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Photoelastic Effect Demonstration Device

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ENGR 491 – Senior Design
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ABSTRACT

The purpose of this project was to design and build an affordable device to demonstrate to engineering students stress patterns in loaded samples of different geometries using the photoelastic effect. These devices use light and polarization filters to demonstrate the photoelastic effect in transparent materials and show their stress patterns. This project aims to improve upon existing designs of similar devices and create a functional device that professors can use to educate students with a visual real-life example. This paper focuses on the research done, design considerations, final decisions, and what was learned. Also, this paper discusses conceptual ideas for designs. First, research was done for the team to get a better understanding of similar devices. After this, research had to be done to better understand the fundamentals of optics relevant to this project. Then, once there was a better understanding of the problem and a better engineering background, some conceptual designs and one final design project for the device was designed.

With our education we were able to design a device that meets the requirements and will function as intended. We were also able to provide more detailed information about what photoelasticity is and how polariscopes work. Also, we were able to simulate stresses on the device and ensure that the device will not fail under the intended amount of load. The team looked at each design and decided upon a final design to build for the final project. The team chose 10 unique geometries for the Lexan samples that will be tested in the polariscope, most of these geometries can be found in engineering textbooks used for talking about stresses. One design choice the team made for the project was to build a device that can fit on an overhead projector so the polariscope can be used in classrooms and projected onto a wall. The team had to cut a piece of square aluminum tubing that is about 5 inches long so the arm holding the head of the projector could be extended upward allowing for the projector to focus further from the base of the projector giving the team more room to build the rest of the project a little taller. The team built the polariscope so that it can be used as a linear or circular polariscope. The filters and mechanism used for applying tension are also easily adjustable up or down to allow for the sample to always be in focus.

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PHOTOELASTIC EFFECT DEMONSTRATION DEVICE

1 Introduction

The scope of this project includes the design and build of a photoelastic effect demonstration device with 10 unique test polycarbonate samples included. This device uses the photoelastic effect to create a visual demonstration of stress patterns through different geometries. Such a device is called a polariscope. The polariscope designed in this project is shown in Figure 1.1 on top of an overhead projector.

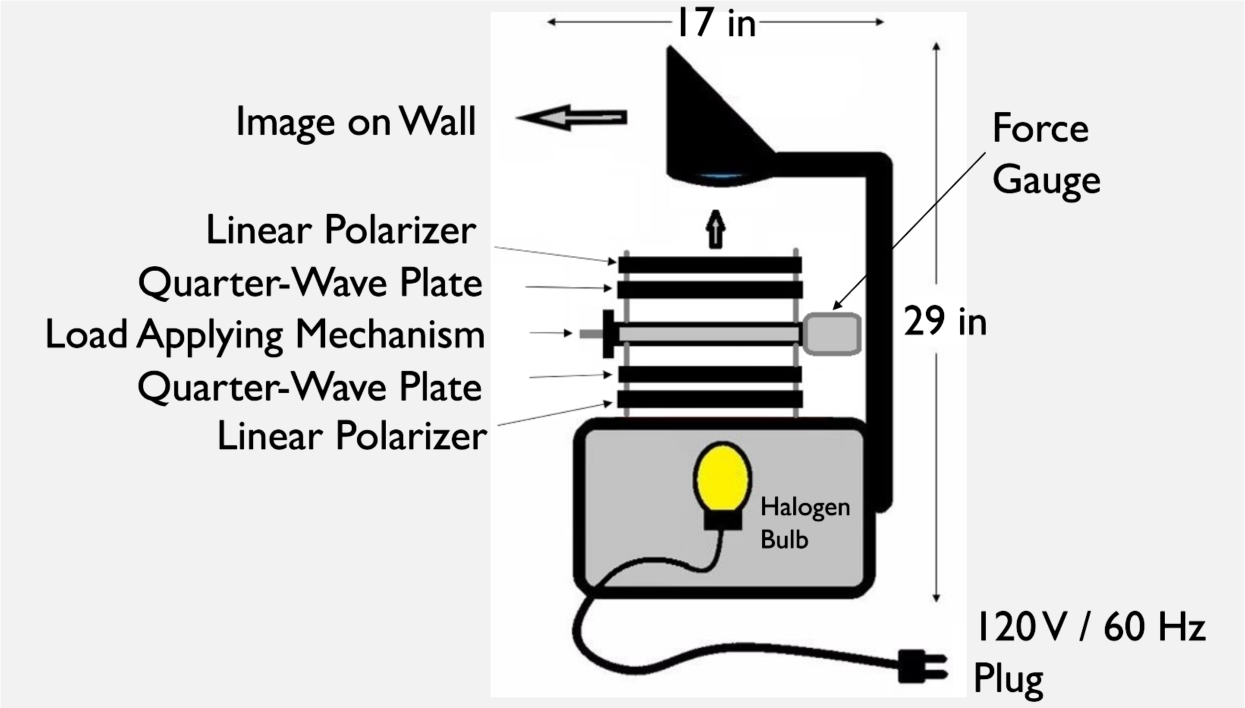

Figure 1.1. Mechanical Block Diagram of Polariscope

The objective of this project is to design and build an affordable polariscope to demonstrate to engineering students stress patterns of different geometries under tensile loads. This device will use the photoelastic effect to show the stress patterns caused by different stress concentrators in the loaded samples.

The deliverables for this project are:

1. Solid Works drawings of the device and samples
2. Fully functional photoelastic effect demonstration device
3. 10 unique samples (different stress concentrators and geometries)
4. Report, Presentation, and Poster

The team does not intend for this device to be used for research purposes. This polariscope is intended to be used for teaching stress patterns, birefringence, and photoelasticity. This device will only be able to show the stress patterns in transparent objects that can become birefringent.

This report includes background of the photoelastic effect and how it is used, a set of requirements, mechanical block diagram, system hierarchy, functional block diagram, concept of operations, budget, and information about polariscopes. Also included are the team's designs for a device that will apply tension loads to samples made of polycarbonate, also known as Lexan.

The stakeholders are often engineers conducting research, professors, and engineering students. A polariscope is a device that uses linear polarizers and quarter-wave plates to manipulate the polarization of light waves that pass through transparent materials, such as Lexan, to show the level of stress in different regions of the transparent material. Photoelasticity shows changes in the optical and transparent properties of a material under stress. It is often used to view and experimentally determine the stress distribution in a material [6].

2 Photoelastic Effect Background

The photoelastic effect uses changes in color to display stress patterns in clear materials with birefringent properties. The effect is useful for demonstrating the impact that stress concentrations have on the flow of stress through a part.

Stress concentrations can be difficult to visualize when first learning about the concept. Students can benefit from a visual representation of stress concentrations and patterns. The University of Southern Indiana engineering department did not previously have a device that could perform this task. The goal of this project is to supply a fully functioning photoelastic effect demonstration device for use in classes here at USI. The engineering problem is to design a mechanism that will apply loads to samples and cast polarized light through the samples and onto a wall to demonstrate the photoelastic effect. Students can benefit from a visual representation of stress concentrations. The motivation for this project comes from wanting to provide a device that can be used by professors to instruct students and visually help them understand stresses in objects. A benefit of having a photoelastic effect demonstration device would be to visually show a real-world object under stress to a class of engineering students in statics class or strengths of materials class. These devices have been used to check simulated models to make sure that everything matches, and nothing was input or simulated incorrectly. These devices can also be used to show areas where there are no stresses, in which case these areas can be removed to decrease the weight and material in an object to decrease cost [3].

As shown in Figure 2.1, the distribution of stress through an object can be visualized using the photoelastic effect. Photoelasticity was first discovered in 1815 by Sir David Brewster. He initially found the photoelastic effect in gels and eventually glass and crystals. Photoelasticity was of academic interest for about a hundred years before Coker and Filon applied it to measuring stresses in parts for machines [6]. When under tension or compression the materials will take on properties of a positive or negative uniaxial crystal. If the stress over a sample is not uniform, neither is the birefringence imposed on a transmitted wave. Superimposed on colored fringes are separate systems of black bands. Using a polarizer, the light will be absorbed by the analyzer which will produce the black band known as an isoclinic band. These fringes provide a map of the stress pattern and can act as a basis for calculations [10].

