for hand and ANSYS® analyses.

Analysis Method	Total Mass lbm.	% Difference in Total Mass	Center of Mass Location (X,Y) in.	% Difference in Center of Mass Locations	
				X	Y
Hand	3.4094	0.08%	(3.2534, 0.5625)	0.07%	0.0%
ANSYS®	3.4065		(3.2531, 0.5625)		

60

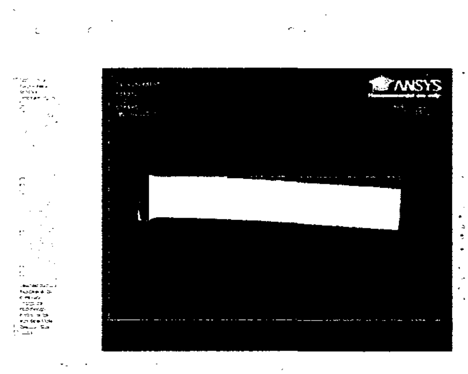
- To view the maximum deflection, Select *General Postproc, Plot Results, Deformed Shape*
- Now on the prompt select *Deformed + Undeformed Edge*
- Now a plot of the magnified deformed beam shape is displayed along with the original location of the edges of the beam shown by a dashed line.



61

- The plot also includes the maximum deflection for the beam. The value displayed is a vector sum of the horizontal and vertical displacements. If only the vertical or horizontal displacement is desired, the contour plot can be obtained from either the nodal or elemental solution.

- Shear Deflection is considered in the ANSYS solution for FEA. The shear deflection can be found by hand using Castigliano's Second Theorem and should be added to the deflection due to bending (equation on right) when comparing analytical and ANSYS solutions.



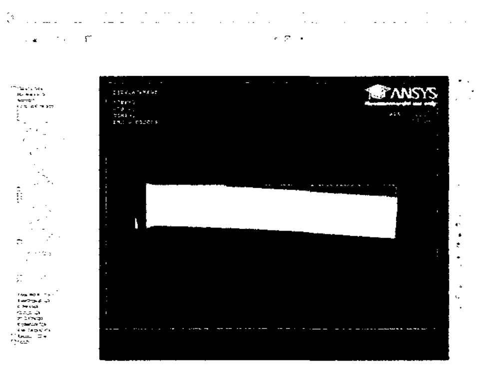
Analytic Solution for Bending

$$y_{@x=l} = \frac{F_{max}}{6EI}[x^3 - 3ax^2 - (x-a)^3] = -0.012 \text{ in.}$$

62

- **Not only can a contour plot be displayed, but a detailed and comprehensive list of either nodal solutions or elemental solutions can be viewed through the *List Results*.**

- **Compare the solution found using analytical methods with the solution found using ANSYS. What is the percent error? If it is a large percentage, what is a possible mistake that may have been made?**

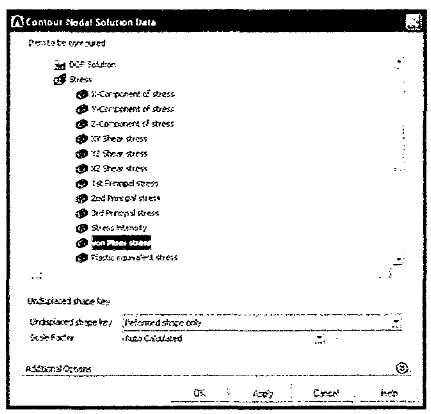


63

- This is done to check the beam for yielding on the first loading cycle, when subjected to the maximum force.
- This solution is available as part of the maximum deflection solution.
- The von-Mises stress is typically used for the stress analysis because it represents an equivalent stress.
- The von-Mises failure criterion states that for a material that reaches its yield stress is deemed to have failed.

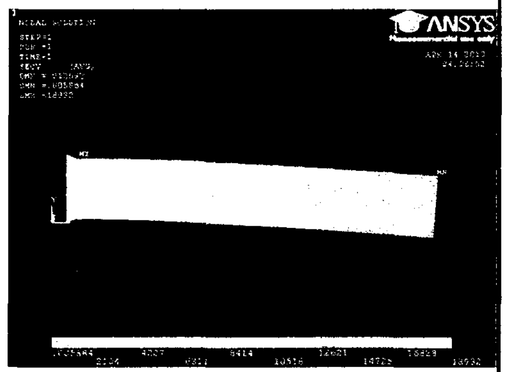
64

- To view a plot of the von-Mises Stress,
- In the *General Postproc*, Select *Plot Results*, *Contour Plot*, *Nodal Solution.*
- The next prompt you need to scroll down slightly to find von-Mises stress as shown to the right, and hit OK.



65

- Notice that the maximum bending stress occurs in the fillet radii at the top.
- Note the value for the maximum loading is far below the Tensile Yield Strength of 60 ksi.
- As with the displacement a *Nodal* and *Elemental solution* are available to be viewed in *List Results* under the *General Postprocessor*.
- We will now complete the same process for the mean and alternating stresses. These stress values will be used to calculate the fatigue safety factor.



66

- We now must go back, delete the previous loading and reapply the load for each case and then solve the model for the current load and find the von-Mises stresses for each loading case as described in the process to view the maximum stress.
- The stresses found from each loading case will be used to calculate the Fatigue Safety Factors found in the text.

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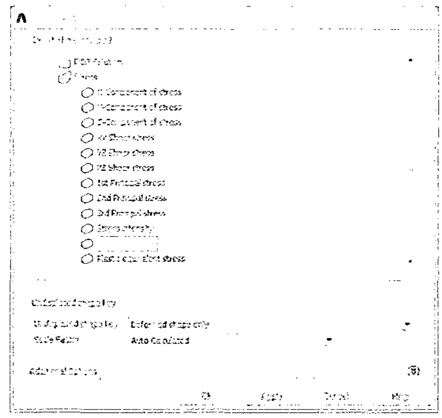
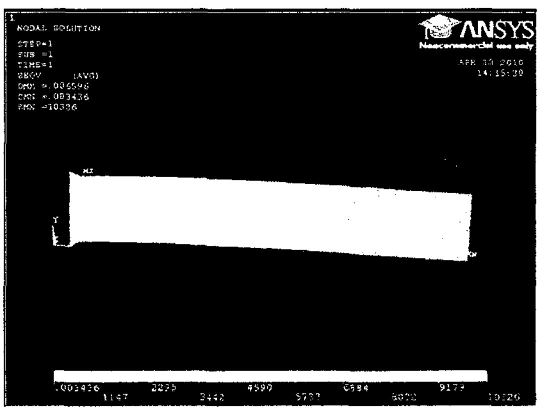
- As a reminder, To view the plot of the von-Mises Stress, following the solution.
- In the *General Postproc*, Select *Plot Results*, *Contour Plot*, *Nodal Solution*.



68

- Mean Case $F_m = \frac{1100+100}{2} = 600\,\boldsymbol{lbsf}$

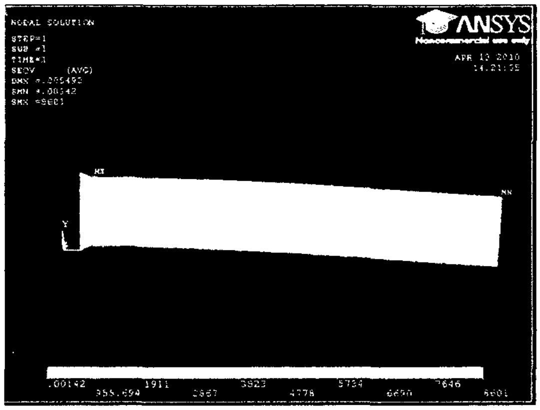


Analytical Solution

$$\sigma_m = K_f \frac{M_m c}{I} = 10454 \text{ psi}$$

69

- Alternating Case $F_{ave} = \frac{1100-100}{2} = 500\,lbs.f$



Analytical Solution

$$\sigma_a = K_f \frac{M_a c}{I} = 8711 \text{ psi}$$

70

- Notice the stress values for both the mean and alternating load cases are less than 2% in error.
- This will give very close to the same answers calculating the fatigue safety factors.

71

- Safety Factors
  - Computing the safety factors from the ANSYS calculated von-Mises stresses is quite simple.
  - In this problem, the Modified-Goodman Diagram is used to find the four possibilities that exist for the lowest possible safety factor.

