Enhancement of mechanics education by means of photoelasticity and finite element method

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The goal of this project is to enhance mechanics education by incorporating experiments using photoelastic stress analysis and finite element analysis within the existing curricula. Specific instructional objectives for students are to: (a) increase conceptual understanding of stress distribution through photoelastic and finite element based visualization, (b) gain experience with photoelasticity and finite elements including their advantages/limitations, and (c) appreciate the synergism between experimental and numerical methods of stress analysis.

At UOP, one transmission polariscope set, one reflection polariscope set, and accompanying accessories have been purchased and installed for students' use. This equipment has also been used for in-class demonstrations and motivational presentations to high school students. Additional apparatus have been made in-house and/or purchased by departments at UOP and USAFA. All mechanical engineering students at UOP have benefited from this project. Several experiments have been introduced in the curriculum, and several student projects have been completed. A similar combination of photoelastic demonstrations plus finite element results has been used at USAFA, which has exposed both engineering and non-engineering majors to this educational enhancement.

Key words: stress analysis, photoelasticity, finite element method, experiments, design projects

1. INTRODUCTION

Stress analysis plays a significant role in the design of parts and structures that must carry load. With the proper knowledge and tools, a designer identifies areas with high stresses (i.e. potential failure points), as well as areas with low stresses (i.e. potential for material removal,
weight reduction, and cost saving). A mechanical engineer should be exposed to the most commonly used tools of stress analysis. A summary of the attributes of the three most commonly used stress analysis methods, outside of the textbook analytical equations, is presented in Table 1 [1].

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain gauge</td>
<td>Relatively easy to apply Remote data collection</td>
<td>Point measurement only</td>
</tr>
<tr>
<td>Photoelasticity</td>
<td>Full-field measurement</td>
<td>Must have visual access Limited temperature range</td>
</tr>
<tr>
<td>Numerical methods</td>
<td>Handle complex shapes, loads and boundary conditions Suitable for parametric studies</td>
<td>Difficulty in building accurate model</td>
</tr>
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The photoelastic test method, which provides both qualitative (visual) information as well as quantitative data, serves as a very appropriate tool of analysis when full-field stress distribution is required. And, it is the only analysis method for specific situations such as investigating assembly stresses. This method has received significant attention in industry as reflected in papers published in the recent proceedings of the Society of Experimental Mechanics (SEM) [2–6]. Furthermore, photoelastic testing recently has been used directly with prototypes made by stereolithography, hence, shortening the design–construction–testing–redesign cycle time [7, 8]. Also, at least, two dedicated conferences have been organized by SEM to focus on the synergism between finite element analysis and structural testing with rapid prototyping.

In addition to the technical significance of the photoelastic method there is also a pedagogical advantage. Substantial research in the area of learning styles of students has shown that a large percentage of them will learn more effectively when concepts are reinforced visually [9–12]. Either the photoelastic technique or finite element based stress plots can effectively provide the visual reinforcement of various concepts related to stress analysis on actual parts. Therefore, integration of visually based stress representations into our curricula is a significant improvement.

2. LEARNING OBJECTIVES

The learning objectives of this project are for students to:

(a) increase their conceptual understanding of stresses through both photoelastic and finite element based visualization;
(b) gain experience with the photoelastic test method and with finite element analysis in order to appreciate their advantages and limitations; and
(c) realize the synergism between experimental and numerical methods for stress analysis.

As mentioned previously, these objectives have been implemented at UOP as well as USAFA. Additional details of the use of these tools at USAFA are presented in [13].
The equipment purchased and experiments/demonstrations developed for this work are explained in the next two sections, followed by specific courses affected by this project. Since courses using the same equipment are offered in different semesters, there is no problem with equipment use overload. The instructor can choose one or several experiments as appropriate for a given course.

3. EQUIPMENT

3.1 Equipment used at UOP

Two major pieces of equipment were purchased for use at UOP in this work. The teaching transmission polariscope, which can be mounted on an overhead projector, is used for teaching the principles of photoelasticity and measurements related to 2-D model studies. The reflection polariscope is used for testing actual parts (under actual loads) that have been coated with a photoelastic material.