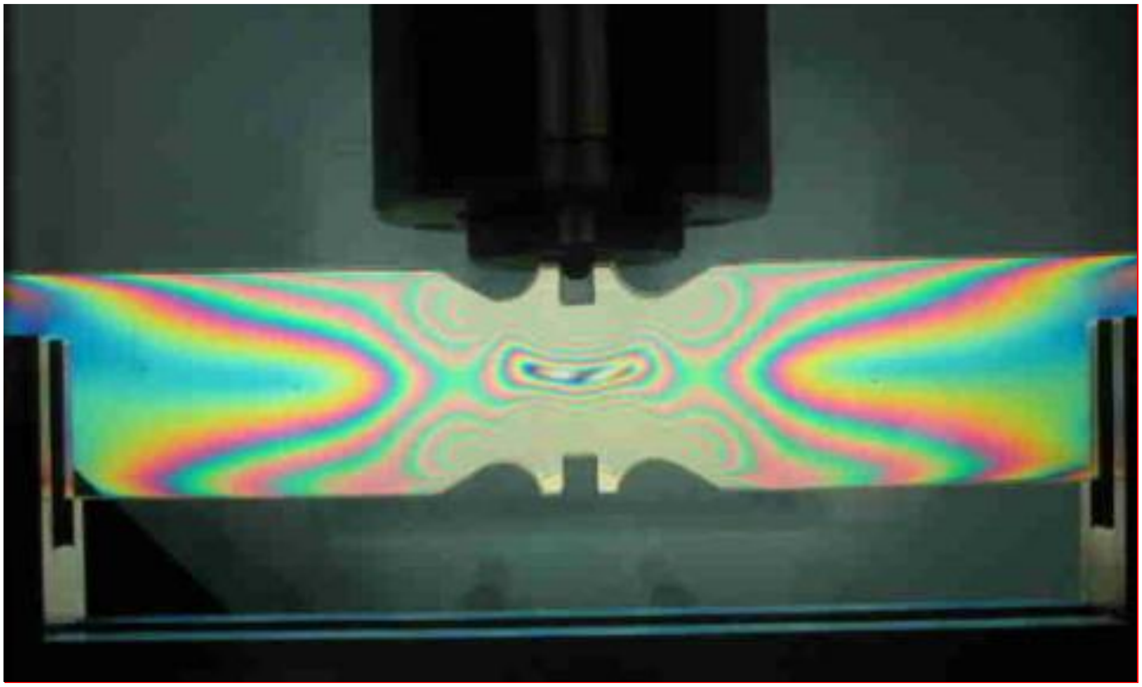

Figure 2.1. Photoelasticity Example [12]

Devices such as polariscopes are used to view photoelastic effects in transparent materials that become birefringent under stress such as polycarbonate, more commonly known as Lexan. Using these types of devices can help identify stresses in objects. When viewing transparent materials such as Lexan, glass, and crystals under a polariscope, one will see discoloration in the sample. This discoloration is caused by a phenomenon known as the photoelastic effect. The photoelastic effect happens when stresses are present in a material which affects the refractive index of the material and causes a slight change in the size, shape, and orientation of the indicatrix [1].

Photoelasticity is a technique for measuring and visualizing stresses in structures. It uses linear polarized light to display the birefringence (double refraction) of clear specimens under stress. Birefringence is a property displayed by some transparent materials that causes the refractive index to vary throughout a sample when under stress. The colorful effect seen in Figure 2.1 is achieved using polychromatic (natural) light.

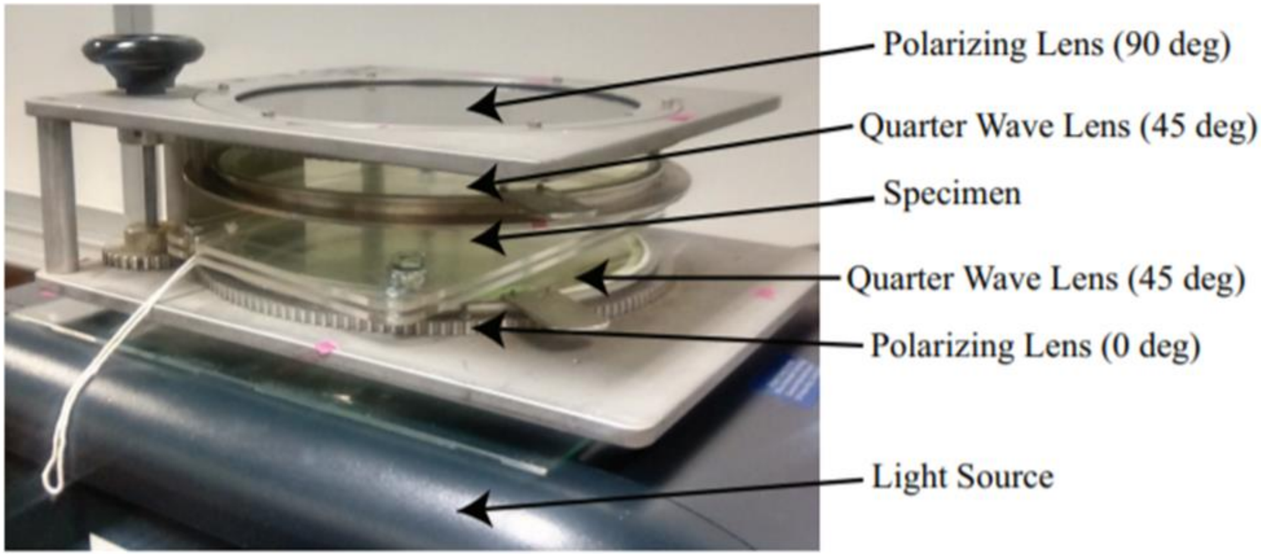

Figure 2.2. Polariscope at Brigham Young University [3]

A device is to be constructed with the same basic materials as the ones used in Figure 2.2. As seen in Figure 2.2, the device will need a light source, two polarizing films, and two quarter wave films. The device will also need an area to secure samples in the middle of the device and a way to apply stresses to the sample. The team would like to enclose all components into one frame and add an analog projector to the top to project the image onto a wall for teaching purposes. Also, the team will need to add a device that can apply tension loads to the samples to induce stress.

An existing polariscope reviewed by the team is the Grey-field polariscope, see Appendix D. This polariscope uses polarized light that passes through a birefringent medium which causes the light to exit elliptically polarized. This device also uses an automatic ellipsometer to analyze the light [4]. The Grey-field polariscope is fully automated and can produce data from the stresses observed. The only problem with this is the device requires a lot of power to function and is not easily transportable, therefore making it not as useful if a professor wanted to use this device to demonstrate to a group of students, in another area, the photoelastic effect and stress patterns in objects.

Another type of device that is like these is a Poleidoscope, see Appendix D. Like the Grey-field polariscope, the Poleidoscope is digital. The difference is that this device splits the polarized beam after it passes through the sample and before it reaches the analyzer elements. The beam gets split into four to provide the needed number of images for phase-stepping analysis. Each beam is then focused on a CCD chip once it passes through its individual analyzer. Each image from the four chips is then combined using a multiplexer device to form a single image [5]. The downside to this device is the cost for the special chips, cameras, and optics to produce the precise image. However, this device is compact and robust so it can be transported, but it needs special equipment and software to demonstrate the photoelastic effect [5].

Figure 2.3. Test Stand ALX-J [11]

A mechanism that can apply stress is needed for our polariscope to work. We did some research on a similar device that can apply compression or tension. Even though this device was not used in the project it helped serve as a concept for one design of many stress applying mechanisms the team constructed. In Figure 2.3 is the model we got one of our design inspirations from. This device from AliExpress is meant to have a force gauge attached to it and then a sample is connected between the force gauge and the hook to apply tension. There are a lead screw and a couple of guide rods that make up most of the mechanism. A device like this would be ideal for this project but the design would be difficult to implement into a device that projects the image onto a wall, so we used this as a base idea and made it fit into our project.

