PHOTOELASTICITY AND ITS SYNERGISM WITH FINITE ELEMENT METHOD

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Abstract

The goal of this project is to enhance mechanical engineering education by incorporating experiments in photoelastic stress analysis within the existing curriculum. Photoelasticity is a visual, full-field technique for determining stresses in parts and structures. In addition to its traditional use in industry, there is a renewed interest in using photoelasticity to test objects made by stereolithography.

Specific instructional objectives are to: (a) increase conceptual understanding of stress distribution through photoelastic and finite element based visualization, (b) gain experience with photoelasticity and its advantages/limitations, and (c) appreciate the synergism between experimental and numerical methods of stress analysis.

Through a National Scieence Foundation matching grant, one transmission polariscope set, one reflection polariscope set, and accompanying accessories have been purchased and installed for students' use. The equipment has also been used for in-class demonstrations and motivational presentations to K-12 students.

All mechanical engineering students at the University of the Pacific have benefited from this project. Several experiments have been introduced in the curriculum, and several student projects have been completed utilizing the equipment purchased with this grant. A similar combination of photoelastic demonstration plus finite element results is being used at the U.S. Air Force Academy to enhance mechanics education there.

Overall, students have experienced that in solving engineering problems one has to choose the appropriate tool of analysis, and recognize that quite often several tools must be utilized to validate the results, e.g., validation of numerical solutions by experimental means. Although the project duration is not completed yet, some of developments made possible by this grant have been disseminated.

I. 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 have experience with the most commonly used tools of stress analysis. A summary of theattributes of the three most commonly used stress analysis methods, outside of the text book analytical equations, is presented below [1].

METHOD	ADVANTAGE	DISADVANTAGE
Strain gage	Relatively easy to apply. Remote data collection.	Point measurement only.
Photoelasticity	Full-field measurement.	Must have visual access. Limited temperature range.
Numerical Methods	Handles complex shapes. Suitable for parametric studies.	Difficulty in building accurate model.

There are a number of applications in which the use of strain gages and numerical methods would not be desirable or applicable to solve for the stresses. Examples include: (a) assembly stress caused by the mechanical assembly of component parts, such as that which occurs during bolting; (b) residual stress that resides in the structure which results from manufacturing processes, such as welding and casting; (c) stresses caused by complex working forces that make it difficult to accurately define the loading and boundary conditions; and (d) stresses resulting from geometric imperfections, fabrication tolerances, and poor fits in the actual structure. Also, prediction of localized yielding is difficult since it is random.

The photoelastic test method, which provides both qualitative (visual) information as well as quantitative data, serves as a very appropriate tool of analysis for the above cases. This method has received significant attention in industry as reflected in papers published in the recent proceedings of the Society of Experimental Mechanics (SEM); e.g., see references 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]. Recently, 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 [e.g., 9-12]. The photoelastic technique can effectively provide the visual reinforcement of various concepts related to stress analysis on actual parts. Therefore, integration of photoelasticity into our curriculum is a significant improvement.

II. 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 to appreciate its advantages and limitations, and
(c) realize the synergism between experimental and numerical methods for stress analysis.

As mentioned previously, these objectives have also been implemented at the U.S. Air Force Academy. Specifics of their use are presented in reference 13.

Specific courses, at the University of the Pacific, affected by this project are presented next. Since these courses are offered in different semesters, there is no problem with equipment use overload. The experiments designed for this work are outlined in the Appendix. The instructor can choose one or two experiments as appropriate for a given course.

III. Impact of the Project

Four courses, Mechanics of Materials, Machine Design, Instrumentation and Experimental Methods (all required), and the Finite Element Method (elective) have been improved through integration of carefully planned experiments and student projects in stress analysis. The equipment has also been used at occasions when faculty make presentations to K-12 students to attract them to engineering. One example is our workshop series conducted for high school students interested in engineering and science. Furthermore, a series of simple experiments, showing a variety of applications, is being developed for dissemination to the nearby high school science teachers.

Mechanics of Materials (ENGR121) - This course is required for all mechanical and civil engineering majors. One class demonstration has been added to enhance students' understanding of stress distribution through visualization. The demonstration includes brief discussion of photoelastic testing method and several short experiments on 2-D beams under different loading conditions. An example is shown in Figure 1. All figures are shown at the end of the paper for clarity.