Other pieces of equipment included two optical null compensators and a loading frame. An optical null compensator is used for each of the polariscope to obtain quantitative data (i.e. the fringe order) from the fringe patterns produced. These data, in conjunction with the optical factor of the photoelastic coating, are essential in determining stresses. The loading frame allows convenient loading of models for the purpose of teaching, demonstration, and experimentation. The photoelastic coating on several objects were prepared by an outside source for better quality, and the 2-D objects have been fabricated in-house, as needed. The photoelastic coating can be done in-house, if desired, but it requires following very careful procedures. For details on photoelastic coating refer to [14, 15].

A digital camera could be used to capture the results of photoelastic experiments on a personal computer (PC). This would enable students to compare experimental and numerical results on the PC, without a need to produce conventional photograph of the photoelastic result.

With the equipment described, students are able to make quantitative measurements on models as well as on actual parts. They can also make qualitative comparisons. As a result, graduates will have experience with empirical work in the area of stress analysis, which will enhance their ability in designing machine parts and structural elements.

3.2 Equipment used at USAFA

Approximately thirty hand-held polarisopes for students’ and one for instructor’s use were manufactured in-house, see Fig. 1. Nine of these were the result of the senior design project described later. Also, about twenty of the torsion testers, as shown in Fig. 2, were made. Both the student polarisopes and the torsion testers allowed the students to have an actual hands-on photoelastic visualization experience. In addition to these photoelastic devices, extensive multimedia software was purchased. This software is being used to further develop the finite element based multimedia content at USAFA.
Fig. 1. Student handheld polarscope.

Fig. 2. Torsion tester.
4. EXPERIMENTS AND DEMONSTRATIONS

4.1 Experiments developed at UOP

Experiment 1. Stress concentration in a beam

Equipment required is a transmission polariscope with a null compensator, several birefringent beam models with various kinds of discontinuity, and a loading fixture. Students become familiar with the use of the polariscope to visualize the fringe pattern produced in the model, for example, see Fig. 3. The fringe pattern indicates stress distribution. Stress data can be obtained with the use of a null compensator, and the stress concentration factor at the discontinuity is determined and compared with the published data. Students also observe how stress concentration diminishes a short distance from a discontinuity.

Experiment 2. Calibration of photoelastic material

Equipment required is a reflection polariscope with a null compensator, an aluminium beam coated with a photoelastic material whose optical factor is to be determined, and a loading fixture. Students become familiar with the use of the reflection polariscope and the method to find (i.e. calibrate) the optical factor of photoelastic coating. This factor plays a crucial role in obtaining stress data in actual parts coated with photoelastic material. The photoelastic optical factor is analogous to the gauge factor in strain gauges.

Experiment 3. Stresses in a pressure vessel

Equipment required is a reflection polariscope with a null compensator, a pressure vessel coated with photoelastic material, ‘separator’ strain gauges, a strain indicating device, and compressed air. A 3 in pipe tee is used as a pressure vessel. (A safety relief valve is included.) Compressed air available in the laboratory is used to pressurize the vessel. Using the optical factor (determined in Experiment 2) and the fringe pattern produced in the polariscope, students determine the difference in principal stresses ($\sigma_1 - \sigma_2$) from the photoelasticity test directly. They also identify areas of high stresses. ‘Separator’ strain gauges are installed to strategic locations to obtain the sum of principal stresses ($\sigma_1 + \sigma_2$). Then, with simple calculations, each of the principal stresses and directions can be determined. In addition, a numerical solution to the pressure vessel has been prepared to be given to students for comparison purposes. Differences between the photoelasticity and numerical results will be discussed and advantages and limitations of the different methods brought out.

Experiment 4. Stresses on a shaft in torsion

Equipment required is a reflection polariscope with a null compensator, several shafts with different cross-sectional areas coated with photoelastic material, and a torsion tester machine. The effect of rounded fillet and sharp changes in diameter on stress distribution is investigated. Students identify stress concentration areas experimentally. In addition, the instructor will provide a finite element solution for the same shaft. Advantages and disadvantages of photoelasticity and numerical solutions for stresses in machine elements will be discussed.
Experiment 5. Load cell optimization

Equipment required is a transmission polarscope with a null compensator, several birefringent load cell models, and a loading fixture. Load cells utilizing strain gauges are
used in numerous measurement applications such as electronic balances. The placement of the strain gauges on the load cell is a crucial design factor. They should be placed at maximum stressed points to improve sensitivity of the load cell. Students conduct photoelasticity experiments on a 2-D model of a load cell and perform a finite element analysis to identify maximum and minimum stressed points. Also, the effect of slight construction changes on the load cell can be easily determined with the model study. Feedback from the photoelasticity tests can be used to help students know where and how much to refine the finite element model to increase accuracy of their solutions.

