Incorporating Experimental Design in a Mechanics of Materials Course

Wendy Reffeor, Ph.D., Jeffrey L. Ray, Ph.D.
Seymour and Esther Padnos School of Engineering
Grand Valley State University
Grand Rapids, MI 49504

Abstract

A necessary part of any engineering design is the development of specifications that define its function. Once these specifications are developed, testing of that design to ensure it meets the design specifications is essential. At Grand Valley State University, we have incorporated design and build projects into most of our engineering courses, including the Mechanics of Material Course. In addition to design and build, in the Mechanics of Materials course, students are required to develop their own design specifications and design an experiment to test their apparatus.

Students were presented with the challenge of creating a combined loading apparatus which models a real situation or to test a real product to determine the stresses incurred by that product in normal use. Strain rosettes were used to evaluate the stresses experimentally. Students determined the criterion by which the apparatus was tested and designed. They were then required to perform the testing. Prior to applying the strain gage and testing their apparatus, they also submitted a complete testing procedure and theoretical analysis for review. Next, a comparison of the test results to results obtained using analytical techniques and finite element analysis was made.

In the process of completing this project, students learned many aspects of experimental design and stress analysis including developing testing criteria, implementation of strain gages for testing designs, correlation of theoretical and experimental results, and how to design an experiment and collect the experimental data so that it is most useful.

Introduction

The "Program Outcomes and Assessment"[1] section of the ABET evaluation criteria for 2001-2002 strongly encourage both the teaching of design and design of experiments in the curriculum. This work addresses several of the ABET program objectives, specifically a, b, c, e and g. The objectives met include:

(a) an ability to apply knowledge of mathematics, science, and engineering . . .
(b) an ability to design and conduct experiments, as well as to analyze and interpret data . . .
(c) an ability to design a system, component, or process to meet desired needs . . .

(e) an ability to identify, formulate, and solve engineering problems . . .
(g) an ability to communicate effectively . . .

In addition to design being emphasized in the ABET criteria, the Seymour and Esther Padnos School of Engineering at Grand Valley State University (PSE) emphasizes design project work and a practical approach to engineering while still upholding standards for the theoretical training of engineering graduates. Over eighty percent of engineering courses at PSE require design and build project work.

In keeping with both ABET criteria and the overall philosophy of PSE; a design project was implemented in PSE's junior level Machine Design I course. Although the title of this course is Machine Design I, only the final two and a half weeks are dedicated to studying fatigue and machine components. However, the remainder of the course is dedicated to Mechanics of Materials. In addition, the laboratory associated with the course is entirely Mechanics of Materials based. Syllabi for the Summer 2001 offering of both lecture and laboratory portions of the course are included in Appendix A and Appendix B.

This project was first implemented three years ago (three offerings of the course) as a basic strain gage use experiment. Since, it has been expanded to include experimental design and correlation with both theoretical and FEA results.

The project incorporated both a high degree of engineering analysis and experimental design and verification. The actual project assignment is presented in Appendix C. It is exceedingly important for students to understand the importance of planning when conducting experiments. To complete this project, students were required to either design a combined loading apparatus that models a real situation or to choose a real apparatus to study. They were then required to model the apparatus analytically and using finite element analysis (FEA). Finally, students designed and conducted an experiment to evaluate their analytical results.

Through completing the project assigned in the Mechanics of Materials course, students learned the importance of designing experiments prior to conducting them, how to compare theoretical and experimental results and how to analyze a real apparatus. In addition, the use of strain gages and combined loading analysis were reinforced. Students also learned how to select FEA elements and model a real situation.

Methods

In the laboratory portion of the Mechanics of Materials course, FEA and basic strain gage use and instrumentation are presented fairly in the semester. In addition, strain gage rosette analysis and use and experimental design are introduced as lecture topics in the lab.