Instrumentation and Experimental Methods (MECH110) - 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. Two experiments have been designed for the laboratory to illustrate applications of photoelasticity in stress analysis (selected from those listed in the Appendix), and students are encouraged to incorporate photoelastic testing in their term projects. One example is study of a C-clamp with strain gages and a 2-D photoelastic model, see Figure 2. A two-hour lecture has been added to this class to reinforce the principles, advantages, and disadvantages of photoelasticity as applied to 2-D model studies and actual objects coated with photoelastic material.

Machine Design (MECH120) - 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 design is shown in Figure 3a. 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, Figure 3b.

Finite Element Method (MECH178) - 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 is shown in Figure 4, where the student studied stress distribution in a crane hook. In another project, a motorcycle brake handle was analyzed 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 [14].

IV. Equipment

Two major pieces of equipment were purchased for 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, see Figure 5.

An optical null compensator is used for each of the polariscopes 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 (Figure 3a) allows convenient loading of models for the purpose of teaching, demonstration, and experimentation. The photoelasctic coating on several objects were prepared by outside source, and the 2-D objects have been fabricated in-house, as needed.

A video camera plus a frame grabber interface is yet to be purchased to capture the results of photoelastic experiments on a personal computer (PC). This will enable students to compare experimental and numerical results on the PC, without a need to photographically record 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, our 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.

V. Evaluation

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. This has been acknowledged through evaluations done by students and others. Several colleagues at other institutions have asked for information on some of the projects described here. Overall, this project will continue to enhance education of our students for the next several years.

VI. Acknowledgments

The National Science Foundation through grant DUE9751315 and the School of Engineering at the University of the Pacific provided the equipment funding. UOP students whose projects are examplified in this paper are Brian Alamo, Bill Cook, Juan Aguirre, Lani Dodge, and Kevin Baskin; student Will Solymanbeyk scanned the photographs. Thomas Corby Jr., Senior Vice Presdient at Measurements Group, Inc., provided the photoelastic coating of several objects used in this project.

References

1. “Seminar on Experimental Stress Analysis Techniques for the Teaching Laboratory,” Seminar Notebook, Measurements Group, Raleigh, NC, 1995.
2. Monkovich, B., “Photoelasticity in the Printer Industry,” Proceedings of the Society for Experimental Mechanics Conference and Exhibition, Milwaukee, Wisconsin, 1991.
3. Gambrell, Jr., S. C., “Use of PhotoStress Techniques to Characterize the Mechanical Behavior of Weldments,” Proceedings of the Society for Experimental Mechanics Conference and Exhibition, Las Vegas, Nevada, 1992.
4. Finlay, J.B. and Little, E.G., “Photoelasticity as a Tool in Orthopedic Research,” Proceedings of the Society for Experimental Mechanics Conference and Exhibition, Dearborn, Michigan, 1993.
5. Slaminko, R., “Contributions of Photoelasticity to the Development of Boeing 777,” Proceedings of the Society for Experimental Mechanics Conference and Exhibition, Dearborn, Michigan, 1993.
6. Allison, I.M., “Photoelastic Studies of the Stresses in Large Buttress Dams,” Proceedings of the Society for Experimental Mechanics Conference and Exhibition, Baltimore, Maryland, 1994.
7. Steinchen, W., Kramer, B., and Kupfer, G., “Photoelasticity Cuts Part-Development Costs,” Photonics Spectra, pp.157-162, May 1994.
8. “Rapid Prototyping Helps Spot Engine-Blade Stress,” Design News, p. 37, Sept. 1994.
9. Stice, J. E., “Using Kolb's Learning Cycle to Improve Student Learning," *Engineering Education*, Vol. 77, No. 5, pp. 291-296, 1987.
10. Felder, R.M. and Silverman, L.K., "Learning and Teaching Styles in Engineering Education," *Engineering Education*, Vol. 78, No. 7, pp. 674-681, 1988.
11. Tan, F. L. and Fok, S. C., "Development of Engineering Courseware for University Undergraduate Teaching Using Computer Animation," *Computer Applications in Engineering Education*, Vol. 3 (2), pp. 121-126, 1995.
12. Ullman, K. M. and Sorby, S. A., "Enhancing the Visualization Skills of Engineering Students Through Computer Modeling," *Computer Application in Engineering Education*, Vol. 3 (4), pp. 251-257, 1995.
13. Brochert, R., Jensen, D., “Hands-on and Visualization Models for Enhancement of Learning in Mechanics: Development and Assessment in the Contest of Myers-Briggs and VARK Learning Styles,” ASEE Annual Conference, Session # 1368, Paper # 4, 1999.
14. Moaveni, S., “Integrating Solid Mechanics and Design in an Undergraduate Finite Element Class,” Proceedings of ASEE Annual Conference, pp. 1902-1905, 1994.