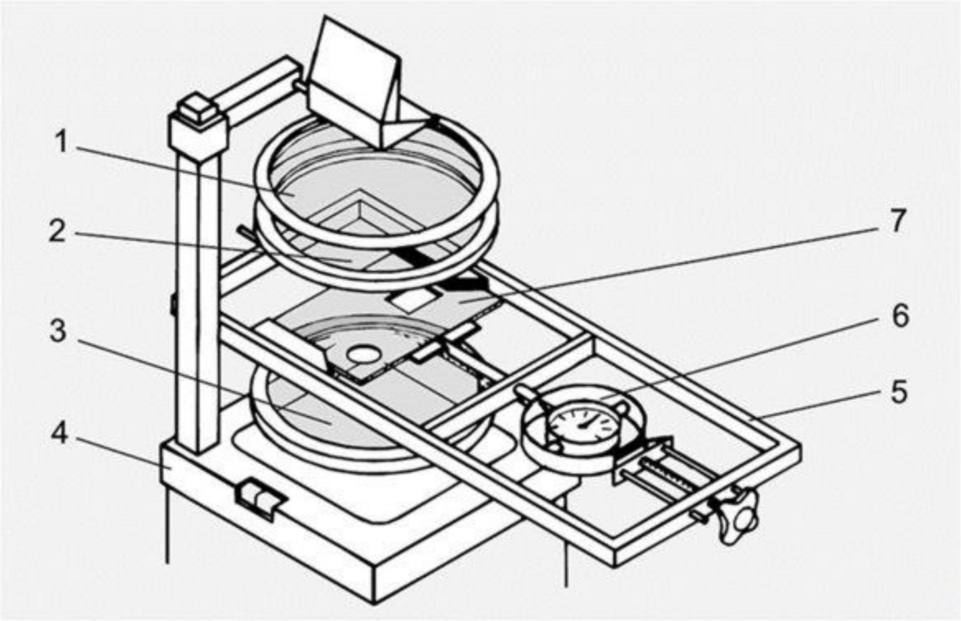

Figure 2.4. USDidactic FL210 Circular Polariscope [12]

The device in Figure 2.4 is made by USDidactic. This device was used as design inspiration for the complete polariscope that the group planned to build. The team liked the way this device was intended to be set on top of an overhead projector with the intent of it being displayed onto a wall for teaching purposes. The team also liked the general setup of the device and used this to design our polariscope with a linear polarizer, quarter wave film, load applying mechanism, another quarter wave plate, and another linear polarizer. The team liked this setup so a linear or circular polariscope can be set up and the stress applying mechanism could slide in and out of the device allowing for easy access when changing samples. Also, the team liked the force gauge that is used and thought it would be a promising idea to implement one into our project so the professor and students can get a general idea of the amount of force acting on a sample.

2.1 Stress

Stress is a measure of the localized force per unit area that particles within a part exert on each other. Stress is usually a result of some load on the part. Stress can also exist when a part permanently deforms or is manufactured with some residual stresses.

2.1.1 Birefringence

When put under loading, some materials exhibit birefringence. Birefringence is a property that many clear materials have where the index of refraction varies throughout a specimen depending on the amount of localized stress. The birefringence of a material modifies the polarization of the light passing through it. Translucent materials can be placed between polarizing filters and subject the object to external loads, each different region of the object can rotate the polarization of the light in accordance with the amount of local stress. Birefringent materials act as temporary wave films which will cause retardation in light causing one axis to slow down in relation to the orthogonal axis. The light is then split into two rays that are perpendicular to each other but travel at different velocities. The light will travel at a speed proportional to associated principal stresses making the light waves emerge out of phase producing an interference pattern which are the colorful lines that can be seen. Different components of the light wave have unique phase shifts causing these locations to appear brighter in these areas.

2.1.2 Polarization

A beam of unpolarized light consists of waves moving in the same direction with their electric vectors pointed in random orientations about the axis of propagation. Plane polarized light, or linear light, consists of waves in which the direction of vibration of the electric field is the same for all waves and can be produced by a linear polarizer with a given axis of polarization. The electric field of light is confined to a single plane perpendicular to the direction of propagation. The analyzer is a subsequent linear polarizer with its axis of polarization at some angle with respect to that of the original linear polarizer. If this angle is 90 degrees, the light is extinguished. Circular polarization is when the electric vector rotates about the direction of propagation as the wave progresses. All regions of the specimen where the principal-stress directions are aligned with those of the polarizer and analyzer will be dark are known as isoclinic.

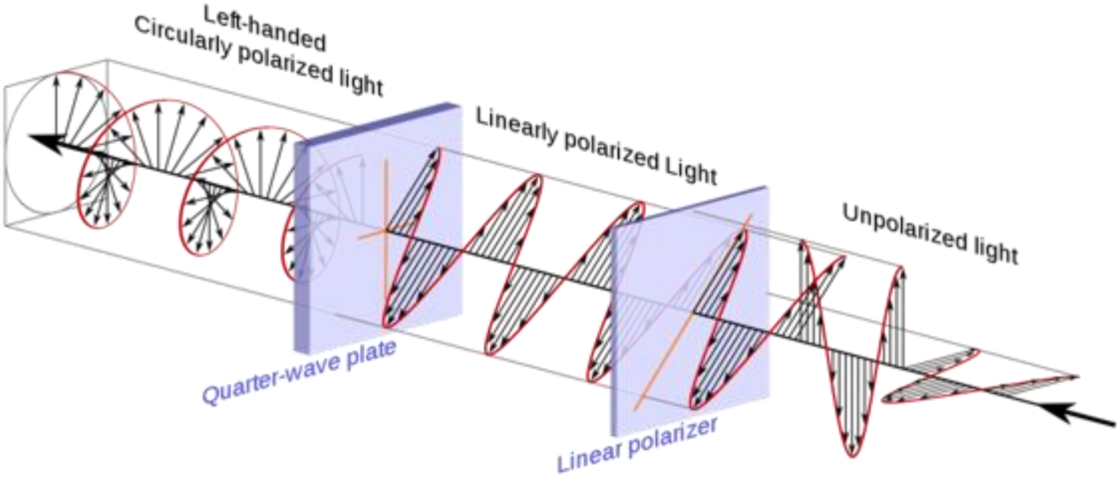

Figure 2.5. Polarization of Light [15]

The electric field of the light consists of two linear components that are perpendicular to each other, equal in amplitude, but have a phase difference of π/2 once the linear polarized light has passed through a quarter wave plate with the fast axis at a 45-degree angle to the linear polarization axis. The resulting electric field rotates in a circle around the direction of propagation. A circular polariscope produces isochromatics but not isoclinics. The lack of isoclinics is often desirable, since the dark isoclinics in a plane polariscope often obscure large areas of the sample. This is known as the dark field. The quarter wave films are crossed while the analyzer is parallel to the polarizer. The image is brighter. The boundary of the samples will be clearer. Isochromatics in a light-field circular polariscope therefore correspond to the orders ½, 1 ½, 2 ½, instead of integer values and are often used to determine principal stress directions.

As shown in Figure 2.5, light enters the system from the right side as unpolarized. After passing through the linear polarizer, the light becomes plane polarized. After passing through the quarter-wave film, the light becomes circularly polarized.

2.2 Linear Polarizers

Linear polarizers are birefringent in a way that allows light waves to pass through with polarization in one direction but not the other. The direction that allows light to pass through is called the axis of polarization. When light passes through a linear polarizer, it becomes plane polarized light. More specifically, the light wave becomes constrained to a single plane defined by the direction of light propagation and the axis of polarization of the linear polarizer.

Linear polarizers can be purchased in the form of a film as shown in Figure 2.6. This project makes use of linear polarizing film. The film is affordable and can be cut to the exact size and shape necessary. The film purchased has its axis of polarization marked with triangular cutouts pointing in the direction of the axis of polarization.

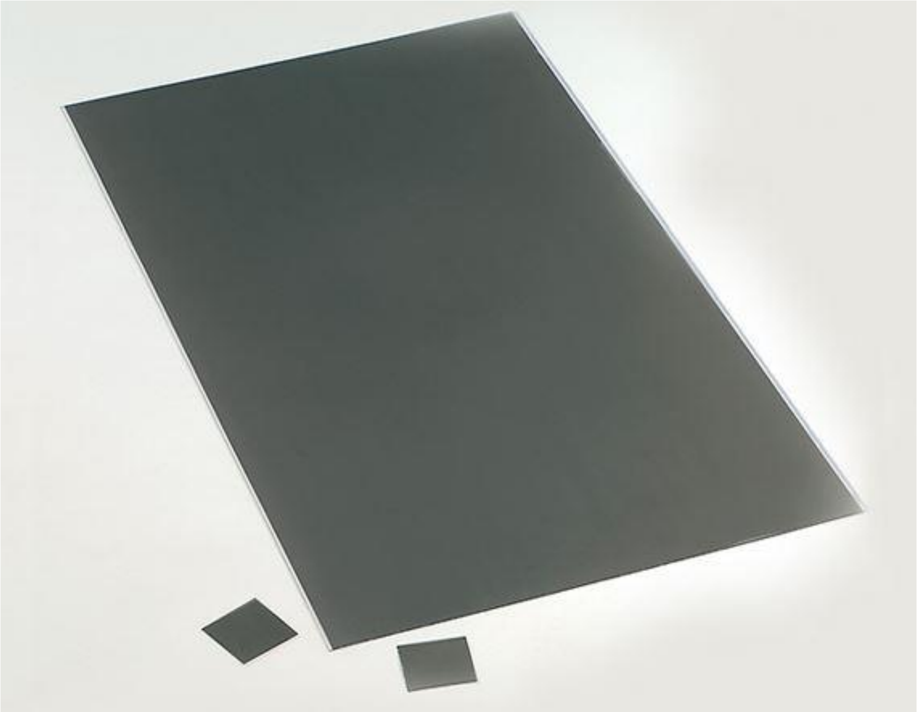

Figure 2.6. Linear Polarizing Film [13]