After teaching students, in the lecture portion of the course, how to approach combined loading analysis, they were assigned, in the laboratory portion of the course, a project to design, build and test a combined loading apparatus. They were given a choice to either design a model of a hypothetical combined loading situation or to choose a real situation to model. They then analyzed that model, designed an experiment to verify their analytical results, built the apparatus and conducted the experiment. Students worked in groups of three to four and were encouraged to divide tasks among group members.

Students first chose their experimental apparatus and either designed it including all dimensions or obtained the actual apparatus. If the students were using an existing apparatus, they took all measurements necessary to conduct the theoretical and FEA analyses.

They then analyzed their model both analytically and using FEA. For both analyses students made their own assumptions and documented them. For the FEA analysis, students selected their own elements, modeling their situation using two-dimensional analysis whenever possible. Both the theoretical analysis and the FEA analysis allowed them to predict the results from their experiments. In addition, students were able to compare their theoretical results to results obtained from FEA. This assured that their preliminary results were correct before proceeding.

Subsequently, they designed an experiment to measure the stress in their apparatus. They were required to include all variables to be recorded, the locations of strain gages to be used and the steps to be taken in gathering data. In determining the experimental procedure, students were encouraged to consider such factors as how the load would be applied, what loading increments would be used, fixturing for holding the apparatus and balance between different loading types. Balance between the loading types was required to assure that the effects of all loading types would be discernable in the results. Students were encouraged to examine their theoretical calculations to determine which quantities needed to be measured before, during and after the experiment. They were required to measure strains at multiple loading steps.

Once all planning was complete and approved, students were allowed to begin constructing and/or instrumenting their experimental apparatus. Strain rosettes were used to determine the strain at a single location while load was increased incrementally. Students were required to determine the best orientation for the strain rosette and to apply the rosette in this direction. Accurate strain gage placement was emphasized to ensure good correlation between theoretical and experimental results.

Students then performed their experiments and compared the experimental results to those obtained analytically and using FEA. To compare results students needed to utilize Mohr's circle to assure results from the strain gages were in the same orientation as those from the theoretical analysis. In addition, the stress-strain transformation equations were utilized to convert strain from the strain gages to stress.

If the experimental results did not match the theoretical results, students were required to troubleshoot their experiment to determine the cause of the error. In most cases the students were required to fix any errors and perform the experiment again to ensure accurate results. In some cases, due to single run nature of the apparatus or extreme difficulty in fixing errors, students were allowed to simply explain differences without fixing them.

Students documented the entire project in a report which was evaluated for technical accuracy and writing skills. Students were required to complete well-written reports, properly referencing figures, tables and sources. They were also required to draw conclusions about the experiment and document them.

Results and Discussion

Students were exposed to a structured experimental design experience. Through a carefully monitored process, they learned to discern crucial variables and measurements in experiments. In addition, they learned the value of careful planning of experiments, how to conduct experiments and how to interpret experimental results.

Students chose to analyze a variety of situations including the stress in a hockey stick, estimating the initial pressure in a propane canister, estimating the stress in an I-beam, and stress in a combined torsion and bending apparatus. Most students chose to base their projects on a combined torsion and bending apparatus as they viewed this as the easiest option. However, many students did chose real scenarios as they found these more interesting and challenging. Strain gage locations were determined based upon ability to obtain strain measurements of significant magnitude.

In general, the project was well received by the students. Students were very positive about learning experimental design, reinforcing strain gage concepts, and reinforcing combined loading concepts. Their biggest single complaint was that the project was too open ended. Students stated that they would have preferred assigned project scenarios rather than being allowed to choose their own scenario.

Students learned the value of understanding expected results when conducting experiments. By completing analytical calculations and FEA analysis prior to conducting the experiment, students were able to see when their experimental procedures led them to incorrect results. As would be true when conducting industrial experiments, this allowed the students to trouble-shoot their experiments and correct any problems.

As combined loading seems to be one of the most difficult topics for students to understand in Mechanics of Materials, having this experience allows students to have a hands-on experience with combined loading. This helps the students absorb and use the material.