72

- The first case assumes that the alternating stress is constant and that the mean stress varies. Use the plot on page 84 and the equations below on the following slides to calculate each case for the safety factors.

$$\sigma_{m@Q} = \left(1 - \frac{\sigma'_a}{S_y}\right) S_y$$

$$N_{f1} = \frac{\sigma'_{m@Q}}{\sigma'_{m@Z}} = \frac{S_y}{\sigma'_m}\left(1 - \frac{\sigma'_a}{S_y}\right)$$

73

- The second case assumes failure occurs at a point P, where the safety factor is a ratio of two lines XP/XZ on the plot on page 84.

$$\sigma'_{a@P} = \left(1 - \frac{\sigma'_m}{S_{ut}}\right) S_f$$

$$N_{f2} = \frac{\sigma'_{a@P}}{\sigma'_{a@Z}} = \frac{S_f}{\sigma'_a}\left(1 - \frac{\sigma'_m}{S_{ut}}\right)$$

74

- The third case assumes failure occurs at point R, on page 84. The safety factor is the ratio of the two lines OR/OZ.

$$\sigma'_{a@R} = \left(1 - \frac{\sigma'_{m@R}}{S_{ut}}\right) S_f \qquad \sigma'_{a@R} = \left(\frac{\sigma'_{a@Z}}{\sigma'_{m@Z}}\right)\sigma'_{m@R} = \left(\frac{\sigma'_a}{\sigma'_m}\right)\sigma'_{m@R}$$

$$\sigma'_{m@R} = \left(\frac{S_f}{\frac{\sigma'_a}{\sigma'_m} + \frac{S_f}{S_{ut}}}\right) \qquad N_{f3} = \frac{\sigma'_{m@R}}{\sigma'_{m@Z}} = \frac{S_y S_{ut}}{\sigma'_a S_{ut} + \sigma'_m S_f}$$

75

- The fourth case assumes a future case where the relationship between the alternating and mean stress is unknown. The point S on the failure line closest to the stress state at point Z can be taken as a conservative estimate of the failure point.

$$\sigma'_{m@S} = \frac{S_{ut}\left(S_f^2 - S_f\sigma'_a + S_{ut}\sigma'_m\right)}{S_f^2 + S_{ut}^2} \qquad \sigma'_{a@S} = \frac{S_f}{S_{ut}}\left(\sigma'_{m@S}\right) + S_f$$

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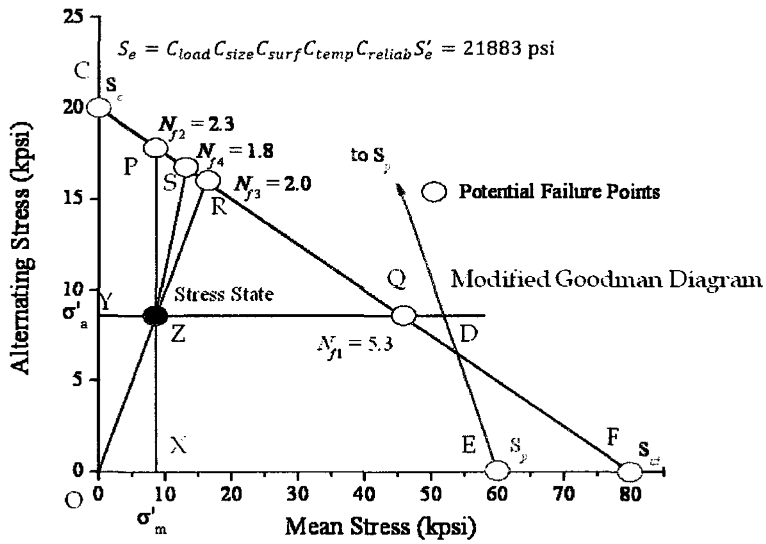
$$ZS = \sqrt{\left(\sigma'_m - \sigma'_{m@S}\right)^2 + \left(\sigma'_a - \sigma'_{a@S}\right)^2}$$

$$OZ = \sqrt{\left(\sigma'_m\right)^2 + \left(\sigma'_a\right)^2}$$

$$N_{f4} = \frac{OZ + ZS}{OZ}$$

77



- It appears the lowest safety factor occurs in Case #3 with a value of N_{f3} = 1.8. Norton calculates this value to be 1.7.
- The increased safety factor provides a difference in the two solution methods of only 5.88%.
- The hand analysis is found to be more conservative than the FE analysis. In the FE analysis, the elements can cause the beam to have an increased stiffness.
- The problem description ask for the design of this beam to have at least a factor of safety of 2.0 for fatigue loading.
- To correct this one of two things can be done. The cross-sectional area of the beam needs to be increased, this can be done by thickening the beam or by increasing the height. All of these will raise the resistance to bending by increasing moment of inertia, thus lowering the stresses.
- The software makes this change very quickly, but recalculating the stresses by hand would take much longer.

- The use of ANSYS to compute the stresses for the determining the safety factors can save time in trying to determine stress concentration values and calculating other variables that reduce the fatigue strength.
- Some problems are almost impossible to work by hand to the degree of accuracy that ANSYS provides. This becomes especially true when working in three dimensions.
- Even the fatigue calculations are available in some commercial software. However, it is important to know what safety factor is being calculated by those softwares. In cases of finite loading life cycles an estimated design life can be computed.
- It is important to realize these are only estimates. Materials are unpredictable and typically do not always behave as we have assumed in this model.

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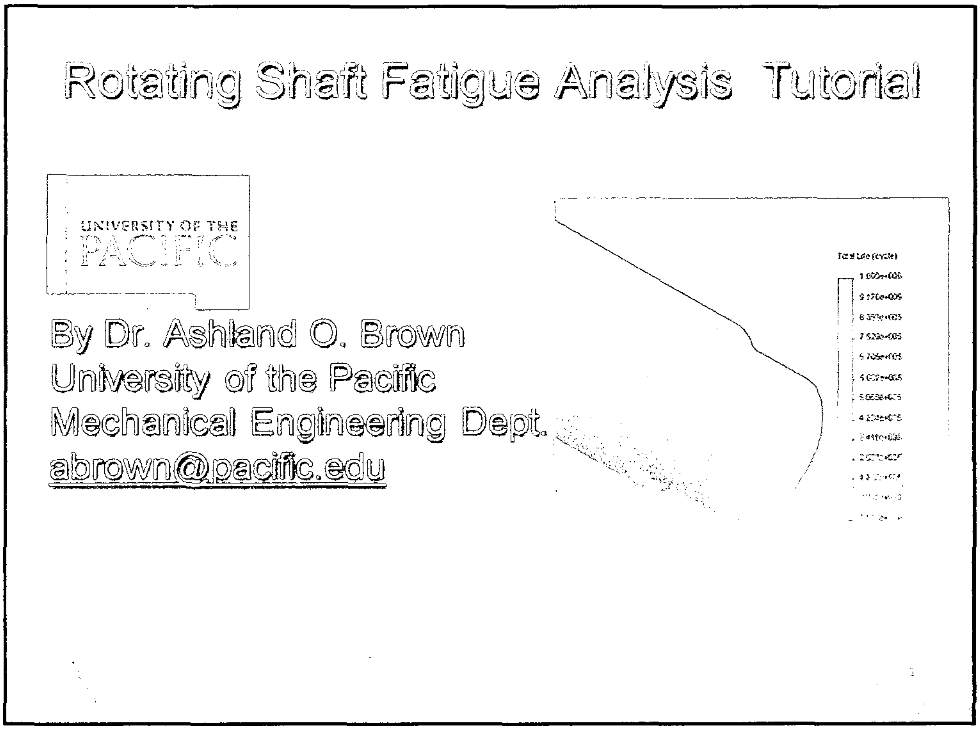
Appendix B. Spring 2009 Rotating Shaft Fatigue Finite Element Learning Module

The following Finite Element Learning Module was developed by Dr. Ashland O. Brown at the University of the Pacific. This module was used by Dr. Jiancheng Liu at the University of the Pacific in the Spring of 2008. The design of this module and the assessment results can be observed in Chapter 3 of this work.



Fatigue Finite Element Learning Module

Fatigue Analysis Learning Module ported to COSMOSWorks Professional 2008 Software by SolidWorks Corporation

Expected completion time for this tutorial is 30 to 45 minutes

Companion Tutorial for Machine Design Courses 120/125

Reference Text: Eighth Edition of *Shigley's Mechanical Engineering Design*

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Table of Contents

3

Educational Objectives

The educational goal is to provide undergraduate engineering students with an understanding of a specific engineering topic and FE theory, along with an ability to apply commercial FE software to typical engineering problems. The educational goal will be accomplished through four educational objectives based upon Bloom's Taxonomy and ABET Criteria 3 as follows;

1. *Engineering topics (Comprehension: 3a, 3k).* Understanding the fundamental basis of engineering topics through the use of finite element computer models.

4

Educational Objectives

2. *FE Theory (Comprehension;3a)* Understand the fundamental basis of FE Theory.
3. *FE Modeling Practice (Application; 3a, 3e,3k)* Be able to implement a suitable finite element model and construct a correct computer model using commercial FE software.
4. *FE Solution Interpretation and Verification (Comprehension and Evaluation; 3a,3e)* Be able to interpret and evaluate finite element solution quality including the importance of verification.

5

Problem Description

- Analysis Objectives
  - Using the COSMOSWorks finite element software you will estimate the fatigue life of a shaft rotating with a steady load being applied.
  - The process of defining the fatigue life using this commercial code will instruct you in the following:

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Analysis Objectives

- Defining a fatigue study
- Setting properties of the fatigue study
- Defining an S-N curve for the part material
- Defining constant-amplitude fatigue events
- Viewing the fatigue results

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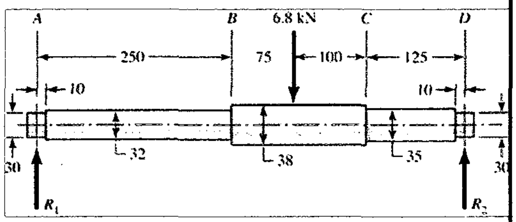
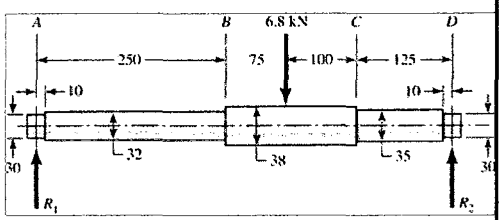
Problem Description

- Example 6-9 page291 8th Edition of *Shigley's Mechanical Engineering Design*
- The figure shows a rotating shaft simply supported in ball bearings at A and D.
- Loaded by a non-rotating force F of 6.9 kN.
- The shaft's material is machined from AISI 1050 cold drawn steel.
- All fillets have 3mm radius.
- The shaft rotates and the load is stationary.
- The material's ultimate strength SUlt is 690 MPa and yielding strength Sy is 580 MPa.