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Appendix

Experiment # 1- Stress concentration in a beam. Equipment needed are 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. 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. The experience gained reinforces material covered in the class.

Experiment # 2 - Calibration of photoelastic material. Equipment needed are a reflection polariscope with a null compensator, an aluminum 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 gage factor in strain gages.

Experiment # 3 - Stresses in a pressure vessel (to be completed). Equipment needed are a reflection polariscope with a null compensator, a pressure vessel coated with photoelastic material, “separator” strain gages, 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 gages 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 purpose. 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 are a reflection polariscope with a null compensator, several shafts with different cross sectional areas coated with photoelastic material, and a torsion tester. 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 needed are a transmission polariscope with a null compensator, several birefringent load cell models, and a loading fixture. Load cells utilizing strain gages are used in numerous measurement applications such as electronic balances. The placement of the strain gages 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 needed are a reflection polariscope with 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 (the fringe pattern) and finite element analysis (the stress contour map). 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 gages to determine the stress magnitudes. In other words, this experiment demonstrates the synergism between the finite element method and photoelasticity technique.

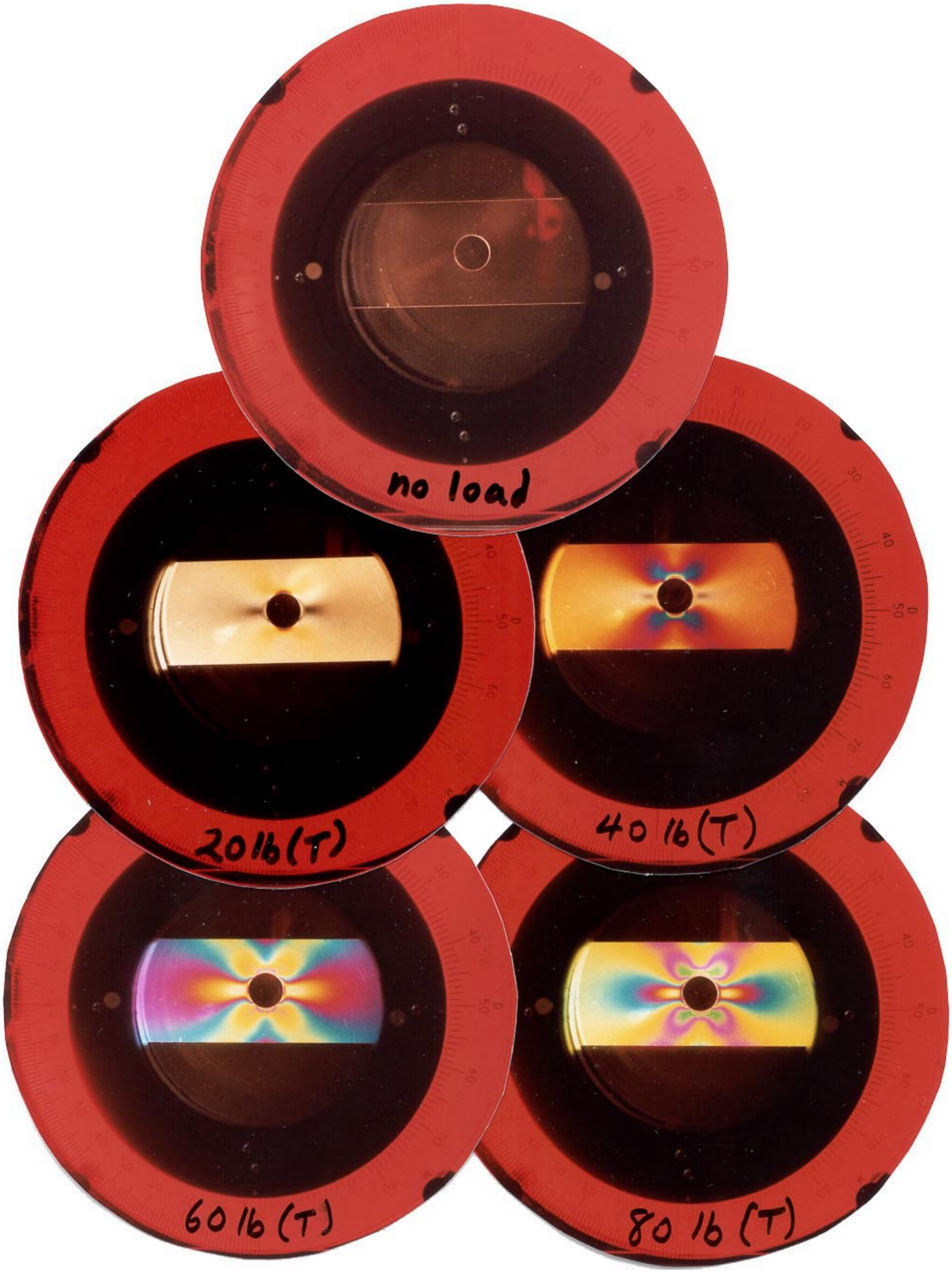

Figure 1. Two-dimensional photoelastic beam, with a hole, under tension as seen in transmission polariscope.