Although FEA is not a primary focus of this course, students were introduced to the use of FEA to verify results. They were taught how to select elements and reduce a problem to its simplest form for modeling. For this project, they were required to determine the appropriate elements to use and how to simplify the apparatus for modeling.

Students also learned that there are advantages and disadvantages to all methods of analysis of real structures. They learned the importance of only using analytical equations for those situations for which the equations are derived. For example, they learned the importance of only using the basic torsional stress equation for circular cross-sections. From the FEA calculations, they learned the importance of mesh refinement and proper element selection. From the experimental section, they learned that extreme care must be taken when making measurements, applying strain gages and applying loads if accurate results are to be obtained.

Finally, students learned that, when properly executed, theoretical calculations, FEA analysis and experimental results correlate very well. This gives students confidence in the tools they have been taught.

Although some students chose to design and build their apparatus and others chose to analyze an existing product, the learning experience was equally challenging. Those students who chose to design and build their apparatus had a higher level of effort in building their apparatus. Those who chose to analyze an existing product had the additional challenge of dealing with the less easily analyzed real situation.

Conclusions

The experimental design project conducted at PSE was very successful. Students learned the value of careful planning when conducting experiments. They reviewed combined loading, element selection in FEA, the use of strain gages to measure experimental strain, stress-strain transformation equations and Mohr's circle. Students were also exposed to trouble shooting in experiments.

Overall, the project was well received. Future iterations of this project will include two improvements. The project will be introduced earlier in the semester to allow students to spend more time choosing their apparatus. In addition, an oral presentation will be added to allow all team members to demonstrate their knowledge of the experiment and to offer students an opportunity to practice their oral presentation skills.

Appendix A

EGR 309 - Machine Design I
Spring Semester 2001

99-00	**EGR 309 Machine Design I**. Topics include combined stress, stress and strain transformation, failure theories, statically indeterminate members, beam deflection, columns, dynamic loading, fatigue, modified Goodman diagrams, fatigue failure theories, design of shafts and springs for both static and dynamic loading. Laboratory. Prerequisite: EGR 209. (3-0-3). Four credits.
Textbook:	James M. Gere and Stephen P. Timoshenko, *Mechanics of Materials*, 4th Edition, PWS Publishing Company, 1997. Robert L. Norton, *Machine Design: An Integrated Approach*, 2nd Edition, Prentice-Hall, 2000.
References:	(1) Joseph E. Shigley, Charles R. Mischke, *Mechanical Engineering Design*, 5th Edition, McGraw-Hill, 1989.

(2) R. C. Juvinall and K. M. Marshek, *Fundamentals of Machine Component Design*, 3rd Edition, J. W. Wiley, 2000.

(3) www.machinedesign.com
(4) www.manufacturing.net
(5) www.nutty.com
(6) www.matweb.com
(7) www.sem.org
(8) http://www.efunda.com/home.cfm

Goals: The goal of this course is for students to be able to:

1. Calculate stresses for complex stress states
2. Calculate stresses and strains
3. Determine forces and deflections in statically indeterminate members
4. Calculate beam deflections
5. Predict column buckling
6. Utilize failure theories
7. Predict fatigue failures
8. Design shafts and springs

Prerequisites by Topic:

1. Statics
2. Differential and Integral Calculus

Computer Usage: Mathcad is used throughout the course for solution of various homework problems. Ansys is taught and utilized in the laboratory portion of the course.
Homework and projects will be weighted so that the class cannot be passed without doing work in each of these programs.

Grading:

Exams (June 4 & July 2)	20% each
Homework	15%
Project and Report	5%
Laboratory	15%
Final Exam	25%

Exams: Make up exams will be at the discretion of the instructor and only in extreme cases. Advance notification is required for consideration of a make-up exam except in cases of medical emergency.