Problem Description

- The material's endurance limit is 345 MPa.
- Its reliability factor is 1.
- The shaft operates at room temperature (25 °C).
- The support loads R1 and R2 are 278 kN and 402 kN when the external load is 6.8 kN.
- Estimate the life of the part when the load is 6.8 kN, 3.4 kN and 1.7kN.



Problem Description

- Assumptions:
  - The problem can be accurately represented with second order tetrahedral elements with 10 nodes in each element.
  - This fatigue analysis begins with a static structural analysis
  - The material is homogeneous and isotropic under room temperatures

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Background Information

- General
  - The purpose of this tutorial is to provide visualization of the structural analysis concepts covered in your course and to introduce the concept of using finite element analysis (FEA) in analyzing a fatigue analysis problem. You begin with building a 3-D solid model of this problem using the SolidWorks software. Once the 3-D model is constructed you then submit it to COSMOSWorks to perform the FEA. FEA consists of two major steps: pre-processing and post-processing. Preprocessing involves preparing the 3-D model, meshing the model, and defining material properties along with placing boundary conditions on this model; the post-processing involves running the FEA analysis and then displaying the results.

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Background

- Finite Element Theory – Basics
  - FEA works with the discretization of the actual structural geometry into small portions called finite elements. These finite elements are joined together by shared nodes, also termed element connectivity. The elements and nodes jointly are referred to as the mesh. The real-life structure being analyzed can be quite complex and hence a closed–form solution may not be available to provide predicted displacement, stress or temperature in the structure. FEA provides approximate solutions to the differential equations defining the physics of structural or thermal models of problems. The unknowns for each finite element are displacements at the nodes for structural analysis and temperature at the nodes for thermal analysis. Each finite element shares at least one node with its neighboring element.

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Background

- Finite Element Theory – Basics
  - The equations are formed from the mesh of nodes and the solutions obtained must satisfy the physical condition that any nodal displacement or temperature must also be the same for all of the neighboring elements. This condition is called capability and is one of the fundamental requirements for a valid design analysis. Many such equations are defined and solved simultaneously to get the approximate solution for a complex structure. Most complex structures have thousands of such nodes approximating the geometry of the structure. These nodes then form the basis of thousands of equations which must be solved simultaneously.

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Background

- Finite Element Theory – Element Types
  - Commercial FEA codes contain many types of finite elements. We will only discuss only three such finite elements in this tutorial: one dimensional (1-D); two dimensional (2-D); and three dimensional (3-D) finite elements .

  One-dimensional elements
  - The bar elements is a 1-D element which does not sustain bending, but can sustain axial loads. Rigid bars and trusses are examples of these type of 1-D elements. Another type of 1-D elements called a beam element which can sustain bending as well as axial loads which makes these elements more useful to users.

  Two-dimensional elements
  - Two dimensional (2-D) elements include plate and shell elements which are usually triangular or quadrilateral in appearance. These 2-D elements are usually thin and can be used to model very curved objects.

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Background

- Finite Element Theory – Element Types

  Three-dimensional elements
  - These type of elements are used for modeling 3-D geometry and are the most widely used element types. Tetrahedral and brick elements are typically used to model solid geometric shapes. The Tetrahedrals are usually more flexible than the brick elements in modeling very complex geometric shapes.

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Background

- Finite Element Theory – Mathematics/Physics
  - A partial differential equation defining the physics of the problem (i.e., the heat conduction equation for thermal analysis) is approximated and solved at specific locations on each finite element and extrapolated to each node of that element. These partial differential equations of meshed 3-D model are approximated with linear arrays of equations. The FEA software has mathematical solvers which are very fast and solve these large arrays of equations for the variable (i.e., temperatures or displacements) at each node of each finite element. The solutions to these arrays of equations provides the basis of the graphical plots shown in the FEA software results.

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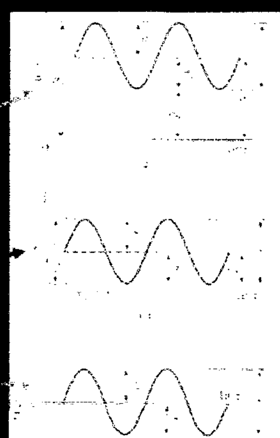
The Nature of Fatigue

- Cyclic or repetitive loading is often characterized by a sinusoid where the most tensile stress represents the top of the wave and the most compressive stress represents the bottom.
- The stress ratio R, the **ratio of the minimum stress to the maximum stress** indicates the magnitude of the alternating stress.
- When R = 0, called zero based loading, R=-1 which indicates fully reversing stress about mean stress.
- And R=1 which is simply static loading. The Fatigue Strength of a material can vary with the magnitude of R.



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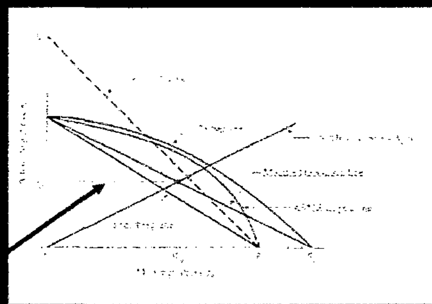
Uncertainty in Fatigue Analysis

- These factors comprise some of the sources of uncertainty in fatigue predictions
- Geometry
  - Stress risers
  - Surface finish
- Load History
  - Physical Measurements
  - Knowledge of System
  - Unexpected load peaks
- Material Properties
  - SN Curve
  - Uncertainty of Scatter of Data
- Fatigue criteria of failure
  - Which failure criteria to use Mean Stress Correction Method (i.e. Goodman, Gerber or Soderberg correction)



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Fatigue Prediction Methods

- Three major methods for determining component fatigue life:
  - Stress Life (SN)
  - Strain Life (EN)
  - Linear Elastic Fracture Mechanics (LEFM)
- **COSMOSWorks** uses Stress Life (SN) Method
- High versus Low Cycle Fatigue
  - **HIGH CYCLE:** Low Stress, >100,000 Cycles, Stress-Life (SN) Valid
  - **LOW CYCLE**: High Stress, 10- 100,000 Cycles, Strain-Life (E-N) Methods more appropriate

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Fatigue Prediction in COSMOSWorks

- Basic Process
  - **Define one or more Static Structural studies**
    - Specify or define a SN curve for each material to evaluate durability.
      - Multiple materials can have their own SN curve
    - Solve for displacement and stress
  - **Define Fatigue study**
    - Specify as either a variable or constant amplitude study
    - Define Events based on previously studies
      - Events can run simultaneously or sequential
    - Set study properties for:
      - Mean Stress Correction
      - Alternating Stress Calculation Method
      - Fatigue Strength Reduction Factor
    - Determine if you need results on just surface or through the entire volume
  - **Solve and review results**

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Overview of this Tutorial

- Create a geometric 3-D model of the rotating Shaft in SolidWorks
- Create a finite element structural static analysis of this model in COSMOSWorks.
- Create a finite element fatigue analysis of the finite element static analysis in COSMOSWorks.
- Post a predicted fatigue life for the three loads in COSMOSWorks.
- Compare this Finite Element Fatigue Analysis (Life) with the text calculated Fatigue Analysis (Life)

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Tutorial General Steps

- Complete a finite element static analysis of the model using the appropriate S-N Curves in COSMOSWorks with outputs of von Mises stress and displacements
- Complete the finite element fatigue analysis of the model using as input the finite element static analysis, select the appropriate R for the cyclic load, the appropriate event, and the appropriate fatigue criteria for the problem
- Post-process the fatigue results of the finite element analysis showing the fatigue life for this shaft model under the 6.8 kN load.
- Run the finite fatigue analysis for the expected life of the shaft for the loads of 3.4kN and 1.7kN.
- Comparison of the analytical hand calculated life of the shaft with the finite element analysis expected life at these three loads.

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Tutorial Step by Step

- Overview of SolidWorks and COSMOSWorks
- Left side of the SolidWorks/COSMOSWorks Window
- Using the SolidWorks interface
- Toolbars, viewport and visual aids
- Online-Tutorials and getting help
- Dimensioning the model in millimeters in SolidWorks
- Creating a SolidWorks 3-dimensional model of the shaft along with defining a "split-line" on the top surface to place the point load
- Verifying the dimensions of the shaft model
- Verify that COSMOSWorks is loaded on your computer

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Tutorial Step by Step Process

- Opening your model inside COSMOSWorks and beginning a finite element static study
- The COSMOSWorks finite element study folders
- Assigning S-N fatigue material properties to the shaft model
- Applying restraints or boundary conditions to the 3-d shaft model at the ends.
- Apply vertical forces to shaft upper surface at the "split-line"
- Selecting the appropriate meshing parameters for the model and running the static finite element analysis.

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Tutorial Step by Step Process

- Opening the results file for the finite element static analysis and viewing the von Mises stresses and displacements.
- Create a finite element fatigue analysis with the results from the finite element static analysis.
- Select the appropriate **R** ratio of minimum to maximum stress for the rotating Shaft and which **Mean Stress Correction Method** (i.e. Goodman, Gerber, and Soderberg correction options)
- Setting the ***Fatigue strength reduction factor (K_f)***
- In the COSMOS Analysis Manager tree, right-click the Loading icon and select ***Add Event***. The Add Event (Constant) Property Manger appears.

