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Optical Device Whit Application to the Study of Stress Concentration in Mechanical Design

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***Abstract* - This paper presents the design and construction of an optical didactic device, which allows us to visualize the stress fields as a color pattern, using polycarbonate specimens which were designed with geometric changes to obtain stress raisers. We begin with a brief explanation of the theoretical bases that explain the operation of the device, such as light polarization and photoelasticity. Finally, the results of the tests performed, the observation of the color bands and their respective analysis are shown.**

Keywords: Stress concentration, polarization, polycarbonate, light source, specimen.

I. INTRODUCTION

In mechanical engineering, one learns to design and select machine elements intended for power transmission. One of the parameters to be considered, when designing these elements, is the stresses that are originated, due to their geometry and the loads that are applied. The term stress concentration is applied to a condition in which high levels of stresses are generated locally as a result of the geometry (shape) of a machine element, common geometries with stress concentrators are shown in Figure 1.

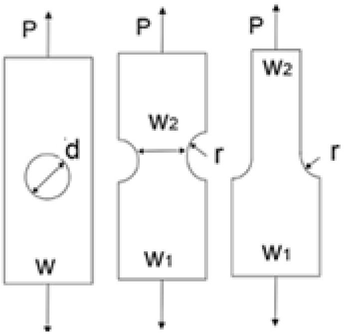

Figure 1: Typical stress raisers

Stress concentration is the local increase of stresses in machine elements, this increase is defined by abrupt geometrical changes in the cross sections, such transitions take place due to holes, slots and changes in diameters, called stress raisers, it is important to visually show such concepts in the teaching of mechanical design[1].

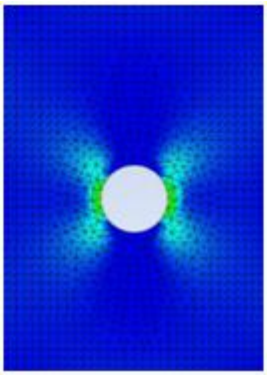

Figure 2: Simulation of stresses in an element with one hole

The analysis of geometric figures to determine stress concentration factors is a difficult problem, since not many solutions can be obtained. One such solution is that of an infinite plate subjected to uniform tension forces containing a circular hole, Figure 3.

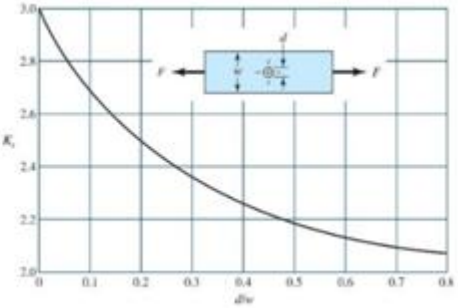

Figure 3: Bar in tension with a transverse hole

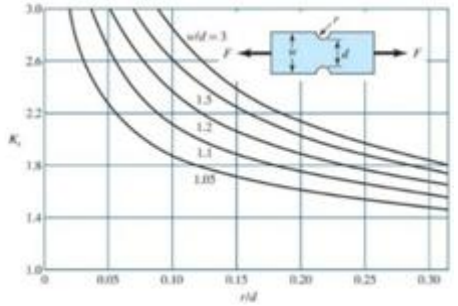

Figure 4: Notched rectangular bar in tension

Photoelasticity is an experimental technique that allows the analysis and description of the distribution of stress fields in birefringent materials subjected to load, based on isochromatic fringe patterns (describing the difference of the principal stresses) and isoclinic fringe patterns (describing the direction of the principal stresses) [2]. This technique is performed in a photoelastic testing device consisting of an instrument for the production and detection of polarized light called a polariscope. Photoelasticity is applied to birefringent materials such as polycarbonate. This method provides a quantitative view of the areas under stress.

The polariscope consists of a white light source, whose rays pass through a polarizing lens that makes them vibrate in a single plane, Figure 5. They then pass through the specimen which, when subjected to a charge, breaks the beam into two out-of-phase components. Finally, when passing through an analyzing lens, these beams vibrate again in a single plane and a pattern of colored bands is shown in the areas where the stresses are concentrated and which is related to the magnitude of the loads.

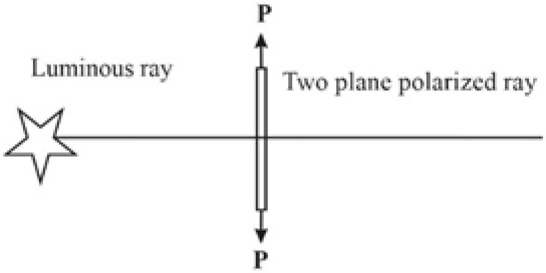

Figure 5: Basic elements of a polariscope

Currently there are several equipments to perform photoelasticity tests, these equipments are digital and marketed from other countries, which is the reason for their high cost. Based on the need to show the importance of stress raisers with a basic device, a portable didactic prototype was designed, with a simple construction and made of a resistant but light material. The tested specimens contain typical stress raisers to facilitate the visualization of the stress fields, Figure 6, in addition to the fact that their study objective is only qualitative.

