2006-407: PHOTOSTRESS IMAGES FOR TEACHING MECHANICS OF MATERIALS

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Photostress Images for Teaching Mechanics of Materials

Abstract

A new approach to teaching Mechanics of Materials is described in this paper with the description of classroom implementation. In particular, it addresses the use of the photoelastic (photostress) images to enhance the learning of axial, bearing, and contact stresses. The images can be used to visualize the limitations of the theory that are not possible within the confines of textbooks. The student’s reaction to the new approach is presented and assessed.

Introduction

Engineering students respond well to visual examples. Several papers have added an instructional perspective to enhance the teaching of mechanics courses to undergraduate students. For example, one paper proposed the use of the optical method of caustics to study the effects of the presence of a crack in machine components and structural members\(^1\); experiments were included as visuals to the students on the state of stress at a crack tip. In 2005, the approach was further extended to study the development of stress concentration around circular holes\(^2\). The impact of demonstrations to acquaint students with the Statics concepts in the context of a real artifact was articulated by Steif\(^3\). A different approach regarding the teaching of a mechanics course came from Philpot et. al \(^4\). They presented examples of instructional media developed for the Mechanics of Materials course, utilizing computer in novel ways that offer the potential for improved instruction.

This article addresses the use of photoelastic method as a means of illustrating several basic concepts in the introductory Mechanics of Materials course. Several images of a tension member with bolted connection plates are presented to illustrate the development of stresses in a two-force member as well as reinforcing the Saint-Venant’s theory.

Mechanics of Materials

At the sophomore level, students in an aerospace, civil, mechanical, and perhaps other engineering programs are introduced to the concepts of stress and strain in a solid body through the Mechanics/Strength of Materials course. The principles and methods used to meet the
Learning objectives are drawn from prerequisite courses in statics, physics, and calculus together with the basic concepts of elasticity and properties of engineering materials. However, due to the time constraints, there is generally insufficient time to verify the assumptions made in developing the theories with experimental verification. Also, a basic Mechanics of Materials course normally deals with a combined loading topic in the analysis of stresses that are produced by three fundamental types of loads: axial, torsional and flexural. The literature review showed that many articles have been written about the use of experiments that deal with the above combination of loads; the literature is bereft when describing the other combinations of loads that the students will encounter.

The topics of axial and bearing stresses are of fundamental importance in the first course on mechanics of materials. It is usually discussed by an instructor, with some assumptions, on a blackboard or computer only with freehand drawings or figures. It is not easy for most instructors to give a second year engineering student a clear picture about either the assumptions or the development of stresses in a structural member or machine component.

The proposed images are aimed to facilitate the understanding of these concepts for both learning and industrial practice. Thus, the objectives of the proposed images are to demonstrate to the students the followings:

- The assumptions (Saint-Venant’s theory) made in developing the axial stress formula
- The development of axial stress in a member
- The effect of bearing stress on a member
- Interaction between axial, bearing, and contact stresses
- An application of optics in engineering

**Basic theory**

The optical method of reflected photoelasticity (photostress) is utilized to achieve the goals in regard to the above objectives. Photostress is a technique for measuring surface strains to determine the stresses on a part or structure during loading. With the photostress method, a special strain-sensitive plastic coating is first bonded to the test part. Then, as test loads are applied, the coating is illuminated with polarized light from a reflection polariscope. When viewed through the polariscope, the coating displays the surface strains on the part as a colorful informative pattern, which immediately reveals the full-field strain distribution over the entire coated area.

Most engineering students learn the fundamentals of optics in a physics class. They are introduced to the geometrical and physical optics and most likely will not use that knowledge learned during the rest of the curriculum. A quick review of the fundamentals of polarized light can be linked to the principal strains as summarized in the following paragraphs.

In a homogenous body, the index of refraction is constant regardless of the direction of light propagation or plane of vibration. However, in crystals, the index depends on the orientation of vibration with respect to index axis. Most plastics behave isotropically, optically and mechanically, when they are stressed. On the other hand, photoelastic materials become
optically anisotropic when stressed. The change in the index of refraction is a function of the resulting strain, analogous to the resistance change in a strain gage.

In the second general physics course, engineering students learn the polarization of light by reflection and Brewster’s law\(^5\). When a polarized beam propagates through a transparent plastic of thickness \(t\), where \(X\) and \(Y\) are the directions of principal strains at the point under consideration, the light vector splits and two polarized beams are propagated in planes \(X\) and \(Y\). If the strain intensity along \(X\) and \(Y\) is \(\varepsilon_1\) and \(\varepsilon_2\), Brewster established that the relative change in index of refraction is proportional to the difference of principal strains or:

\[
(n_x - n_y) = K(\varepsilon_1 - \varepsilon_2)
\]

(1)

Where \(n\) is the index of refraction. The constant \(K\) is called the strain-optical coefficient and characterizes a physical property of the material. It is a dimensionless constant usually established by calibration and may be considered similar to the “gage factor” of resistance strain gages. The relative retardation\(^6\), in reflection, between the two beams in the \(X\) and \(Y\) directions is:

\[
\delta = 2tK(\varepsilon_1 - \varepsilon_2)
\]