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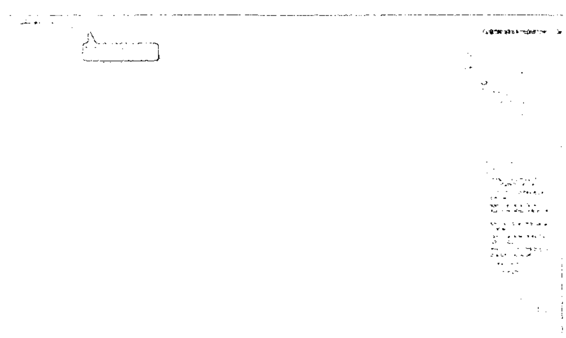
Tutorial Step by Step

- Set Cycles to 1000
- Set Loading Type to Zero based (LR=-1)
- In the Study Association cell , click the cell under Study column the select Fatigue Analysis
- Click
- The software creates an icon in the Loading folder
- Run the finite element fatigue analysis and when completed select the results file.
- Open the results file for part fatigue life

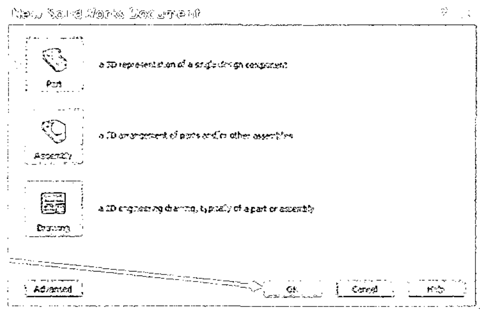
SolidWorks

- To begin a new SolidWorks Part
- Select the New Icon which begins a new part



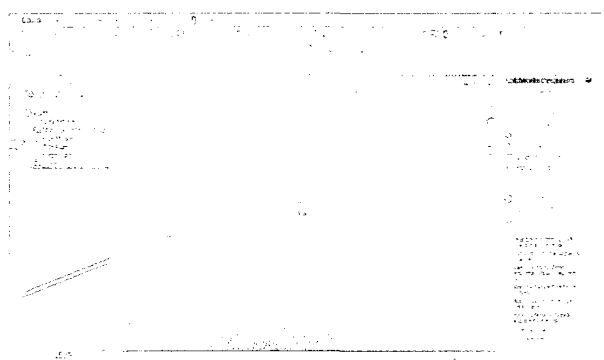
Creation of Fatigue Shaft

- To create the Fatigue Shaft
- Select the Part Icon and then
- Choose OK



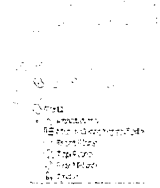
SolidWorks Interface

- Toolbar area
- Feature Manager window
- Graphical Interface window

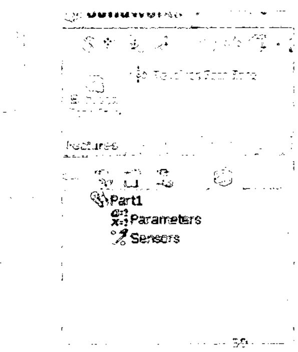


Left Side of SolidWorks Window

- Feature Manager icon
- Feature Manager design tree

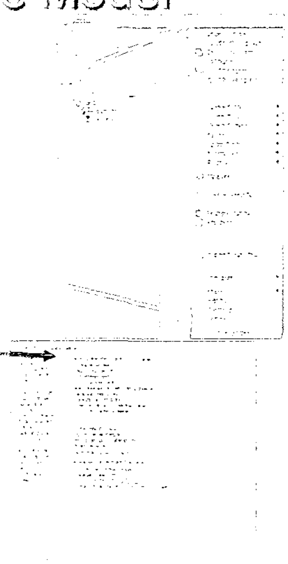


- COSMOSWorks icon
- COSMOSWorks Manager tree



Dimensioning the Model

- Dimensioning the Model
  1. Go to *Tools* menu.
  2. Click on Options.
  3. Under the *Systems Options Menu*, select Document Properties

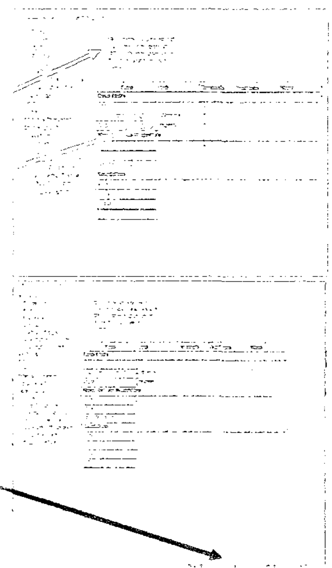


Dimensioning the Model

4. The Document Properties will now appear, select units

5. Then select MMGS and millimeters inside this document to set the dimensional units.

6. Finally select OK

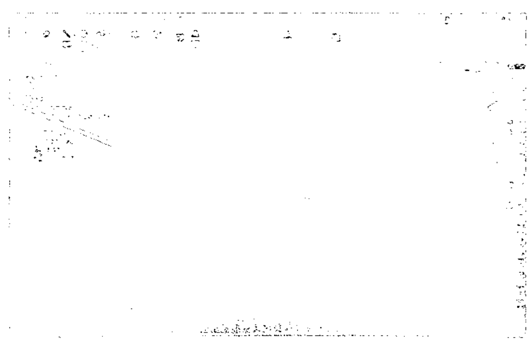


Constructing the Shaft

1. To begin extruding the shaft select Extrusion Boss Base icon
2. To extrude the shaft you must select which of three planes, we choose the Right Plane

Constructing the Shaft

3. A sketch plane will appear inside your viewing port with grids to assist you.



Constructing the Shaft

4. Use the Circle icon to sketch a rough shape of the left end of the Shaft in the center of the viewport.

5. Now dimension the sketch using the dimension icon. Smart Dimens

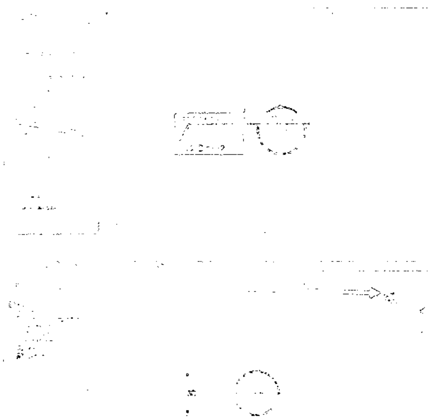
6. Left click the dimension icon then select the Circle diameter to be dimensioned and double click to open the dimension box.

7. Inside the dimension box enter the dimension (30 mm) in millimeters then click the green check to close.

Constructing the Shaft

8. Once the Circle dimension are entered choose the green check icon to close the sketch.

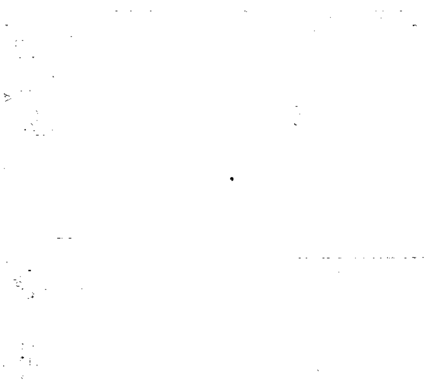
9. Now select the Confirmation Icon to close the sketch and to extrude the shaft



Create the Shaft

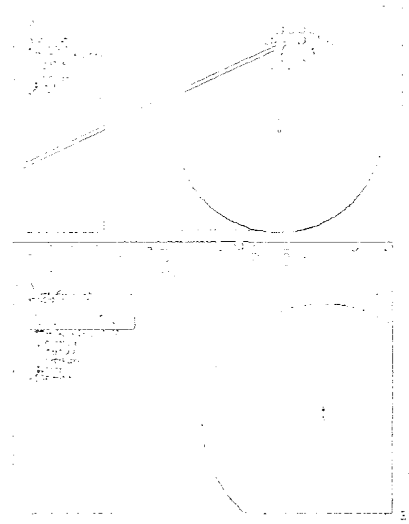
The Shaft end is now Extruded

1. Under direction 1
   Select Blind
2. Under D1 select a shaft distance of 20 millimeters
3. Finally select the green check mark to finalize the shaft dimensions
4. Name (*Fatigue Shaft*) and Save your model to your directory



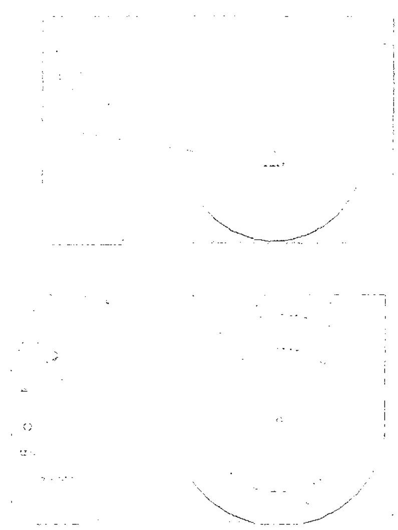
Constructing the Shaft

- The shaft is composed of five segments of various diameters and lengths.
- We will extrude each segment on to the initial and adjoining segment beginning at the left of the project figure.
- 1. Lets first rotate the initial shaft to look at the its end.
- 2. Then select the Extruded Boss/Base icon to extrude the next portion of the shaft.