2.3 Quarter-Wave Plates

Quarter-wave plates are birefringent in a specific way that allows light waves plane polarized 90 degrees from each other to be delayed by ¼ of a wavelength, hence the name. A quarter-wave plate is one of many types of retarders. Each quarter-wave plate is designed to create a 90-degree delay between the perpendicular axes of the light wave. The axes by which the retarder exhibits birefringence are called the fast axis and slow axis. This 90-degree delay only happens at one specified wavelength but approximates a quarter-wave at nearby wavelengths. This means that a quarter-wave plate designed for the middle wavelength of the visible spectrum (~500 nm) will approximate a quarter-wave for the entire visible spectrum (~300 nm–700 nm). A quarter-wave plate can be used in conjunction with a linear polarizer to create circularly polarized light. The light must first pass through the linear polarizer so that it is plane polarized when it reaches the quarter-wave plate. The fast axis of the quarter wave plate needs to be 45 degrees to the polarization axis of the linear polarizer. After passing through the quarter-wave plate, the light becomes circularly polarized. The light wave creates a spiral about the axis of propagation. When circularly polarized light passes through a quarter-wave plate, the light becomes plane polarized because the film separates the perpendicular waves by an additional 90 degrees, which brings the waves back into alignment.

Quarter-wave plates can be purchased in the form of a film as shown in Figure 2.7. This project implements quarter-wave films because they can be purchased as large sections and cut to a specific size and shape. Quarter-wave plate film is also much more affordable than glass alternatives allowing them to fit within this project’s budget.

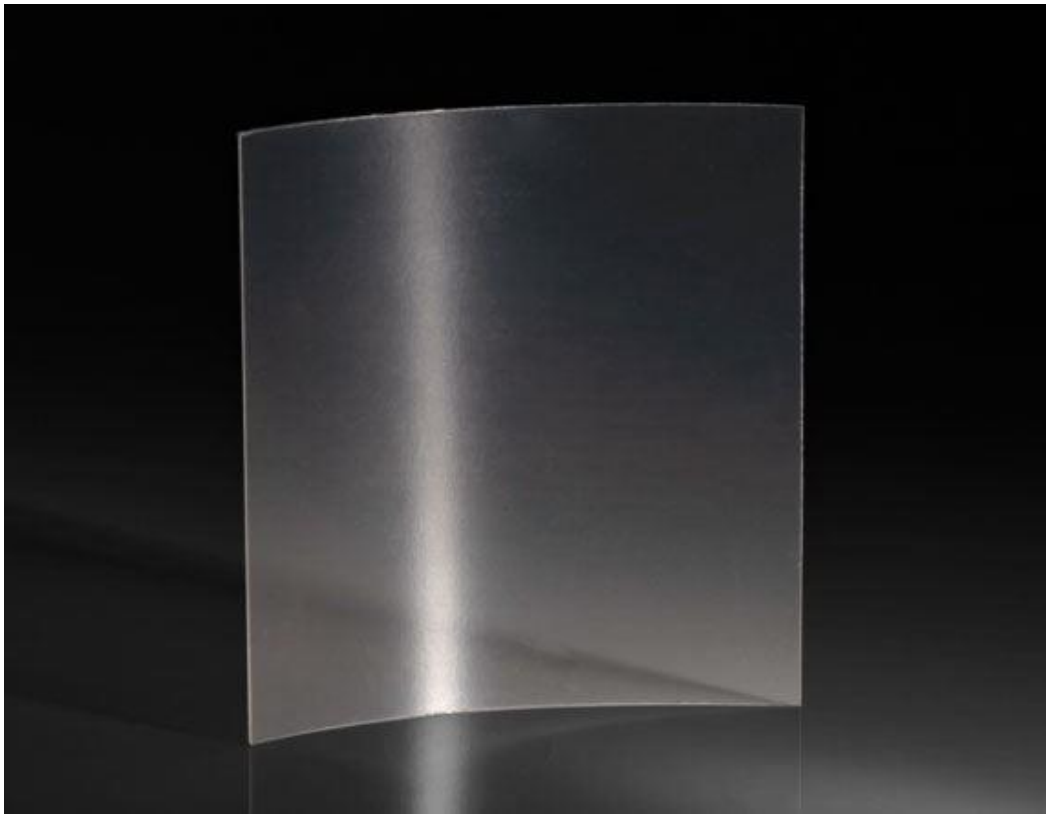

Figure 2.7. Polymer Quarter-Wave Plate Film [14]

2.4 Requirements

The polariscope shall be no larger than 18 in x 18 in x 30 in so it is easy to store and move. It shall weigh no more than 50 pounds, so it is easy to carry to and from classrooms without risk of injury. The polariscope shall cost no more than $500 for an affordable teaching device. It shall apply only tension loads to samples so the samples become birefringent. The device shall be able to apply a load of 60 pounds to samples to produce the desired effect. The device shall project an image onto the wall so the device can be used easily in a classroom for teaching purposes.

The samples shall have at least 10 unique geometries (stress concentrators) to display different stress patterns. They shall measure at most 6 in x 1.5 in so they can fit in the load applying mechanism. The samples shall be made of a translucent material, Lexan in our case, that becomes birefringent when stressed. The light source shall emit natural light so the colorful effect can be observed in the samples. It shall also be powered by 120V/60Hz wall outlet so there are no batteries or special power supplies needed.

Table 2.1. List of Requirements

Type	Requirement Description
Polariscope	The polariscope shall be no larger than 18 in x 18 in x 30 in.
	The polariscope shall only apply tension loads to samples.
	The polariscope shall apply a minimum force of 60 lbs. to samples.
	The polariscope shall project an image onto the wall.
Weight	The polariscope shall weigh no more than 50 lbs.
Cost	The polariscope shall cost no more than $500.
Samples	The samples shall have at least 10 unique geometries (stress concentrators).
	The samples shall measure at most 6 in x 1.5 in.
	The samples shall be made of a translucent material that becomes birefringent when stressed.
Light Source	The projector must emit natural light.
	The projector must be powered by 120 V /60 Hz wall outlet.

3 Polariscope Classification

There are multiple ways to configure a polariscope to meet unique needs. Some polariscopes are used to accurately model parts to predict the stress caused by loading and geometry. These devices need to be extremely accurate with sharp fringes. Other polariscopes are used for demonstration purposes only and require a bright, colorful display to fulfill their purpose. This project seeks to create a demonstration device for use in a classroom. This fundamental requirement is used to decide the type of polariscope that is best for this project.

3.1 Linear Polariscope

A linear polariscope uses two linear polarizers to create the photoelastic effect [20]. The polarizers must be oriented with the axes of polarization crossed. This should block out most of the light from passing through the polarizers. This effect creates a “dark field.” The specimen must be placed between the two polarizers with its flat face parallel to the faces of the polarizers. A light source must be placed on the opposite side of the polariscope from the viewer. Refer to Figure 3.1 for the configuration of a linear polariscope. Stress must be present in the specimen between to introduce the birefringence of the material. This type of polariscope can be an excellent way to demonstrate the photoelastic effect, but because it creates a dark field it is difficult to project an image through the polariscope onto a wall and it makes it difficult to see the edges of the specimen and it allows some dark spots to appear in the specimen.