Figure 6: Design of four different test specimens

In the paper "Teaching strategies and teaching-learning methods in Higher Education", it is concluded that as part of the teaching strategy, didactic resources should be developed to provide information, motivate students, guide learning, develop skills, evaluate knowledge and skills, and provide spaces for expression and creation [3]. For this reason, it is necessary to build a prototype that allows analyzing and visually showing the stresses induced by applying a load on test specimens.

Many crystalline substances, i.e. substances whose atoms are arranged according to some kind of regular repeating series, are optically anisotropic. Their optical properties are not the same in all directions within a given piece or specimen.

Light can be treated as a transverse electromagnetic wave, whose plane of vibration is fixed. As is known, light propagates through transparent matter by excitation of the atoms within it. The electrons are driven by the electric field and radiate. These secondary waves recombine and the resulting refracted wave travels forward.

The velocity and, consequently, the refractive index are determined by the difference between the frequency of the electric field and the natural or characteristic frequency of the atoms. An anisotropy in the bond strength will therefore manifest itself in an anisotropy in the refractive index. A material with a refractive index dependent on the polarization state of light is birefringent.

In 1816 Brewster discovered that normally isotropic transparent substances could be converted into optically anisotropic ones by applying mechanical stress. This phenomenon is known as mechanical birefringence or photoelasticity. If the material is subjected to tension or compression it acquires uniaxial properties, i.e. the effective optical axis is in the direction of the stress and the induced birefringence is proportional to this stress.

Photoelasticity forms the basis of a technique for studying stresses in both transparent and opaque mechanical structures. Since birefringence varies from point to point on the surface of the model, when placed between crossed polarizers, a complex and varied fringe pattern reveals internal stresses [4].

Polarizer. It generally consists of a thin sheet of polyvinyl alcohol heated and stretched before attaching it to a supporting sheet of cellulose acetate, the face of the polyvinyl being colored with liquid containing iodine. When the incident ray reaches the polarizer, it decomposes into two rays vibrating in perpendicular planes, one of which absorbs. The light emerging from the polarizer is therefore considered to vibrate in a single plane.

Analyzer. It is analogous to the polarizer, in such a way that if they are placed crossed, i.e. with their polarization planes orthogonal to each other, an observer located to the right of the analyzer will not be able to see any light. On the contrary, when the polarizer and the analyzer are placed parallel, that is, when the polarization planes of both are coincident, the light will be transmitted through them.

II. PROPOSED DEVICE

The device must support and apply loads to the specimen, as well as allow it to be placed between the polarizer and the analyzer, the polarized light will be divided into its components according to the main directions of the stress state in the plane created by the load. The two vibrations emerging from the model will experience a certain phase shift because the refractive indices are different according to the main directions. Through the analyzer, the emerging vibrations are the components of the two waves coming out of the model. As these two waves are polarized in the same plane, the function of the analyzer will be to establish the necessary conditions of coherence so that they can produce optical interference.

Figure 7 shows the schematic diagram used in the design, with the relationships of the optical device and the surrounding elements.

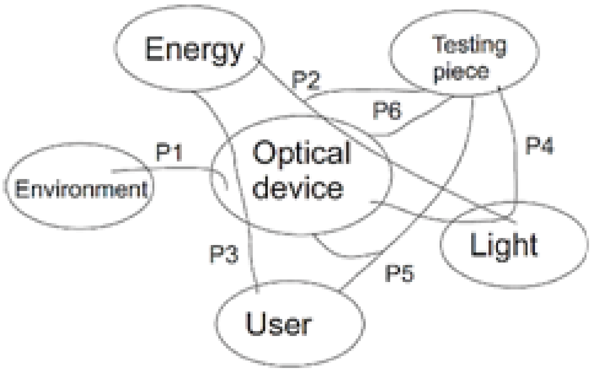

Figure 7: Schematic of the optical device and surrounding elements

The service functions considered in the top-down functional analysis of the device are listed below:

- P1. Host the device
- P2. Show the stresses
- P3. Connect the power
- P4. Project the light
- P5. Place the piece testing
- P6. Perform the test

The global service function obtained from the functional analysis considered in the design of the device is shown in Figure 8.

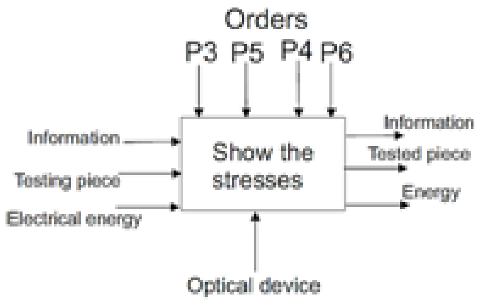

Figure 8: Global service function of the optical device

Different types of professional and didactic polariscopes were analyzed. The following typical components were identified:

1. Light source
2. Polarizing lens
3. Analyzer lens
4. Frame
5. Charge application system.

The experimental test was performed on a basic optical device, containing the parts necessary for the production and detection of polarized light, Figure 9.