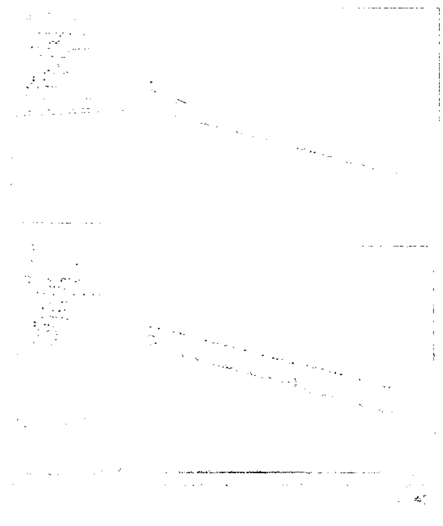
Constructing the Shaft

- 3. Next select the plane of the existing shaft to add the new extrusion.
- 4. Choose the Circle icon for your new sketch on the end of the existing shaft.
- 5. Then dimension this circle and extrude it the required length.



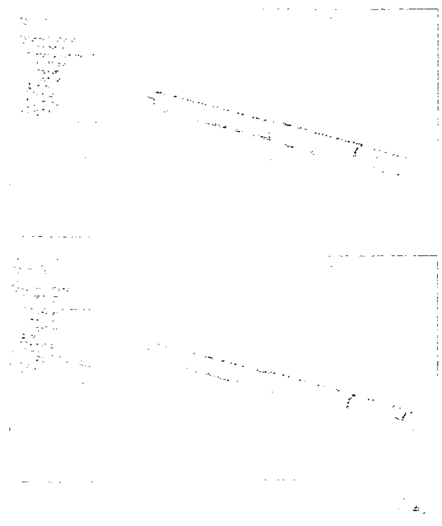
Constructing the Shaft

- 6. This second shaft segment has a diameter of 32 mm and a length of 240mm.
- 7. Continue by placing the third shaft segment on the end of the second segment using a Circle sketch and the Extrusion Base/Boss. This segment has dimensions of 38mm diameter and length of 175 mm.



Constructing the Shaft

- 8. The fourth shaft segment has dimensions of 35mm diameter and a length of 115 mm.
- 9. The fifth and last shaft segment has dimensions of 30 mm diameter and length of 20 mm.

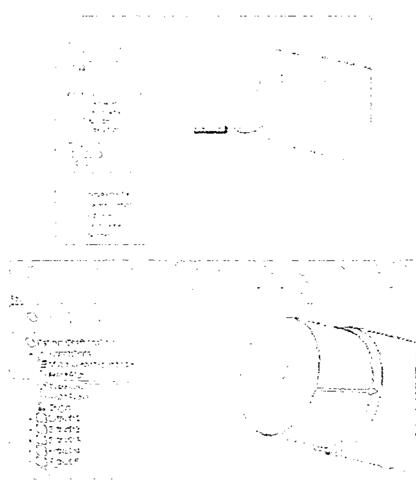


Adding the Fillets to the Shaft

- To add the fillets , select Features at the top of the tool screen.
- 1. Now the fillet icon will become visible.
- 2. Then select the Zoom to Area Icon and draw a box around a segment connection.
- 3. Next select the Fillet icon and choose the segment connection and

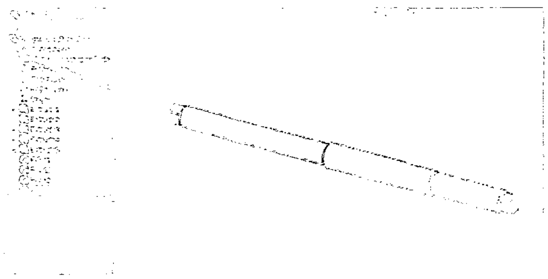
Adding Fillets to the Shaft

- 4. Now once the Fillet icon is selected the Fillet Manger appears.
- 5. Select constant radius fillet and a dimension of 3mm for the fillet
- 6. Finally select the green check mark to close the Fillet Manager.
- 7. Add 3mm fillets similarly to each of the five segment connections



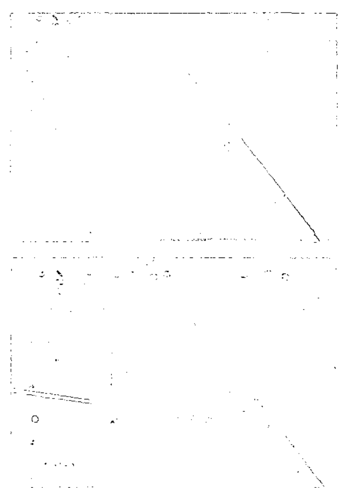
Adding Fillets to the Shaft

- 8. The shaft with all four fillets should appear similar to model.



Addition of a Split-Line for the Vertical Load

- To facilitate loading this shaft a Split-Line will be place on it at the appropriate distance from the end.
- 1. Enter into a sketch mode and select the Top Plane.
- 2. Once the Top Plane appears select a Circle and place it near the end of the third shaft segment as shown here. Keep the circle diameter small approx 5 mm
- 3. Click the green check mark to exit the sketch mode



Addition of a Split-Line for the Vertical Load

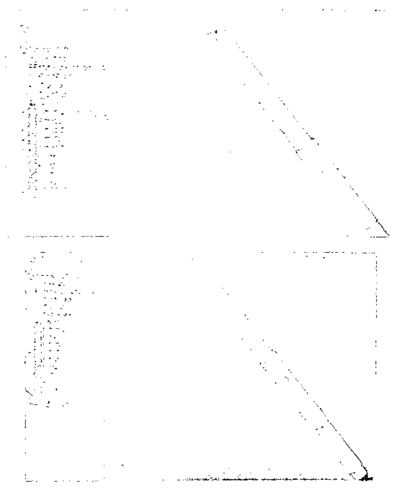
- 4. We now need to position the sketch circle at the proper distance from the right end of the shaft.
- 5. Select the smart dimension icon and select the circle and then the end of the shaft.
- 6. The circle should be 235 mm from the right edge of the shaft.

Addition of a Split Line to the Shaft

- 7. Now go to the top menu and select Insert and locate Curve and select Split-Line.
- 8. Once the Split-Line Manager appears make sure the type of Split-Line has Projection selected
- 9. Under selections it will have your current sketch, then under face select the outer face<1> of the third shaft segment.
- 10. Finally click the green check mark to exit the Split-Line Manager.

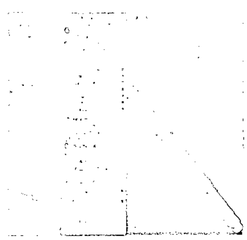
Addition of a Split-Line to the Shaft

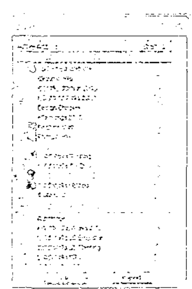
- 11. The split-line will appear as a small circle on the surface of the shaft s third segment.
- Now we have positioned the split-line precisely on the shaft.
- The split-line icon will now appear in the SolidWorks Manager



Verify that COSMOSWorks is loaded on your Computer

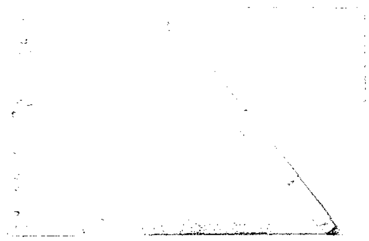
1. Left-mouse-click the Tools item in the menu and select Add-Ins.
2. The Add-Ins box should appear; verify that the COSMOSWorks 2008 box is check and click OK





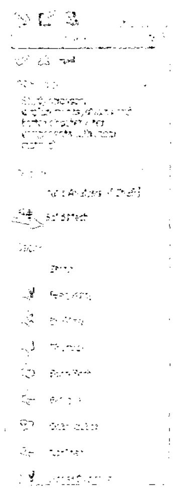
Opening the model inside COSMOSWorks

- Left-mouse-click the COSMOSWorks Manager tab
- Right-mouse-click the file name that you just created under the COSMOSWorks Manager and select Study. The Study dialog box appears.
- 1. Give you part a name (Static Study) then verify that your model has a Solid Mesh and finally select Static analysis.



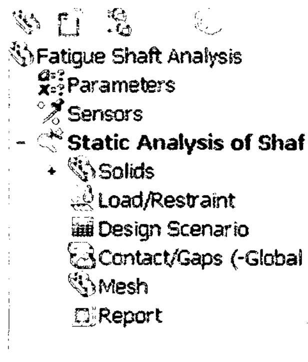
Creating a Study in COSMOSWorks

- In the Study dialog box type in the name for this thermal study: Static Analysis of Shaft
- Select Solid Mesh
- Under Type of Study select Static
- Close by clicking OK.
- Notice that COSMOSWorks creates the study in the COSMOSWorks Manager.



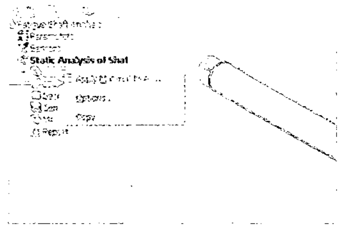
The COSMOS Study Folders

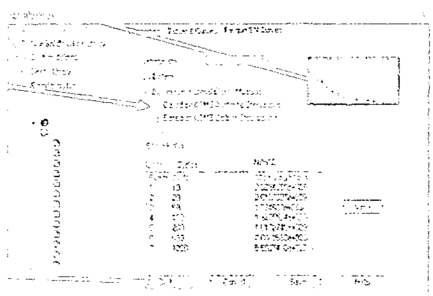
- COSMOSWorks automatically creates a folder called L-Bracket Transient HT with the following sub folders:
- Solids
- Loads/Restraints
- Design Scenario
- Contact/Gaps
- Mesh
- Report
- In this tutorial we will use only the Solids, Loads/Restraints, and Mesh sub-folders. The other folders will be explained in future tutorials.