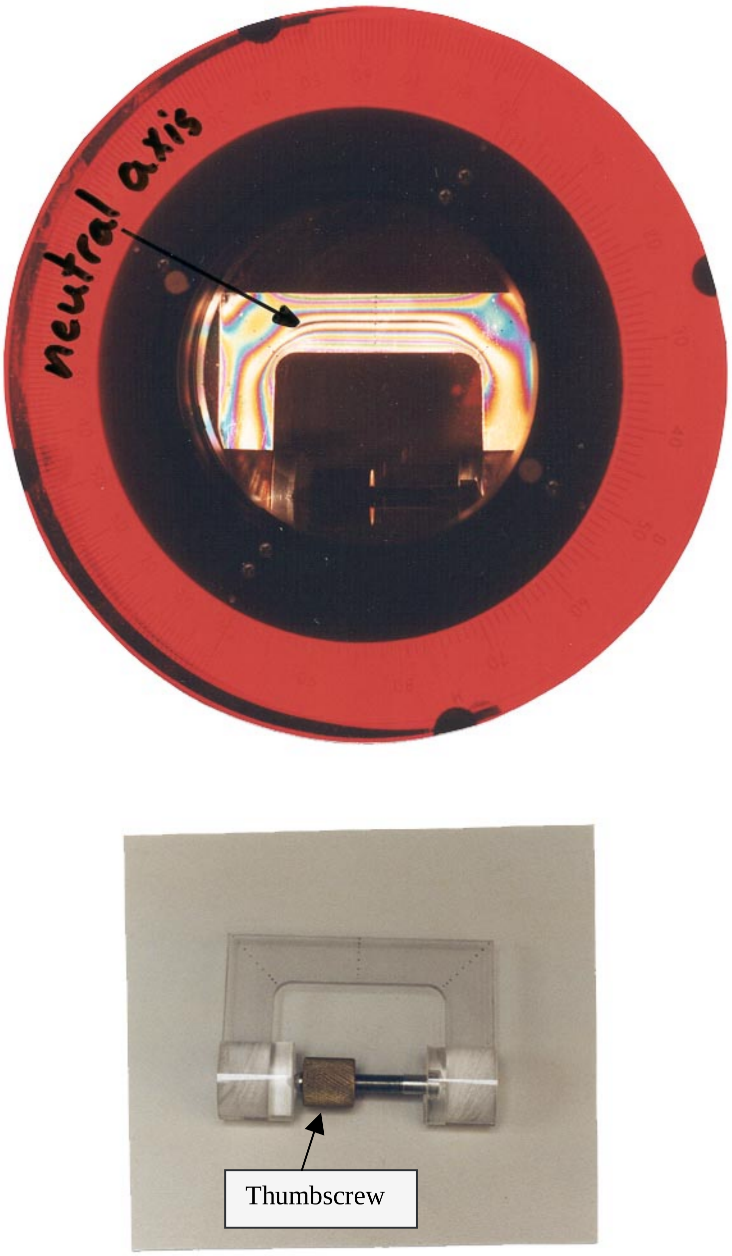

Figure 2. Photoelastic model of a loaded C-clamp as observed in polariscope (top photo). C-clamp constructed by students Juan Aguirre and Lani Dodge for a class project. Thumbscrew allows loading of the clamp.

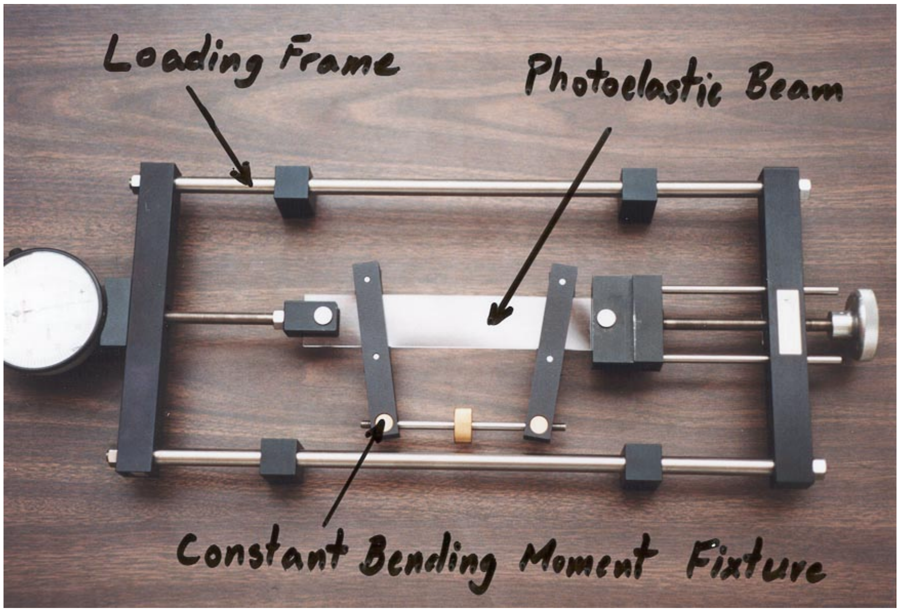