Homework: Homework is due at the beginning of the class period listed on the syllabus. Late work will not be accepted as solutions will be posted immediately following the class in which the homework is due.

Students are encouraged to discuss course material and homework assignments. Each student must, however, submit his/her own original work. Utilization or sharing of another's computer files is prohibited.

All homework is required to be submitted on engineering computation paper unless submitted to the web or printed out from a computer program. Please complete homework in a neat orderly manner. Free body diagrams and other helpful diagrams used in solving the problem should be included whenever used. A problem statement will be included at the top of the problem regardless of submission media. Please staple all problems in a given assignment together in numerical order.

Academic Honesty: In order to learn this material, each individual must do homework problems. Since there is no absolute right answer when designing, many questions arise in performing even the simplest of problems. If you have not done your own homework, you will not have overcome these obstacles and will not know how to approach a different problem on an exam. In addition, and more importantly, you will not know how to approach these problems when you are faced with them during your career. Therefore, each student is required to submit his/her own work. No copying will be tolerated. This also applies to all work performed in the class including homework, reports, labs and exams.

Homework Grading: Homework will be awarded points according to the following:
1-10 pts. Problem complete, range to account for errors
0 pt. Problem incomplete
-5 pt. Problem not substantially attempted

Note that although homework is only 15% of the overall grade, you can actually lose 22.5% on your final grade if you do not complete your homework. This would mean that the maximum a student could get if homework is not turned in is 76.5% or a C.

All other Work: All other work will be graded in a manner consistent with the grading for homework.

Date	Day	Topic	Reading
6-13	W	Plane Strain	7.7
6-14	Th	Pressure Vessels	8.1-3
6-18	M	Maximum Stresses in Beams	8.4
6-20	W	Combined Loadings	8.5
6-21	Th	""	""

6-25	M	Differential Equations of the Deflection Curve, Deflection by Integration of Bending Moment	9.1-3
6-27	W	Review	
6-28	Th	Exam	
7-2	M	Deflections by Integration of the Shear-Force and Load Equations	9.4
7-5	Th	Method of Superpostition	9.5
7-9	M	Statically Indeterminate Beams	10.1-4
7-11	W	Columns Buckling with Pin Ends	11.1-3
7-12	Th	Columns with Other End Conditions	11.4
7-16	M	Static Failure Theories	5.0-2
7-18	W	Fracture Mechanics, Using Failure Theories	5.3-4
7-19	Th	Fatigue Failure (Strength)	6.0-6
7-23	M	Fatigue Failure (Stress)	6.7-11
7-25	W	Multiaxial Fatigue and Design	6.12-15
7-26	Th	Surface Failure & Spherical Contact	7.0-8
7-30	M	Cylindrical and General Contact & Dynamic Contact	7.9-14
8-1	W	Belts	17.1-3
8-2	Th	Chains	17.4-7
		Final Exam	

Appendix B

EGR 309 - Machine Design I Lab
Spring Semester 2001

Purpose:

These laboratory experiences are designed to:

1. Improve your understanding of the theories and mathematical models used in solid mechanics.
2. Introduce you to experimental stress analysis techniques and measurement procedures commonly encountered in solid mechanics.
3. Introduce the finite element method for linear stress and strain problems under static loads.
4. Further develop your knowledge of the creative engineering design process.

Requirements:

The laboratory section of EGR 309 will meet once a week for three hours. There will be eight regular lab periods and three labs devoted to your project. You will be required to submit a lab report for each of the eight regular lab periods. This report will be due at the beginning of the following lab. Details of the write-ups are included below.

Feel free to discuss items with the instructor. The labs are designed for you to learn; do not let questions go unanswered, problems go unresolved, or curiosity go unsatisfied.

Although you will be working at least partially in groups in the lab, each student must do his/her own work; write-ups are not to be shared between students and shared write-ups will not be accepted.