Assigning SN Material Properties

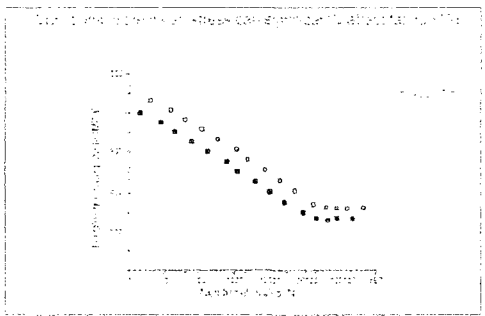
- In the COSMOSWorks Manager, Right-mouse-click the Solids icon and click Apply Material to All...
- 1. The material dialog box appears. select Custom defined.
- 2. COSMOSWorks provides a utility for estimating SN curve based on the elastic moduli of various steels. This is based on an ASME specification and will yield representative curves for ASME Austenitic Steel. These curves may not be the exact ones for the material.
- 3. We will focus solely on trends, thereby using a consistent curve here and the fatigue trends should be valid. Finally select OK





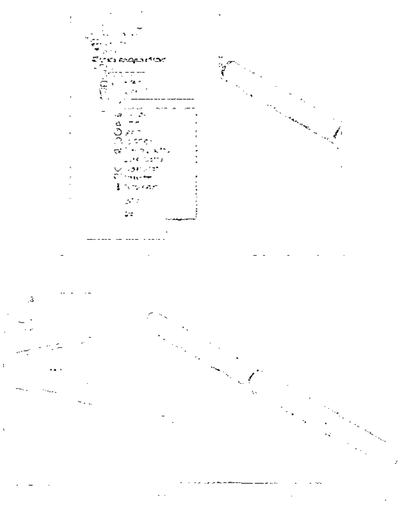
Mean Stress Correction

- Variations in the mean stress can significantly affect fatigue life.
- An important concept is that stress measurements at different R values may yield different fatigue strengths. R is directly related to the mean stress in a cyclic load application.
- Consequently, some techniques have been developed over the years to adjust the prediction of fatigue in a physical event having one Mean Stress by using test data derived from another mean stress.



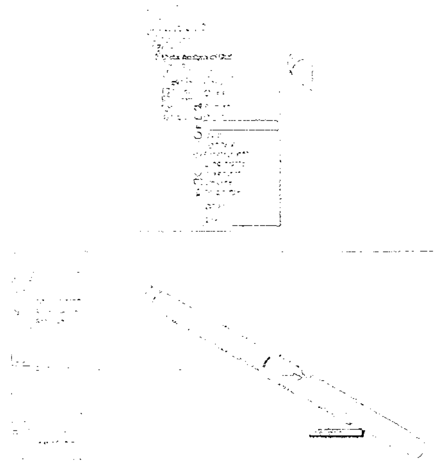
Applying Restraints to the Shaft

- In the COSMOSWorks Manager, Right-mouse-click Load/Restraint and select Restraints.
- 1. Now the Restraints window appears and scroll through the first window and select Immovable Restraints (no translational movement allowed)
- 2. Then select both ends of the shaft to simulate the roller bearings



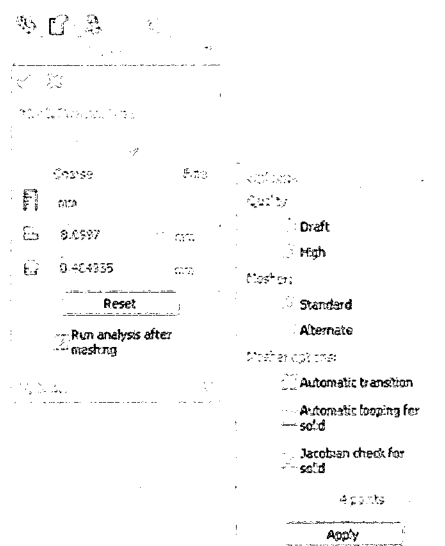
Applying the Load to the Shaft

- In the COSMOSWorks Manger now right- mouse click the Loads/Restraint Icon and select the force Icon.
- 1. Now once the force window opens select Apply normal force and the "split-line" that you constructed for force of 6800 N.



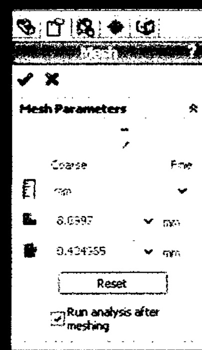
Creating the Mesh

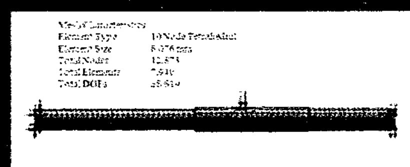
- In the COSMOSWorks Manager, Right-mouse-click Mesh and click Create Mesh.
- The MESH Property Manager appears.
- Click Options.
- The Options dialog box appears with the Mesh tab active
- In the Options manager select:
  Quality- High
  Controls- Automatic Transition unchecked
  Controls - Smooth Surface checked
  Automatic Looping- unchecked
  Jacobian Check- 4 points
  Mesher to use- Standard
- Finally to Mesh the model and Run the Analysis check the run button and click the green OK button.



Meshing the Model and Running the Study

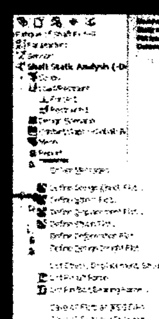
- Click **Run analysis** after **meshing** and accept the default mesh size.
- Finally, click [icon] or press *Enter* to mesh the model and run the finite element analysis.
- The running of the finite element solver will take approximately 2 minutes on your computer

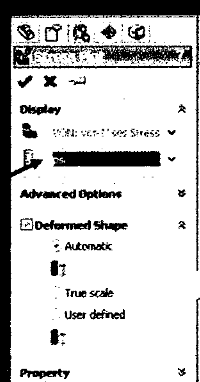




Viewing the Results of the Finite Element Static Analysis

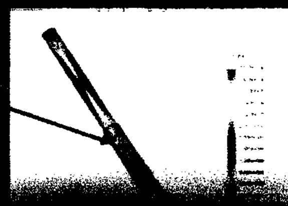
- 1. Right-mouse-click the Results Folder and select **Define Stress Plot.**
- 2. The **Stress Plot manager** will appears and should look similar to the window here.
- 3.The default Stress is von **Mises** and we will change it to units of **psi.**

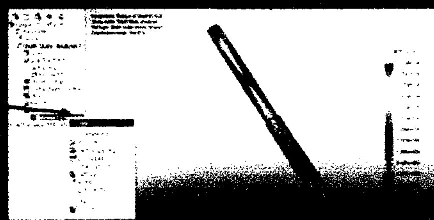




Viewing the Finite Element Static Analysis

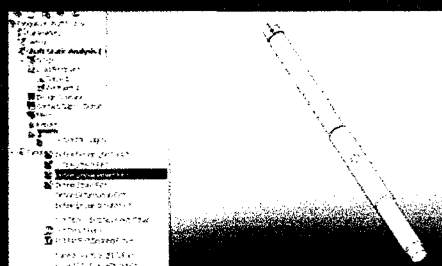
- We will first view the von Mises stresses in the shaft.
- 1. The von Mises stresses are shown here for a load of 6.8kN applied at the "split-line".
- 2. To hide the visual simply left-mouse-click the von Mises stress icon and select hide.

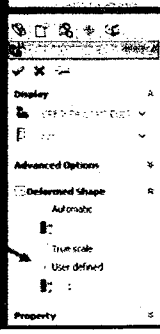




Viewing the Finite Element Static Analysis

- We now will view the displacements in the shaft from applying the load.
- 1. Left-mouse-click the Results folder and select Define Displacement Plot……
- 2. The Displacement Plot Manger window will appear.
- 3. Now select units of **mm** and **True Scale of 1.**



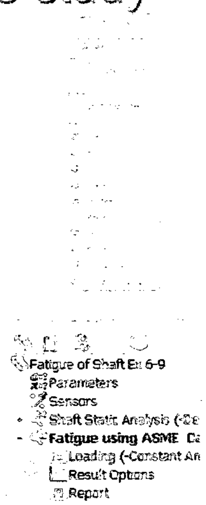


Viewing the Finite Element Static Analysis

- The displacement plot for the shaft is now displayed
- The displacement units are in mm

Create the Fatigue study

- 1. Left-mouse-click the SolidWorks Model Icon Fatigue of Shaft Ex 6-9 and select study.
- 2. Create a fatigue study named Fatigue using ASME Carbon Steels, then select the Fatigue for the type study no mesh is needed.
- 3. Finally select OK
- 4. A new set of Fatigue Folders will be formed for :
  - Loading
  - Results Options
  - Report

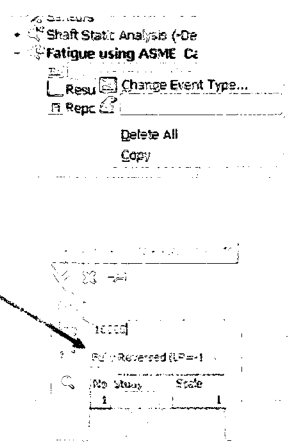


Creating the Fatigue Study

5. Right-mouse-click on Loading and choose Add Event, enter 10000 for the number of cycles.

   Select Fully Reversed loading R= -1 for Loading Type

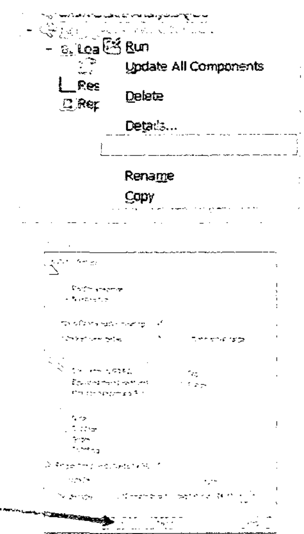
   Select Shaft Static as the Study Association name, and make sure the Scale value is 1