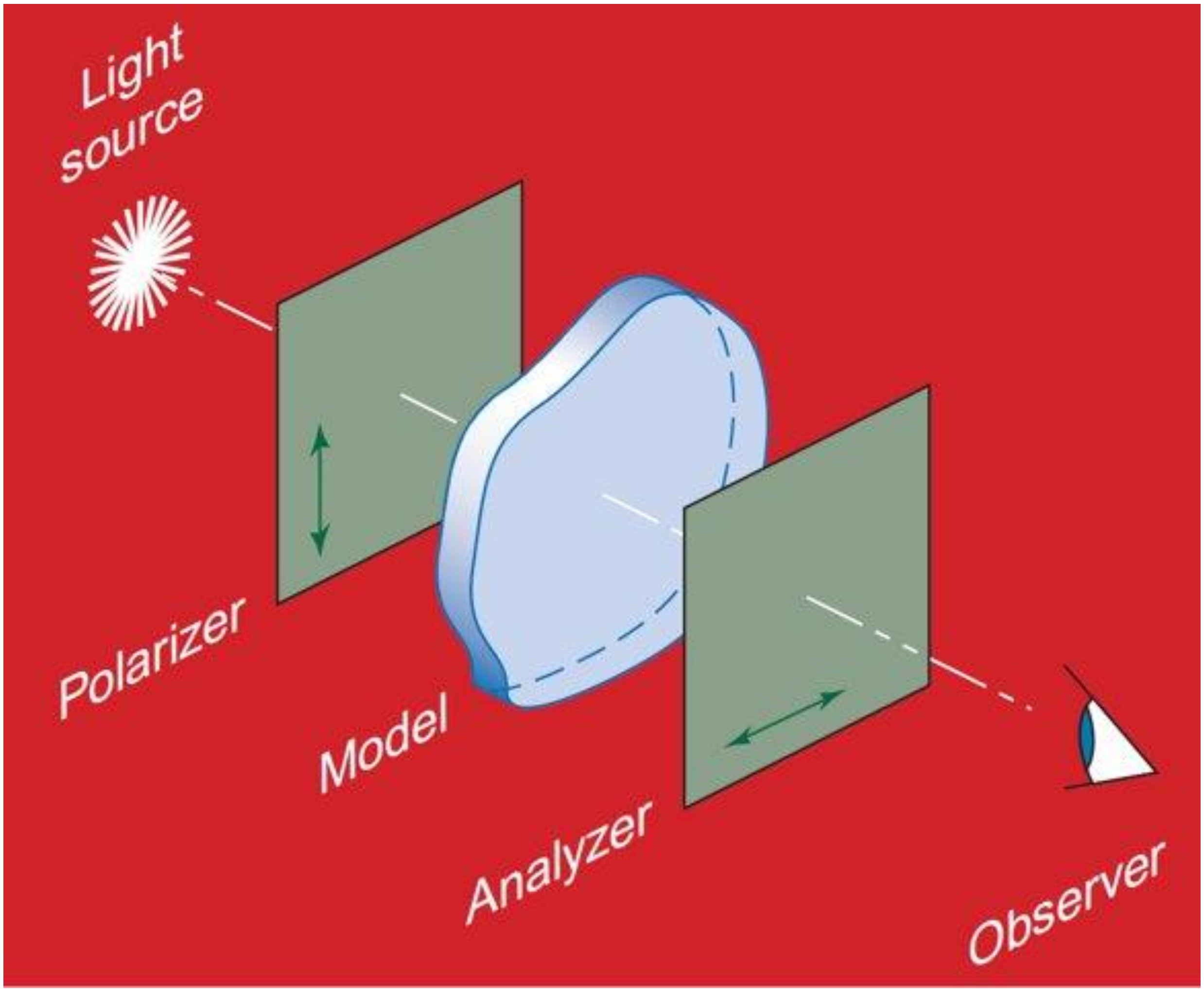

Figure 3.1. Diagram of a Linear Polariscope (Axes of Polarization Indicated by Double-Headed Arrows) [15]

As shown in Figure 3.2, it is difficult to see the borders of the specimen. The background is entirely black along with any region within the specimen with little stress. The colors can be clearly seen, but the image is very dark. The specimen would not be visible if there were no stresses in the specimen.

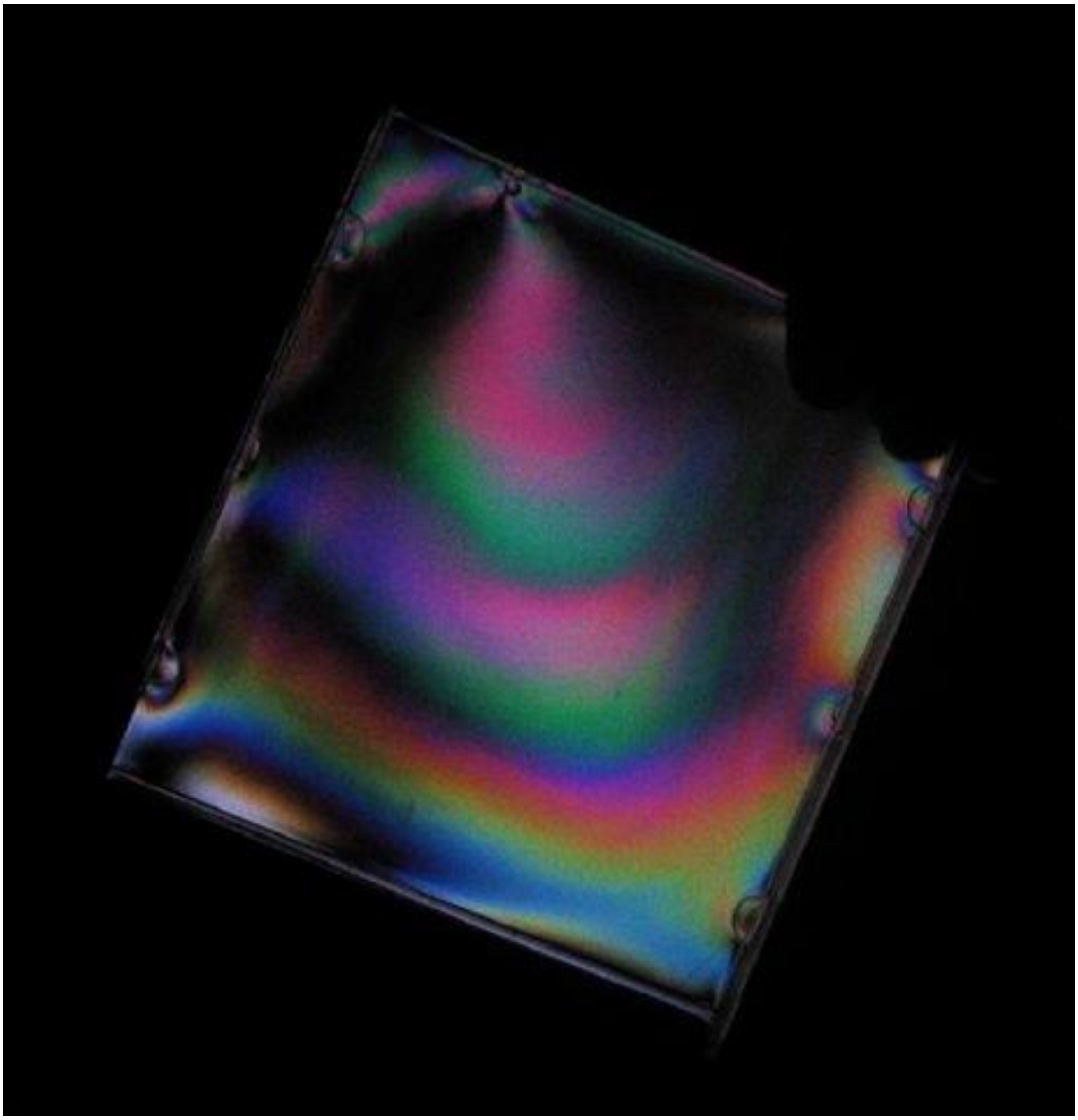

Figure 3.2. Jewel CD Case Linear Polariscope Photoelastic Effect [16]

In Figure 3.3, an image from this project's device, in a linear polariscope configuration, is shown with a sample installed. The sample has rectangular shaped cutouts to demonstrate the effect the stresses within a part that has sharp edges.