Figure 3a. Constant bending moment fixture designed and fabricated by student Bill Cook for a class project. The loading frame was purchased.

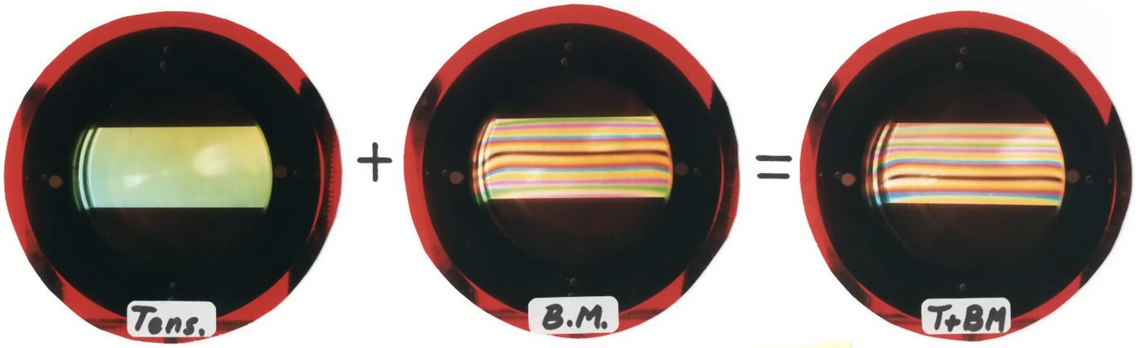

Figure 3b. Superposition principle: photoelastic beam under tension (left), bending moment (center), tension <u>and</u> bending moment (right). Note the relocation of the neutral axis, represented by black line.