6. Finally Click OK

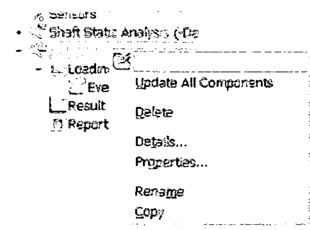
Creating the Fatigue Study

- 7. Review and change Fatigue study Properties by left-mouse-clicking on the fatigue Study Name and selecting Properties
- 8. Constant Amplitude Event Interaction is irrelevant in this case because only a single event is defined
- 9.Change Computing alternating stress using to Equivalent stress of von Mises
- 10. Select Gerber method for Mean stress correction
- 11The Fatigue strength reduction factor (Kf) should be set to 1.
- 12 Leave shell surface Top
- 13. Click OK

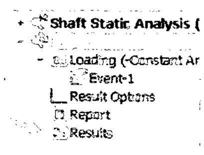


Creating the Fatigue Study

- 14. To run the Fatigue Analysis left-mouse-click the name of the Fatigue Study and select Run

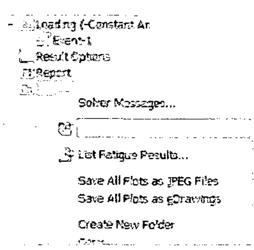


- 15. The Fatigue Analysis should only take a few minutes to complete and when finished a Results Folder appears.

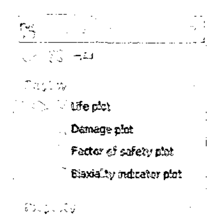


Creating the Fatigue Study

- 16. Now left-mouse-click the Results Folder and select the Define Fatigue Plot.....



- 17. When the Fatigue Plot Manager comes up select to Display Life plot

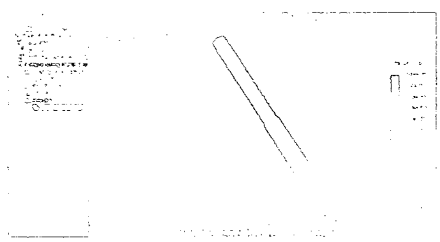


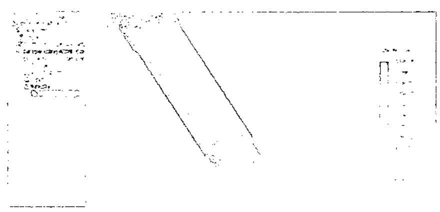
Creating a Fatigue Study

18. The Life Plot shows the expected life of this shaft under the 6.8 kN load.

19. The expected life is within a range of 11,580 to 93,900 cycles and the failure locations are near the two ends of this shaft. This compares well with the text hand calculated life of 68,000 cycles

20. Repeating this Fatigue Analysis for the lower loads of 3.4 kN and 1.7kN produces Infinite Fatigue Life.





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Comparison of Fatigue Results

- Fatigue Life using text hand calculations
- 6.8kN Load 68,000 cycles
- 3.4 kN Load
- 1.7kN Load

- Fatigue Life using COSMOSWorks
- 6.8kN Load 11,500 to 93,900 cycles
- 3.4 kN Load Infinite Life
- 1.7 kN Load Infinite Life

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Summary and Discussion

This finite element fatigue analysis reinforces the basic nature and concepts related to fatigue analysis. The differences between failure prediction for cyclic loading and static loading. The scatter in life predicted by this finite element analysis is typical of real world predictions, but well within the scope of classic text practices. The advantage of using this sophisticated computational method is that it is rapid and optimization studies to refine the part or system designs can be completed rapidly once the user becomes familiar with the fatigue analysis software. The accuracy of the SN material curves is key to the accuracy of this technique.

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Appendix A: Finite Element Theory

The discretization process, better known as meshing, splits the continuous 3-D computer aided drawn models into finite elements with nodes. The type of elements created in this process depends on the type of geometry meshed, and the accuracy of the analysis that needs to be executed. Most commercial FEA software codes have multiple types of finite elements. We will define only three types of elements in this tutorial: one-dimensional elements or line elements, two-dimensional elements or shell elements and three-dimensional elements or solid tetrahedral elements. COSMOSWorks Professional Educational Edition 2007-2008 offers three types of elements: three-dimensional tetrahedral solid elements, for meshing solid geometry, two-dimensional triangular shell elements, for meshing very curved surface geometry and one dimensional beam elements for meshing frame structures. These three types of finite elements will solve most typical engineering problems.

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Finite Element Theory

The beginning point for COSMOSWorks is a 3-D geometric model of the problem, a part or assembly, representing the object that needs to be analyzed. We then assign material properties and define structural or thermal boundary conditions for the model. For structural analysis the model must be constrained to generate stresses, without proper constraints the model would have free body motion in space whereby no loads or stresses are developed. We next split the geometry into relatively small and simple shaped entities called finite elements. Creating finite elements is commonly called meshing. The smaller the mesh size the more accurate the finite element analysis, but at a cost of more computer time to solve the additional equations generated.

The COSMOSWorks mathematical solver approximates a solution to the constitutive partial differential (PD) equations of the meshed model. COSMOSWorks has three high speed math solvers; one using a direct-method of solution to the PD equations and two using a iterative method of solution to the PD equations.

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Finite Element Theory

The tetrahedral solid elements can be either first order (draft quality) or second order elements (high quality). The user decides whether to use draft quality or high quality elements for meshing the 3D geometric model. However only high quality elements are used in analysis of importance. First order tetrahedral elements have four nodes, straight edges and flat faces. Second order tetrahedral elements have ten nodes, curved surfaces, and are more accurate in modeling complex problems. The second order elements are the elements of choice for accurate results.

The use of the elements with the higher number of nodes has improved accuracy with but with additional computational time over the elements with less nodes. Each tetrahedral element with either 4 or 10 nodes per element has three degrees of freedom (DOF) for each node. The degrees of freedom of a node in a finite element mesh define the ability of the node to perform translation or rotation. The number of DOF that a node posses depends on the type element that the element belongs to.

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Finite Element Theory

Nodes of solid elements have three degrees of freedom (DOF) while nodes of shell elements have six degrees of freedom. This means that in order to describe transformation of a solid element from the original to the deformed shape, we need to know three translational components of nodal displacement usually x, y and z. In the case of a shell element we need to know six DOF or three translations and three rotations for each node.

Each degree of freedom (DOF) of each node in a finite element mesh constitutes an unknown. For structural analysis a partial differential equation defining the physics of the problem is solved for displacements at specific locations on each finite element and extrapolated to each node. Once the displacements are calculated the strains and stresses can be calculated for the model.

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Finite Element Theory

Contrary to the first order solid and shell elements, two-node beam elements model the two out-out-plane deflections as cubic functions and the axial translations and torsional rotations as linear. The shape of the two-node beam element is initially straight, but it can assume the shape of a cubic function after deformation takes place.

Each two-node beam element features six degrees of freedom (DOF) at each end node: three translations and three rotations. The same mapping considerations that apply to the first order solid and shell elements apply to the two-node beam element as well.

Beam elements represent structural elements where all of the cross-sectional characteristics are accounted for during the derivation of the element stiffness matrix. As a beneficial consequence, the cross-sectional characteristics do not need to be reflected in the finite element mesh, thus greatly simplifying the model preparation and analysis.

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Finite Element Theory

In thermal analysis, the primary unknowns are nodal temperatures of the mesh nodes. Temperatures and heat flow are determined from the solution to the partial differential equations representing conduction or convection in the model. Since temperature is a scalar displacement, and not a vector-like displacement, then regardless of what type of elements used, there is only one unknown temperature to be found for each node. The fact that there is only one unknown to be found for each node, rather than three or six, makes thermal analysis less computationally intensive than structural analysis.

Errors in FEA. The process of creating a mathematical model and discretizing it into a finite element model introduces unavoidable errors. FEA errors can be categorized into three areas: 1. mathematical modeling errors, 2. discretization errors during meshing, and 3. solution errors which are round-off errors accumulated by the solver. In most instances these errors are usually very low (3% or less) when compared with classical closed-form Partial Differential Equation solutions.

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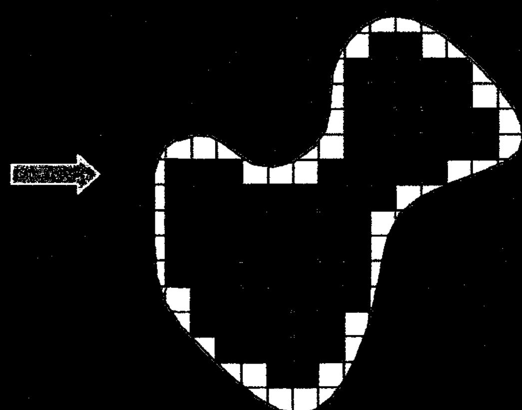
FEA Analogy: Area

What do we do to improve the accuracy of the area measurement? CREATE A FINER MESH!



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FEA Mesh: Elements

- Each element is a simple solid.
- Elements are connected together at locations called NODES.

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FEA Mesh: Elements

Brick element

Tetrahedral (Tet) element

- A BRICK element.
- A "TET" element.