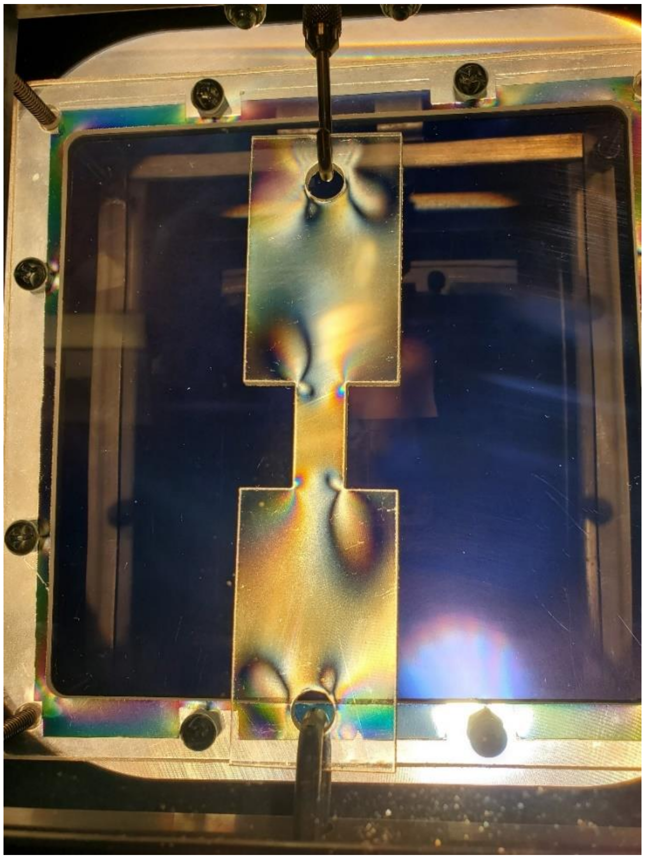

Figure 3.3. Specimen Under Tension Load in Linear Polariscope

3.2 Circular Polariscope

A circular polariscope utilizes two linear polarizers and two quarter-wave films in its design [20]. The quarter-wave films are placed on each side of the specimen with the fast axis aligned with the slow axis of the other quarter-wave film. The linear polarizers are placed outside of the quarter-wave films with their axes of polarization 45 degrees from the fast axis or slow axis of the quarter-wave films. The linear polarizers can either be oriented with their axes of polarization aligned or 90 degrees from each other. Refer to Figure 3.4 for circular polariscope configuration. By orienting the polarizers 90 degrees, the effect achieved is remarkably like that of the linear polariscope. When the polarizers are aligned on their axes of polarization, a “light field” can be seen. This means that the image is much brighter than a linear polariscope which removes dark spots in samples and the edges of the sample can be seen clearly. Quarter-wave films tend to be more costly than linear polarizers, so a circular polariscope costs much more than a comparable linear polariscope.

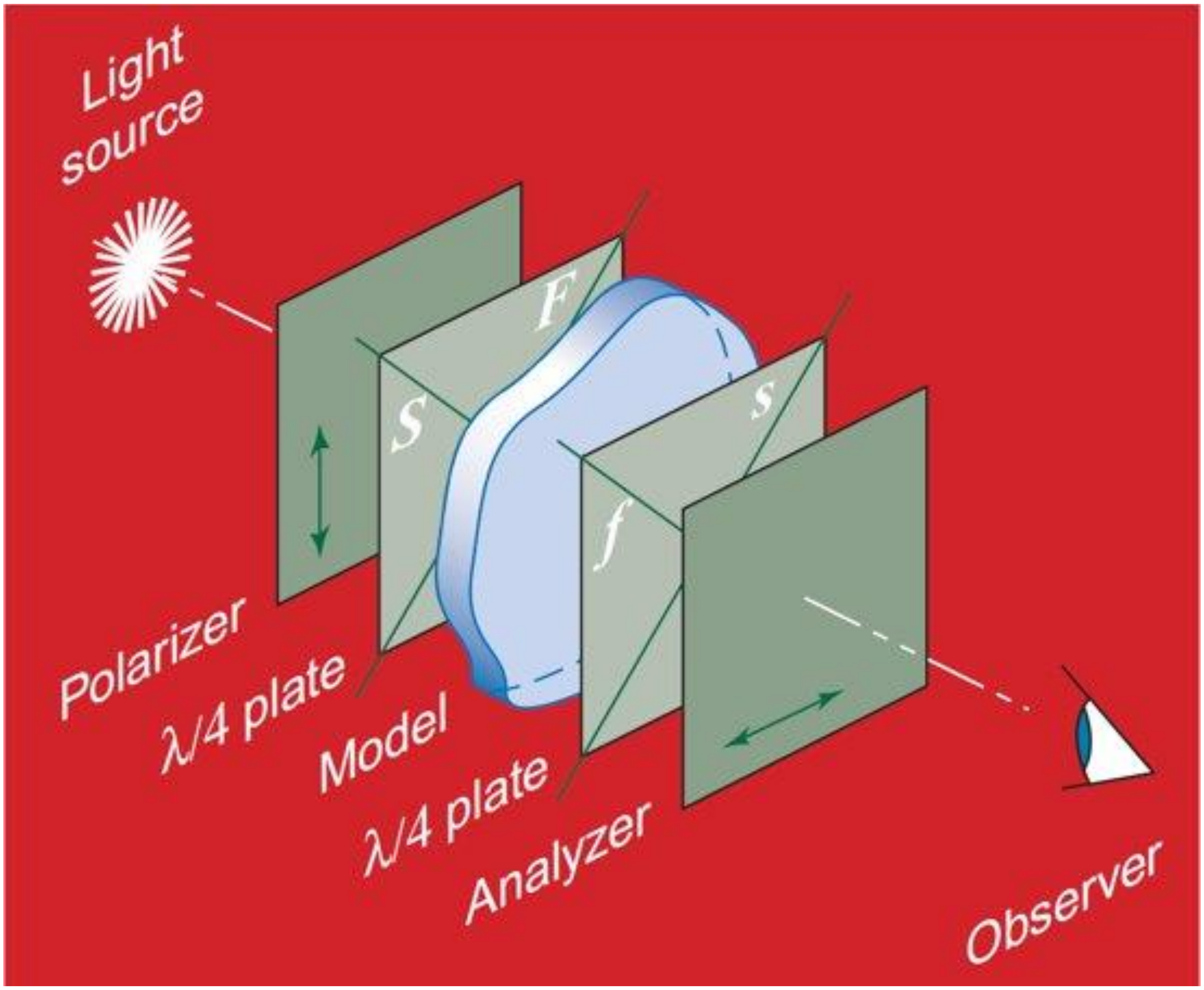

Figure 3.4. Diagram of a Circular Polariscope in Dark Field Configuration (Axes of Polarization Indicated by Double-Headed Arrows, Fast Axes and Slow Axes Indicated by F and S) [15]

The brightness of a circular polariscope in its light field configuration can be seen in Figure 3.5. The CD case contains internal stresses that appear to be concentrated on corners and geometric features. The background is bright, and no black spots are seen in the specimen. The colors are still very visible with good contrast and the borders of the specimen are sharp and easy to see.