You will not receive credit for labs in which you do not participate. You cannot "just get the data" from your team members and then do the write-up. If you miss a lab, you will have to make it up by attending another lab or arrange to make up the missed work later. You must have a good reason to attend another lab.

<u>Laboratory Write-up Policy:</u>

Write-ups for each regular lab should include:

1. A centered header that contains the following lines:
    a. Course Number and Name
    b. Title of Experiment
    c. Your Name
    d. Date
2. Raw Data and Reduced Data
    a. All measurements made in the lab should appear in the report in tabular form. (This is easy to do using Mathcad's table input feature or Excel.) Large data sets may be acquired using a computer and saved to a disk file. A printout of this data, limited to one page, should be appended to the lab write-up. For data sets larger than one page, a computer plot of the raw data is acceptable.
    b. Your raw data sheet must be signed by your instructor in the lab when you do the experiment. It is your responsibility to get this signature. Make your raw data sheet the last page of the lab write-up.
    c. Sample calculations showing how the data was reduced. Provide just sufficient information that your instructor can follow how you analyzed your raw data. If you utilize excel to perform the calculations, print a copy of the worksheet showing the formulas used.
3. Graph(s) of the Results
    a. It is very easy to create quality graphs with Mathcad or Excel. Graphs should include a title, axis labels with units, and be properly scaled such that the data is professionally presented.
4. Short Discussion and Conclusions

a. Write a short discussion and conclusions section of less than 250 words (one long paragraph or two short ones). It should summarize (1) what you did, (2) how you did it, (3) with what results, and (4) to what accuracy. (Always estimate the accuracy of your results for every experiment.)

Tentative Schedule:

Week	***Topic***
1	Introduction to Finite Element Analysis using Ansys
2	Using FEA to predict normal stress
3	Stress concentration factors using FEA
4	Bracket stress and deflections using FEA
5	Project 1--FEA Design of Mill Support
6	Determining material properties using tensile testing
7	Strain gage mounting and applications
8	Beam flexure using experimentation and FEA
9-12	Project--Design of Combined Loading Experiment

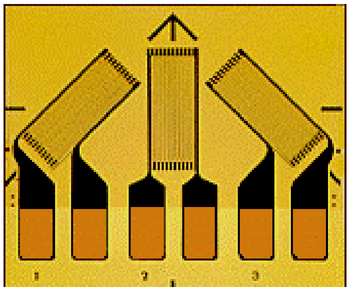
Appendix C

Grand Valley State University
EGR 309—Machine Design I
Project
Summer 2001

Purpose: To conduct an independent experiment using a strain rosette to determine the stress and strain in an object for which the theoretical strains can easily be calculated. The theoretical values will be compared to the experimental values obtained using the strain gage and a finite element model of the structure. The structure to be analyzed must include at least two types of stress at the point being examined.

Introduction: Throughout the semester, experiments have been conducted using finite element analysis and structural testing including using a strain gage rosette. This project will give you, working in teams of three, the opportunity to design an experiment of your own to test a structure and compare your results to those obtained theoretically and through the use of finite element analysis.

Theory: Although single strain gages are excellent for measuring the strain where the principal strain direction is known, they are limited to those applications. For applications where the state of strain is more complex, the strain must be measured in three directions in order to fully define the strain state and determine the principal directions. This measurement is done using a strain rosette. A 45° strain rosette is shown in Figure 1.



The strains measured by the rosette must be converted into two perpendicular normal strains and a shear strain in order to determine the principal strains. Since strain gages only measure normal strain in the direction of the long axis of the gage, a rosette gives three normal strains. These three normal strains are converted to the two normal and one shear strain using the strain transformation equation. This is:

$$\varepsilon_\theta = \varepsilon_x \cos^2\theta + \varepsilon_y \sin^2\theta + \gamma_{xy} \sin\theta \cos\theta$$