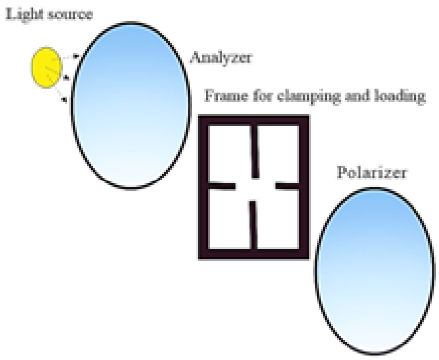

Figure 9: Optical device components

Figure 10 shows the virtual assembly of the designed device, with the basic parts: a guide, a load frame, and three posts, to place two lenses and the white light source.

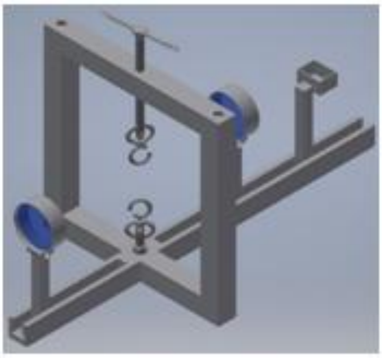

Figure 10: Device design

In addition to containing the above parts, the design of the device must meet the following requirements:

a) The elements to be analyzed, in this case the lexan specimens shown in Figure 11, will be subjected to tensile stresses.
b) The lenses, polarizer and analyzer, must have the possibility of being moved closer or farther away from the specimen.
c) The complete system should be light to facilitate its transport.
d) The lenses should have the possibility of being rotated on their horizontal axis.

Figure 11: Lexan test specimens

However, it is common to find, mainly in machine design, parts with variable cross-section subjected to uniaxial tension or compression. Any change in the cross-section of the part subjected to uniaxial tension or compression alters the stress distribution in the area where the cross-section decreases [5].

III. RESULTS AND DISCUSSIONS

An effective configuration was obtained in the designed optical device. Applying the photoelastic method and testing specimens in which the stress intensity can be observed. Analyzing Figure 12, we can see the place where the stripes or patterns appear and the direction they take, giving us information about the stresses and where they are concentrated. These color patterns of the light spectrum appear along the specimen, starting at the point where the load is applied and are distributed up to the notches and fixed supports.

The center point, which remains dark throughout the load application, is an isotropic point (zero stress difference and normal stresses are equal in all directions). This dark point is a reference point to determine our maximum stress in each pattern, counting out from this point to where the load is being applied along it, with careful inspection.

With the tension test and by means of photoelasticity we have been able to evaluate how a real element would behave under a real point load, placing a specimen with the same characteristics and simulating the conditions that it could have for an ideal analysis, this specimen gives us visual information about the stresses that are distributed along it.

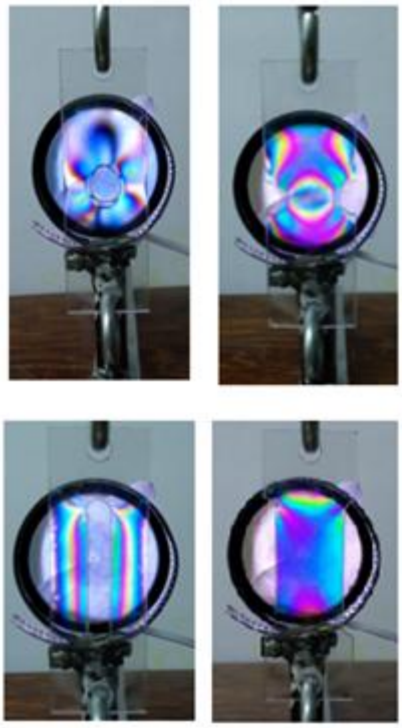

Figure 12: Stress patterns of a four different pieces testing in tension

Figure 12 shows that the specimen center hole and notches are potential areas where the part may fail, as the patterns are concentrated on such changes in geometry.

IV. CONCLUSION

When the test loads are applied, the test piece is illuminated with a polarized light from a light source. When viewed through the optical device, the stresses are displayed in color, their overall distribution on the specimen is revealed and the high stress areas are determined.

The stress distribution in the investigated specimen made of an optically active material can be visualized experimentally. The same stress distribution exists in the real part, because the character of stress distribution depends on its shape and the type of loading.

The images observed during the test show us how a real element that supports a tensile force behaves and the stresses are distributed over the entire width and length of it. Therefore, the geometry of the specimens behaves in a stable way during the test and shows us in a didactic way the behavior of the stresses. The shape of the strip pattern reveals qualitatively the localized distribution of stresses on the specimen.

Photoelastic analysis is a reliable method when it comes to stress distribution analysis, which makes it one of the best didactic methods in the teaching of mechanical design, for the analysis of elements with complex geometries. The mechanism of stress concentration is clear; any abrupt change of geometry in a material subjected to certain forces creates a concentration.

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