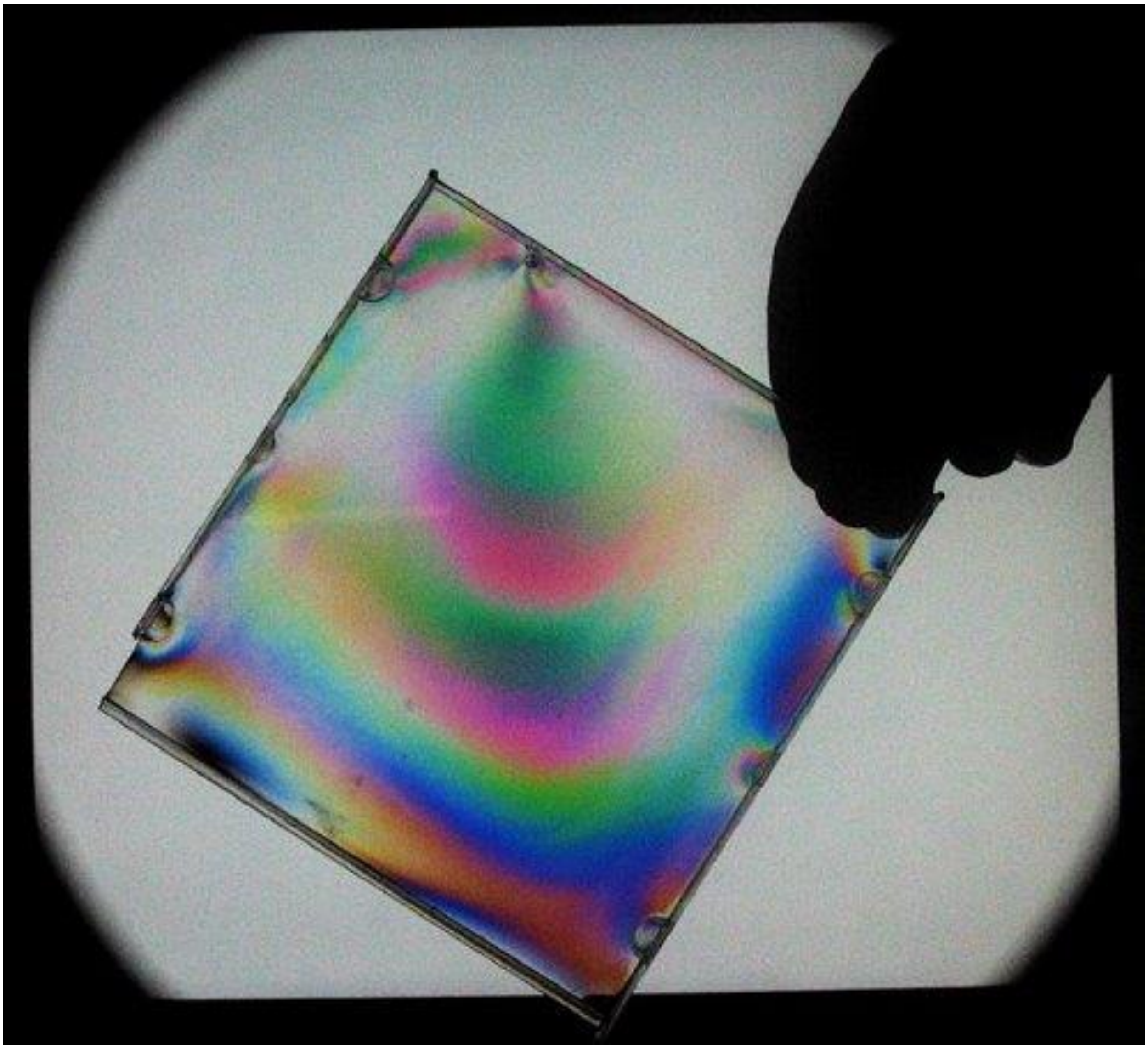

Figure 3.5. Jewel CD Case Circular Polariscope Light Field Photoelastic Effect [17]

Figure 3.6 shows this project's device configured in a light field circular polariscope configuration. The borders are sharp, and colors remain visible. This proves the range of use this device can cover.

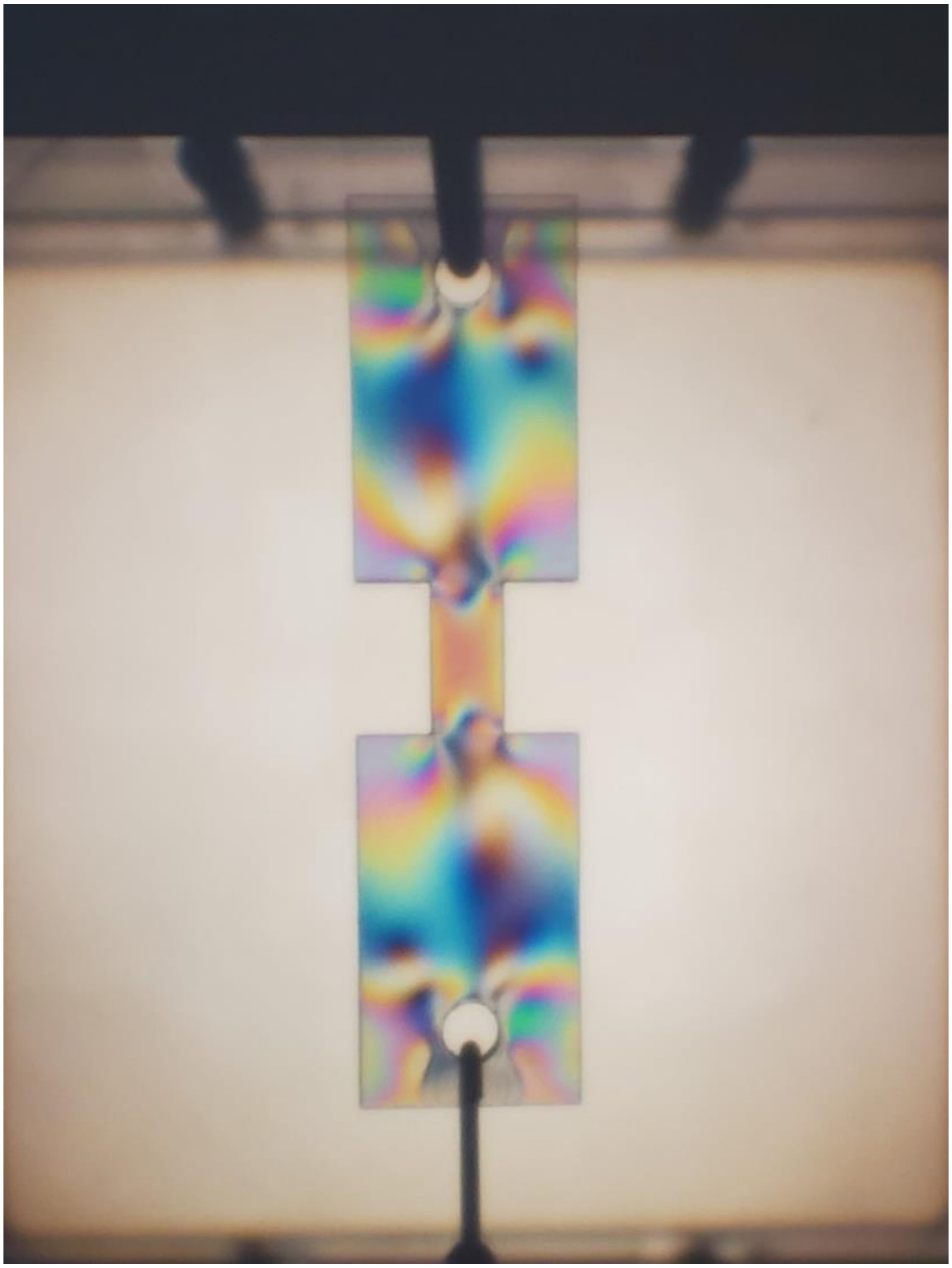

Figure 3.6. Specimen Under 40 Pound Tension Load in Light Field Circular Polariscope

4 Polariscope Design and Construction

This project calls for a device that demonstrates the photoelastic effect to students in a classroom. It is important that the device is bright so it can clearly and effectively show the colors in the samples. For this reason, a light field is desirable. A light field can be achieved by using a circular polariscope. A circular polariscope will best meet the needs of this project. Since all the parts necessary to construct a linear polariscope are included in a circular polariscope, this will be a modular design that will allow polarizers and quarter-wave films to be easily removed and rearranged if desired. Figure 4.1 shows the layout of the circular polariscope. In order to operate this polariscope as a linear polariscope, the quarter-wave plates are removed, and the linear polarizers' axes of polarization must be 90 degrees to each other.

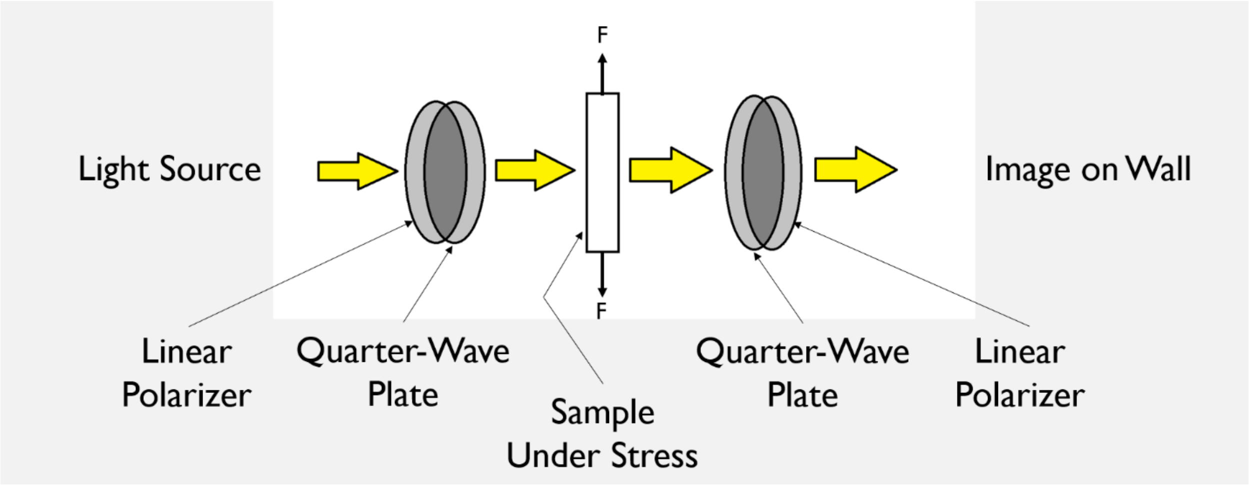

Figure 4.1. Diagram of Circular Polariscope with Separate Quarter-Wave Films and Linear Polarizers for Modularity