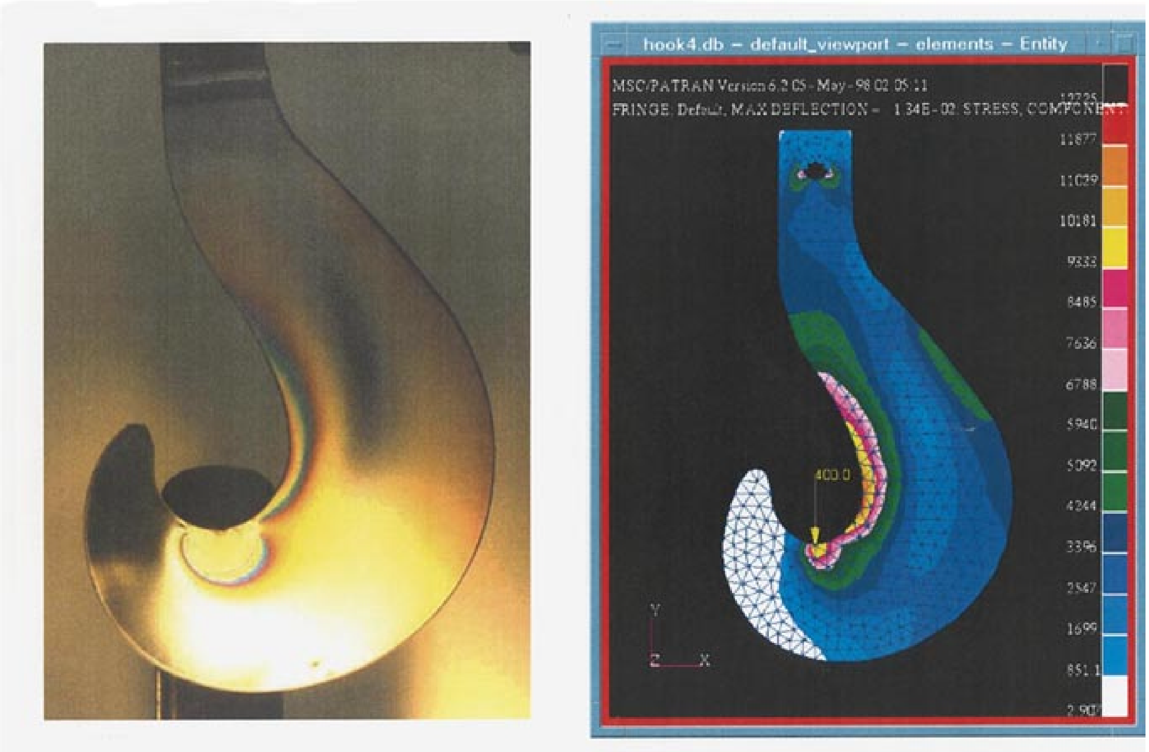

Figure 4. Stress distribution in an aluminum crane hook as seen with reflection polariscope (left) and as predicted by finite element method (right). Applied load = 400 lb. Student Brian Alamo worked on this project. The hook was coated with photoelastic material.

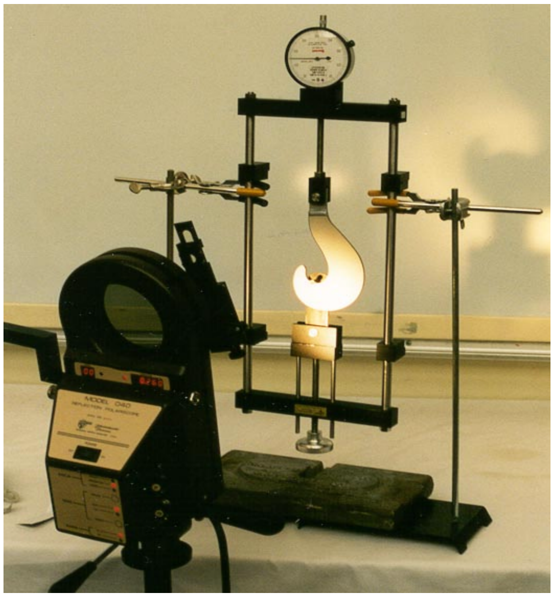

Figure 5. Trnasmission polariscope and the crane hook setup.