(2)

Therefore, the basic relation for strain measurement using the photoelastic coating technique is:

\[
(\varepsilon_1 - \varepsilon_2) = \frac{\delta}{2tK}
\]

(3)

In a circular polariscope, the relationship between the fringe order \(N\) and the relative retardation is:

\[
\delta = N\lambda
\]

(4)

Where \(\lambda\) is the wavelength. Thus, the difference between the principal strains can be calculated as:

\[
\varepsilon_1 - \varepsilon_2 = \frac{\delta}{2tK} = N\frac{\lambda}{2tK} = Nf
\]

(5)

The fringe value of the coating \(f\) contains all constants and its value is provided by the manufacturer of the photoelastic coating. Using generalized Hooke’s law, the difference between the principal stresses can be calculated from:

\[
\sigma_1 - \sigma_2 = \frac{E}{1 + v} Nf
\]

(6)

Equation (6) represents the basic relationship underlying the photostress method of calculating the stresses in a member. It is clear that the difference between principal stresses can be determined simply by observing the fringe order (color), since the mechanical properties of the specimen and the fringe value of the coating are known values in a typical experiment.
Whenever the stress state is known to be uniaxial, there is only one nonzero principal stress in the plane of the test part surface, and this can be obtained directly from Eq. (6).

\[ \sigma = \frac{E}{1 + \nu} NF \]  

Equation (7) will be used as the basis for discussion during the rest of the paper. Thus, different types of stresses will be considered rather than strains.

**Classroom lecture supplements**

The goal is to visualize the development of stresses rather than calculating them. However, it is essential to spend sometime in lecture to link the Physics and the Mechanics of Materials topics, equations 1 through 7. This will enable the students to comprehend the development of stress in the member. The sequence of colored fringes produced by increasing stress is black (zero), gray, white, pale yellow, orange, dull red, purple, and blue (maximum). As a reminder to the students, this fringe identification sequence could be listed with every image. The purpose of each photostress image is to acquaint students with the full-field stress regions. Thus, it is more advantageous and time efficient to have the images ready for the lecture than doing the experiments in the laboratory. Any bolted joint connection that can be used with a tensile machine is sufficient for this task. The photostress images that will be discussed combine contact, bearing, and axial stresses; these stresses were demonstrated by the use of joint connection shown in Fig. 1.

![Figure 1: Bolted joint](image)

The effective length, width, and thickness of aluminum specimen used were 19”, 5”, and 1/8” respectively. The specimen shown in Fig. 2 was coated based on the procedures outlined in references7.
Axial load

Utilizing the photoelastic images, one can instantly identify critical areas, highlighting overstressed and understressed regions. The photoelastic image of the specimen subjected to a load of 1500 lb is shown in Fig. 3. The zero stress field is obvious by its black color. The validity of the axial stress formula in the plate is apparent by the remaining orange region. The dashed curve in Fig. 4 clarifies the assumption made in developing the $\sigma = P/A$ equation. It separates the axial stress region from the assembly stress region resulting from the bolts.

![Test specimen](image)

Figure 2: Test specimen

![Photoelastic image for 1500 lb load](image)

Figure 3: Photoelastic image for 1500 lb load
At this stage, engineering students start appreciating the application of optics and light to understand practical engineering problems. Emphasis should be given to the interplay that exists between the understanding and practice of engineering mechanics in the learning process and beyond. This can be accomplished by showing some of the images about the areas of application of photostress such as: automotive, aircraft and aerospace, biomedical, and others\(^8\).

**Bearing stress**

Engineering students learn about joint connections in the Statics course. For example, the joint connections in a truss are usually formed by bolting the ends of the members to a gusset plate. Bearing stresses develop on surfaces of contact where the shanks of bolts are pressed against the sides of the hole through which they pass. Since bearing stresses are compressive normal stresses in nature, they can be uniquely added to the photoelastic image. The bolts and nuts should barely touch the stiffeners, (torque approximately .0), to minimize the effect of contact stress significantly. The oval in figure 5 approximates the black fringe area where the stress is zero in spite of the applied tensile load of 1500lb. Thus, the magnitude of compressive bearing stress equals that of the tensile axial stress. This will introduce the students to the combined axial and bearing stresses.
Figure 5: Combined axial and bearing stresses

Figure 6: Image for a load of 3500 lb
Figure 6 shows the image for a load of 3500 lb. The area where axial and bearing stresses are equal (black) has decreased significantly in the vicinity of the bolts. Thus, the magnitude of the change of the axial stress is greater than that of the bearing stress. The students can observe the marked dashed region in which the stress level corresponds to the previous load of 1500 lb, figures 3-5. This stress region is equivalent to the stress at the center of the plate when the applied load was 1500lb shown in figure 3.