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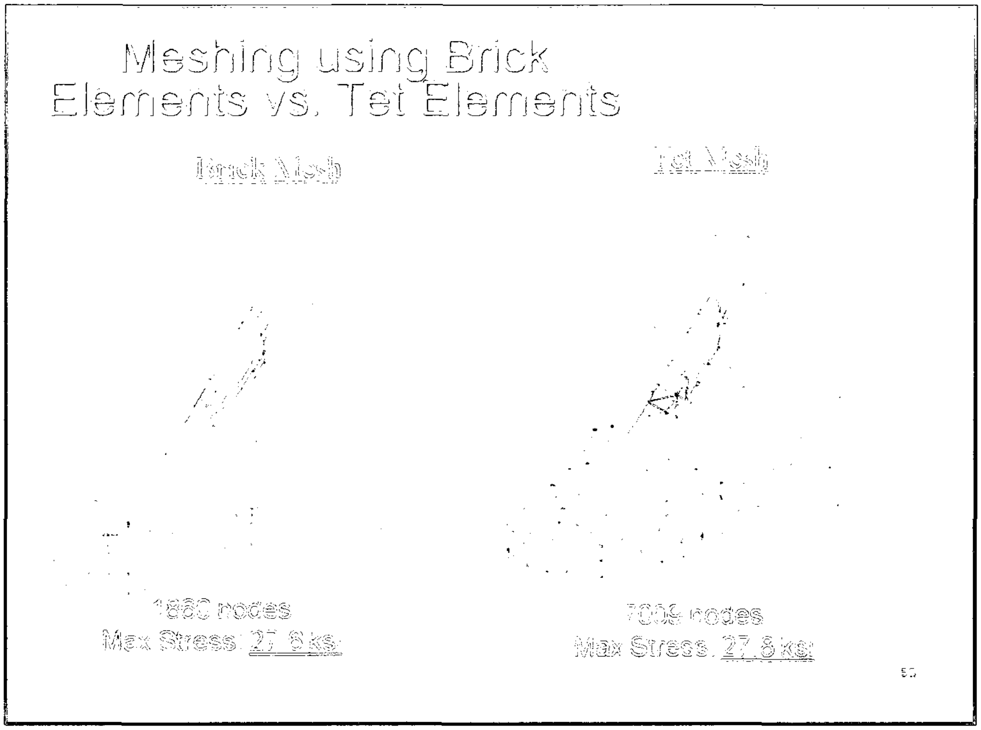
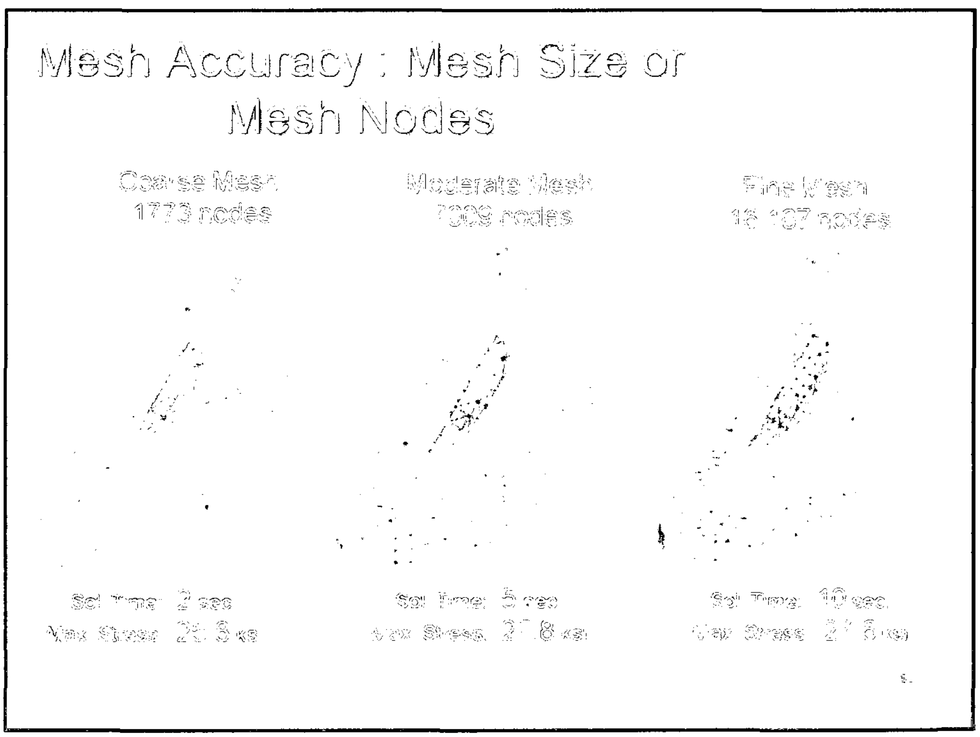

Meshing using Brick Elements vs. Tet Elements
Brick Mesh
Tet Mesh
nodes
Max Stress
nodes
Max Stress: 27.8 ksi


Mesh Accuracy : Mesh Size or Mesh Nodes
Coarse Mesh
1773 nodes
Moderate Mesh
nodes
Fine Mesh
nodes
Sol Time: 2 sec
Sol Time: 5 sec
Sol Time: 10 sec

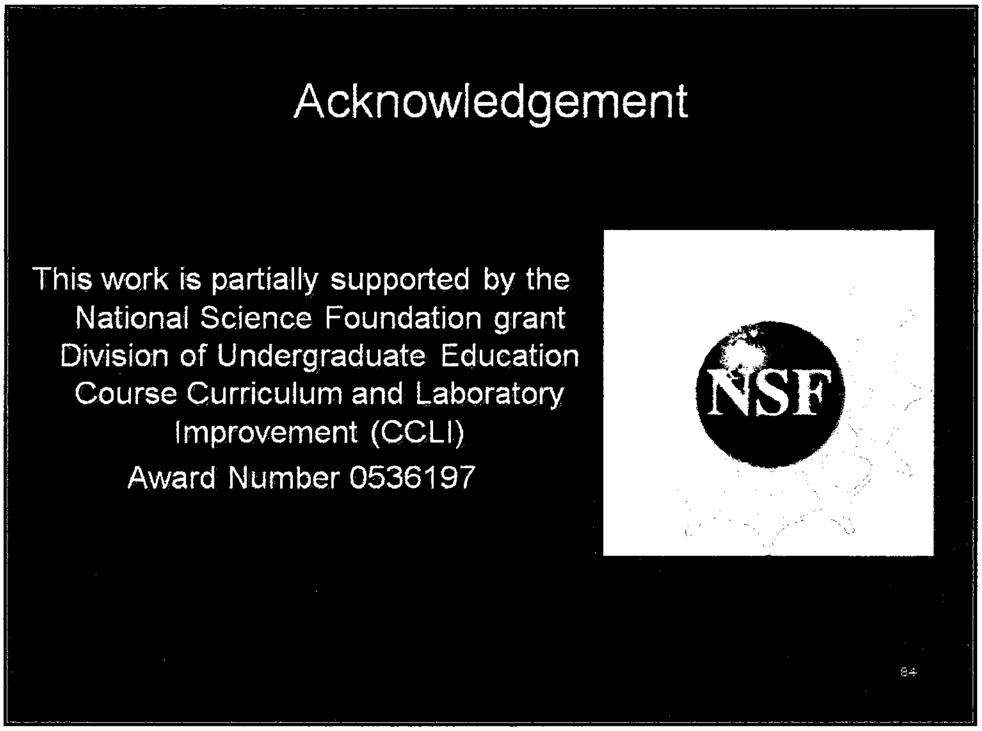
Finite Element Theory

- **Limitations of COSMOSWorks linear FEA analysis .** We need to appreciate some important limitations of the linear FEA software: material is assumed as linear, deformations are small, and loads are static. Material we assign to be analyzed will be assumed to be linear or that the stress is proportional to strain in linear manner. There is a COSMOSWorks non-linear FEA software available for the solution of unique non-linear problems.
- In "real-life" there is a yield or ultimate stress that the material cannot exceed without rupturing. A linear model omits these "real-life" end conditions. We therefore must review the level of stresses very carefully in our linear FEA results. The fact that we assume small deformations requires that those deformations be "small" in relation to the size (3% or less) of the structure and that the "structural-stiffness" matrix remains relatively the same during the deformation process. All loads, as well as restraints, are assumed not to change with time, meaning that dynamic loading conditions are not being analyzed with COSMOSWorks linear FEA analysis. This time limitation implies that loads are applied slowly enough to ignore inertial effects.

Finite Element Textbooks

Reference List of Texts

- Sprakos, C., Finite Element Modeling, Algor, Inc.,1996.
- Moaveni, S., Finite Element Analysis Theory and Application with ANSYS, Prentice Hall,1999.
- Chandrupatla, T., Belegundu, A., Introduction to Finite Elements, Prentice Hall, 2001.
- Hutton, D., Fundamentals of Finite Element Analysis, McGraw Hill, 2004.
- Engineering Analysis with COSMOSWorks Professional 2007, by Paul M. Kurowski, Schroff Development Corporation, 2007.
- COSMOSWorks Designer 2007 , Structural Research Corporation, 2007.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Award Number 0536197
NSF
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Appendix C. Abstract to Contract Poster Competition: The Third Annual Graduate Student Research Symposium & Career Networking Event

Presented by Josh Coffman at:
The University of Arkansas, Fayetteville, Abstract to Contract: The Third Annual Graduate Student Research Symposium & Career Networking Event. February 12, 2010.
Poster and Presentation Winner.