Experiment 6. Stresses on a crane hook

Equipment required is a reflection polariscope with a null compensator, a crane hook coated with photoelastic material, and a tensile machine. The objective is to determine the magnitude of the maximum stress. Students obtain stress distribution from photoelasticity testing and finite element analysis, see Figs 4 and 5. Some tuning of the finite element model (e.g., boundary and loading conditions) may be required to obtain a finite element stress contour that resembles that of the photoelasticity. Once this resemblance is obtained, the finite element results can be reliably used to determine maximum stresses. This procedure eliminates the need for 'separator' strain gauges to determine the stress magnitudes. In other words, this experiment demonstrates the synergism between the finite element method and photoelasticity technique. Similar work was reported in the literature [16].

Fig. 4. Stress distribution in an aluminium crane hook as seen with reflection polariscope (left) and as predicted by finite element method (right). Applied load = 400 lb. Student Brian Alamo worked on this project. The hook was coated with photoelastic material.
4.2 Demonstrations developed at USAFA

Demonstration 1. Visualization of torsion based stress

Equipment required is a student hand-held torsion tester as shown in Fig. 2. The objective of the demonstration is to illustrate the radial distribution of the torsion based stress. The student applies force to the torsion tester’s ‘arms’ which creates a good approximation to pure torsion on the photoelastic material located in the centre circle. The results are circular fringes indicating the radial distribution expected in accordance with the equation $\tau = Tr/J$.

Demonstration 2. Visualization of bending based stress

Equipment required is a student (and/or instructor) hand-held polariscope (see Fig. 1) and a photoelastic beam. The objectives of the demonstration are to show the stress distribution both down the long axis of the beam and through its height (including location of the neutral axis). In addition, either cantilevered or simply supported boundary conditions can be simulated. An additional benefit of this demonstration is the illustration of St. Venant’s Principle as it applies to either concentrated loads or boundary conditions.

Demonstration 3. Visualization of combined loading stress

Equipment required includes the student (and/or instructor) hand-held polariscope and a photoelastic beam. The loading for this demonstration must be a combination of axial and bending which is made possible by using the thumb screws on both the top and the side of the polariscope. The objectives are to illustrate the effects of combined loading on the stress distribution. Specifically, the location of the neutral axis and the maximum overall stress can be investigated.
Demonstration 4. Visualization of stress concentrations

Equipment required includes the student (and/instructor) polariscope and various photoelastic beams with cutouts, see Fig. 6. The objective of the demonstration is to illustrate the effect of certain geometry changes (holes, cuts, etc.) on the stress pattern in the beam. The effect of the orientation of the cut-out can also be investigated.

Fig. 6: Five beams used for stress concentration demonstrations.

5. IMPACT OF THE PROJECT

5.1 Course affected at UOP

At UOP four courses, Mechanics of Materials, Machine Design, Instrumentation and Experimental Methods, and Finite Element Method have been improved through integration of carefully planned experiments and student projects in stress analysis. The equipment has also been used on occasions when the faculty makes presentations to high school students to attract them to engineering. One example is a workshop series conducted for high school students interested in engineering and science.

Mechanics of Materials

This course is required for all mechanical and civil engineering majors. One class experiment/demonstration has been added to enhance students' understanding of stress
distribution through visualization. It includes a brief discussion of photoelastic testing methods and several short experiments on 2-D beams under different loading conditions. See Experiment 1 above.

**Instrumentation and Experimental Methods**

This is a required course for all mechanical engineering students and an elective for other engineering majors. A formal laboratory with six well-defined experiments in different areas accompanies this course. There is also a term project that requires students to design, construct, and test a device, and write an engineering report. Experiments have been designed for the laboratory to illustrate applications of photoelasticity in stress analysis (selected from Experiments 1–6 above), and students are encouraged to incorporate photoelastic testing in their term projects. One example is the study of a C-clamp with strain gauges and a 2-D photoelastic model, see Fig. 7. A two-hour lecture has been added to this class to reinforce the principles, advantages, and disadvantages of photoelasticity method.