Starting with the unloaded test part, and applying the load in increments, fringes (colors) will appear first at the most highly stressed points, which is the area close to the plate’s center in this article. As the load was increased, new fringes appeared and the earlier fringes were pushed toward the area of lower stress.

**Combing axial, bearing, and contact stresses**

This section deals with the combined axial, bearing, and contact stresses. Although contact stress is not normally covered in the first Mechanics of Materials course, the author found that it was beneficial to introduce its effects optically utilizing the photoelastic method. This can be achieved by introducing the bearing stress on the surfaces of contact between the head of the bolt and the top thick plate and between the nut and the bottom thick plate. This bearing stress can be produced by increasing the torque on the bolt, which translates to a contact stress between the thick plates and the test thin plate.

The photostress image for a load of zero and a torque on the bolts of 10 lb-in is shown in figure 7. Since there is no axial load applied, the students expect an area of black fringe (zero stress) which is located above the dashed red line. The fringes close to the bolts, and hence to the contact line between plates, identify the area that contact stress affected the test plate.

The next logical image is to superimpose the previous stress combination (axial + bearing) onto this contact stress. The resulting image of a load of 4500lb and bolt torque of 10 lb-in is shown in Fig. 8. The black fringe, where the bearing stress was dominant, has diminished significantly. With further loading, additional colors were generated in the highly stressed region and moved toward region of zero stress. The pure axial stress region is close to the plate’s center and it is the highest stress level in the plate. Below that is the region where the stress level is equal of that for a 3500lb load that was at center of the plate in figure 6. Therefore, the combined effect of the compressive bearing and contact stresses is equivalent to a tensile axial stress resulted from an extra 1000lb applied external load. The bottom region indicates a significant bearing and contact stresses as the color corresponds to a stress level that is mostly equivalent to that resulted from a 1500lb load shown in figure 3.
Figure 7: Contact stress effect

Figure 8: Image for a load 4500 lb and torque of 10 lb-in
Assessment

The author used the photostress images in the fall 2005 semester. Eighteen students were registered for the Mechanics of Materials course. It was felt that the images helped the students achieve the intended visualization objectives. The images generated a great deal of discussion and involvement by the students. This was accomplished by asking the students questions regarding the stress regions as well as the level of stresses. The students enjoyed the supplementary images in learning axial, bearing, and contact stresses. One means of gauging the students’ reaction to validity of this approach was to conduct a survey. The result of the survey is listed in Table 1.

<table>
<thead>
<tr>
<th>The photoelastic images helped me understand:</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>average</th>
</tr>
</thead>
<tbody>
<tr>
<td>The assumptions made in developing the axial stress formula</td>
<td>6</td>
<td>10</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>4.22</td>
</tr>
<tr>
<td>The region where the axial stress formula is valid</td>
<td>11</td>
<td>5</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>4.50</td>
</tr>
<tr>
<td>The bearing stress effect in connections</td>
<td>9</td>
<td>2</td>
<td>6</td>
<td>1</td>
<td>0</td>
<td>4.05</td>
</tr>
<tr>
<td>The combined loading concept (axial + bearing)</td>
<td>9</td>
<td>5</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>4.27</td>
</tr>
<tr>
<td>The combined axial, bearing, and contact stresses</td>
<td>5</td>
<td>10</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>3.94</td>
</tr>
<tr>
<td>The effect of assembly stress in practice</td>
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<td>6</td>
<td>5</td>
<td>2</td>
<td>0</td>
<td>4.11</td>
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<tr>
<td>An application of optics in engineering</td>
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<td>4</td>
<td>6</td>
<td>0</td>
<td>1</td>
<td>3.88</td>
</tr>
</tbody>
</table>

*Rating scale: 1 nothing 2 very little 3 modest amount 4 quite a bit 5 a lot*

The results show that the objective of using photostress images was achieved. Further anecdotal evidence supporting the impact of using the photostress images is the continuing discussions of these stresses as well as the experimental stress analysis method. Indeed, the discussion continued after class and during office hours, which indicate that it generated some extra interest in the subject.

In addition, below are some of the early typical student reactions:
“Bearing stress can help designer by adding bolts at different locations or different torques.”
“Very interesting optics application to see something used in the field of engineering.”
“I liked it a lot because we are finally getting a taste of real engineering.”
“Very helpful to see multiple images together to compare.”
“Would like to compare different connections.”
“Pictures gave me a better understanding of the materials.”
“Great visual aids!”
“Pictures really helped me understanding the materials.”

Conclusions

The paper presents examples of using photostress images for reinforcing many ideas of bearing stress and connections that are cursorily presents in an introductory Mechanics of Materials course. To understand the behavior of a member under loads, full-field visualization of stresses is highly recommended in teaching the course. The photostress images can be used as a tool to supplement the approach normally used in lecture and textbook formats. The details of classroom implementation and assessment of the efficacy of this approach are presented. The early assessment results indicate that the supplementary images helped the students understand the development of basic axial, bearing, and contact stresses.

Bibliography