Since $\varepsilon_x, \varepsilon_y,$ and γ_{xy} are the necessary strains, this equation will be written three times, once for each strain gage. These three equations will then be solved for the three unknowns, $\varepsilon_x, \varepsilon_y,$ and γ_{xy}. For a 45° strain rosette assuming that the x-axis is along the long axis of the center gage, this becomes:

$$\varepsilon_{45^\circ} = \varepsilon_x \cos^2 45 + \varepsilon_y \sin^2 45 + \gamma_{xy} \sin 45 \cos 45$$

$$\varepsilon_{-45^\circ} = \varepsilon_x \cos^2(-45) + \varepsilon_y \sin^2(-45) + \gamma_{xy} \sin(-45)\cos(-45)$$

$$\varepsilon_0 = \varepsilon_x \cos^2 0 + \varepsilon_y \sin^2 0 + \gamma_{xy} \sin 0 \cos 0$$

Simplifying these,

$$\varepsilon_{45^\circ} = \frac{1}{2}\varepsilon_x + \frac{1}{2}\varepsilon_y + \frac{1}{2}\gamma_{xy}$$

$$\varepsilon_{-45^\circ} = \frac{1}{2}\varepsilon_x + \frac{1}{2}\varepsilon_y - \frac{1}{2}\gamma_{xy}$$

$$\varepsilon_0 = \varepsilon_x$$

Solving these for $\varepsilon_x, \varepsilon_y,$ and γ_{xy},

$$\varepsilon_x = \varepsilon_0$$

$$\varepsilon_y = \varepsilon_{45} + \varepsilon_{-45} - \varepsilon_0$$

$$\gamma_{xy} = \varepsilon_{45} - \varepsilon_{-45}$$

Once $\varepsilon_x, \varepsilon_y,$ and γ_{xy} are known for one orientation, the principal strains and thus stresses can be found using Mohr's circle for strain and the triaxial stress-strain transformation equations.

Project Requirements:

1) Prior to receiving a strain gage, each group must present a detailed experimental procedure including the structure to be analyzed, the placement of the strain gage, and the testing procedure including data to be collected. This is due no later than the lab period the week of July 17.
2) Upon approval of the experimental procedure, the experiment is to be conducted and data collected in accordance with that procedure.
3) The formal report will be graded according to the attached grade sheet. Please use the sheet as a guideline for your content. This is due August 11 and should be a group report.

Grading:

Experimental Procedure	15%
Report	65%
Peer Evaluations	15%
Your attention to peer evals	5%

If you do not submit peer evaluations, you will lose the entire 20% allotted for them.

EGR 309 Machine Design I
Project Grading Form
(Please submit this blank with your report)

Student:____

Section:____

Technical Content: Executive Summary:__________/10

Theoretical Development:______/15

Experimental Procedure:__________/20

Collection and Presentation of Data:________/15

Error Assessment:_______/10

Conclusions:__________/15

Total:__________/85

"Mechanics" Spelling, Grammar, Punctuation:________/5

Outline:_________/10

Total:__________/15

Overall Total:________/100

Comments:

References

1) ABET Board of Directors (Ed.). (2000). *Criteria for Accrediting Engineering Programs--Effective for Evaluations During the 2001-2002 Accreditation Cycle*. Baltimore, MD: Engineering Accreditation Commission.

Biographical Information

Wendy Reffeor, Ph.D. is an Assistant of Engineering in the Padnos School of Engineering at Grand Valley State University. She holds a BS in Mechanical Engineering from GMI Engineering & Management Institute, an MS in Mechanical Engineering from Purdue University and a Ph.D. from Michigan State University. Since joining GVSU, she has focused on introducing design in traditionally analytical courses in the Engineering Mechanics sequence.

Jeff Ray, Ph.D., is an Associate Professor of Engineering in the Padnos School of Engineering at Grand Valley State

University. He holds a BS and MS in Mechanical Engineering from Tennessee Technological University and a Ph.D. from Vanderbilt University. His primary teaching responsibilities are First-year engineering courses and coordinating the Senior Capstone Design sequence.