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Fig. 7. Photoelastic model of a loaded C-clamp as observed in polariscope (top photo). C-clamp constructed by students Juan Aguirre and Lani Dodge for a class project. Thumbscrew allows loading of the clamp.
Machine Design

There is no formal laboratory component for this required course. Since stress distribution is an important topic in the design of machine elements, one project has been assigned that required students to design a fixture that could be used to apply constant bending moment to a beam while being pulled upon. One example of such a design is shown in Fig. 8(a). This happened to be an excellent addition to our equipment since students can now visualize the superposition principle in terms of combined loading of a beam as seen in Fig. 8(b).

![Loading Frame](image)

![Photoelastic Beam](image)

![Constant Bending Moment Fixture](image)

(a)

![Tons.](image) + ![B.M.](image) = ![T+B.M.](image)

(b)

Fig. 8. (a) Constant bending moment fixture designed and fabricated by student Bill Cook for a class project. The loading frame was purchased. (b) Superposition principle: photoelastic beam under tension (left), bending moment (centre), tension and bending moment (right). Note the relocation of the neutral axis, represented by black line.
Finite Element Method

This is an elective course for mechanical and civil engineering majors. Students taking this course are asked to conduct a project that incorporates finite element analysis and photoelastic testing of a real object. Students, therefore, use the results of photoelasticity test to complement and verify the result obtained by the finite element analysis. An example can be seen in Fig. 4; the student studied stress distribution in a crane hook (see Experiment 6 above). In another project, a motorcycle brake handle was analysed and a good qualitative agreement between the numerical solution and photoelasticity test results was observed. It is interesting to note that successful integration of physical experiments into numerical methods courses has been reported in the literature [17].

5.2 Course affected at USAFA

Three required courses at USAFA, Introduction to Mechanics, Mechanics of Materials and Senior Design have been improved through use of the demonstrations which combine photoelasticity and finite elements to demonstrate stress based phenomena.

Introduction to Mechanics

This course is required for all cadets regardless of major. Enrollment is approximately 500 cadets per semester broken down into sections of approximately 20 students. Three specific class demonstrations were developed (see Demonstrations 1–3 above), implemented and assessed. These demonstrations highlighted stresses associated with bending, torsion and combined loading. Enough photoelastic devices were manufactured to allow each group of 2–3 students to have their own device, see Figs 1 and 2. Finite element based visualization of the stress concepts was accomplished by using colour stress plots and was originally viewed in class using transparencies. Since then PowerPoint shows have been developed. These finite element based visualizations were each framed in the context of an interesting industrial case study. Technical specifications and drawings for the photoelastic device used by the students are available from the first author. The finite element based visualizations are available in PowerPoint format from the second author.

Mechanics of Materials

This is a required course for all engineering mechanics and mechanical engineering majors. One set of demonstrations showing stress concentrations was implemented in this class (see Demonstration 4 above). Several student hand-held polariscopes and various beams were manufactured for use in the study, see Figs 1 and 6, respectively. In addition, an instructor hand-held polariscope was constructed which, for comparison purposes, allowed the use of two beams at one time. The different beams were machined to include a variety of stress concentrations as described in Demonstration 4 above.

Senior design

In this class a group of four students was tasked with designing, manufacturing, using and assessing the hand-held polariscope used in Mechanics of Materials course. The task included use of a full set of design methods as well as extensive structural analysis and human factors considerations. Manufacturing included building eight student hand-held
polariscopes and one instructor hand-held polariscope. Assessment included use of quizzes, surveys, exam questions and focus groups.

6. EVALUATION

An extensive, multifaceted assessment programme has been implemented to determine the effectiveness of these experiments/demonstrations. The assessment involved use of five specific assessment instruments: (a) short written feedback from students taken before and after each lecture; (b) quick quizzes designed to measure conceptual knowledge of the stress concept being taught; (c) specific exam questions; (d) focus groups, and (e) qualitative feedback from the professors involved.

These tools provided extensive qualitative and quantitative feedback. Student’s responses were also correlated with the student’s Myers Briggs Type [18, 19] in an attempt to determine how specific learning styles respond to these experiments/demonstrations. The details of this assessment are presented in [13, 20]. Students’ response has been very positive.

In summary, the results of this project (i.e. laboratory experiments, student projects, class demonstrations, and outreach activity) have positively affected the learning of the users of the equipment. Several colleagues at other institutions have asked for information on some of the projects described here. This project will continue to enhance education of many students for the next several years.

7. ACKNOWLEDGEMENTS

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REFERENCES