A force gauge is desired to display the amount of tension applied to the samples when being loaded. This will allow the user to make comparisons between geometries to demonstrate the effect of different stress concentrations on the local stresses within a part. To select an appropriate force gauge, the range and accuracy must first be known. The accuracy is decided to be no greater than 1% of the range. The following equations show the necessary range based on the geometry of the samples and fringe order desired. A fringe order of 1.0 is chosen to maximize the range of color that can be displayed without requiring any additional tension. Equation 4.1 [19] shows the calculation of stress required to see a 1st order fringe in the samples where thickness $t = 0.118\ in = 3\ mm$ and $\text{Brewster's constant}\ \ C_B = 84$ for polycarbonate and wavelength $\delta_{nm} = 570\ nm$ for 1st order fringe.

$$\sigma_{MPa} = \frac{\delta_{nm}}{t_{mm} * C_B} = 2.262\ MPa = \mathbf{328.1\ psi}$$

(4.1)

Equation 4.2 [19] shows the cross-sectional area of the largest sample. This is the control sample because there are no cutouts to create stress concentrations. The thickness is 0.118 inches, and the minimum width is 1.5 inches.

$$A_{max} = 0.118\ in * 1.5\ in = 0.177\ in^2$$

(4.2)

The tension load required to see a 1st order fringe in the sample with the highest cross-sectional area is calculated in equation 4.3 [19].

$$P = \sigma * A = \mathbf{58.1\ lbf}$$

(4.3)

Equation 4.4 [19] shows the cross-sectional area of the sample with the smallest cross-sectional area. Several of the samples have 0.5 inch cutouts on each side so the minimum width in the sample is 0.5 inches. The thickness is 0.118 inches.

$$A_{min} = 0.118\ in * 0.5\ in = 0.059\ in^2$$

(4.4)

The tension load required to see a 1st order fringe in the samples with the smallest cross-sectional is calculated in equation 4.5 [19].

$$P = \sigma * A = \mathbf{19.4\ lbf}$$

(4.5)

In order to have accuracy within 1% of the necessary range, the accuracy must be 0.01 multiplied by the necessary load. This calculation is shown in equation 4.6 [19].

$$a \leq 0.01 * 58.1\ lbf = \mathbf{0.581\ lbf} \tag{4.6}$$

With this information, an appropriate force gauge can be chosen. The range must be at least 58.1 pounds to achieve a 1st order fringe in the sample with the largest cross-sectional area and the accuracy must be less than 0.581 pounds. A digital force gauge from Amazon with a range of 110 pounds is selected. This force gauge has accuracy to 0.01 pounds and threaded holes for mounting. The cost of this gauge is $95.99. An image of this gauge is shown in Figure 4.2.

Figure 4.2. Digital Force Gauge [18]

The team chose to make the polariscope easier to use for teaching purposes. To make it easier and a better learning experience the team decided to place the polariscope onto an overhead projector for a light source, that uses the proper light needed, and to be able to project an image onto a wall allowing for an entire class to see the image at once rather than looking down on the polariscope one at a time, USI's IT department was gracious enough to donate an older unused overhead projector. The team was having issues with the overhead projector being able to focus on the sample while it was in the polariscope due to the overhead projector head not being able to be adjusted high enough to focus the image. To fix this problem the team had to go to the AEC and find some square tubing that the overhead projector's lens arm could snugly fit inside. Once the square tubing was found the team cut a 5-inch section, drilled a few holes into the tubing, and attached the arm to the tubing and the tubing to the overhead projector to allow the head to be raised higher and focus the image. The projector is able to focus at a range of 3 feet to 10 feet after the modification.

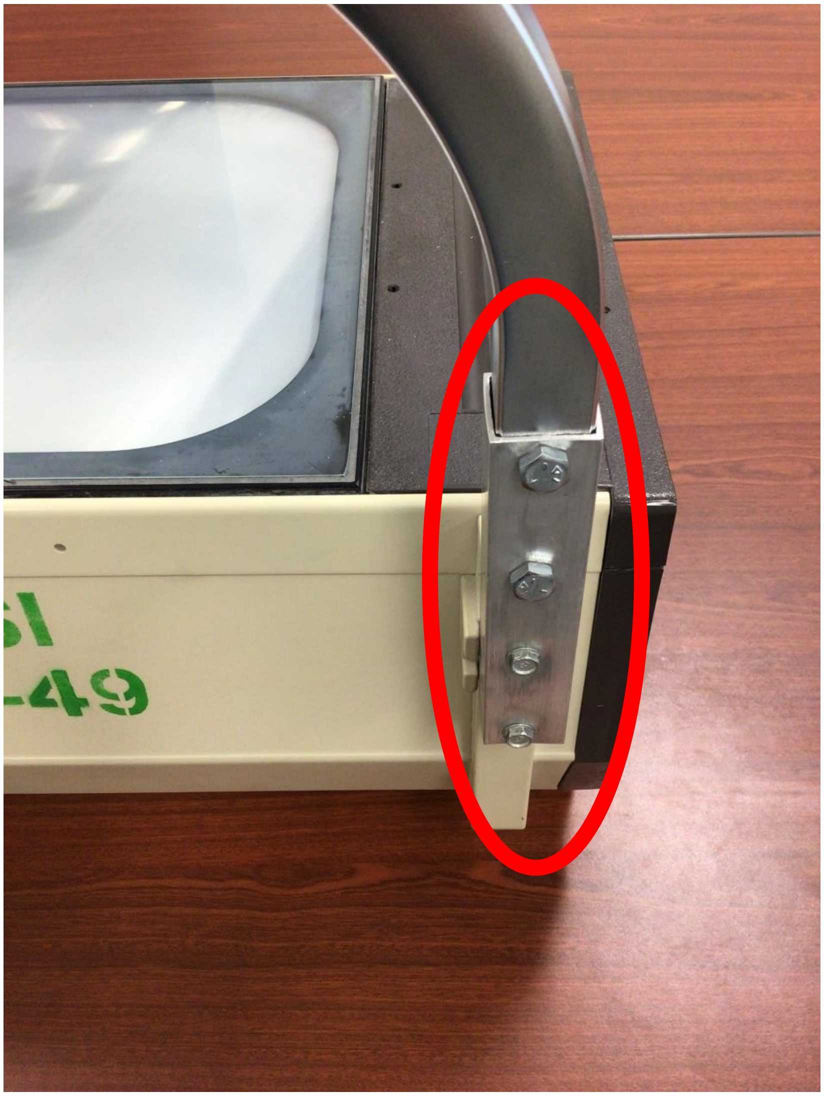

Figure 4.3. Modified Overhead Projector (Lens Arm Riser Indicated by Red Oval)

4.1 Frame for Applying Tensile Loads

The device in Figure 4.4 is one of a few load applying mechanisms that the team designed and considered using, and it is only a concept design and not the final design. This mechanism has a film on either end of the device which can be secured to the frame of the polariscope. There are also two guide rods and a lead screw, these allow the section in the middle to move in a straight line back and forth freely by turning the handle on the end of the lead screw. An advantage to this design is the force gauge will be secured to a sample that extends into the middle of the polariscope thus keeping the other components on the outside of the sample and not obstructing the light. This device also allows for the user to turn the handle on the lead screw easily applying a tension load. Also having this lead screw will allow for the user to leave the device and keep the load constant. A disadvantage to this device is the complexity and the cost it would take to build this design. This design was strictly focused on the mechanism that will apply loads to the samples. The rest of the polariscope will be discussed later, such as the frame, light source, projector top, and the decision on the films. In Figure 4.4, the Solid Works 3D model of the load applying mechanism can be seen. This model was made to provide a better visual and understanding of what the mechanism would look like and how the samples would be placed in the device. The device is 12 in long, 6 in wide, and 3 in tall.

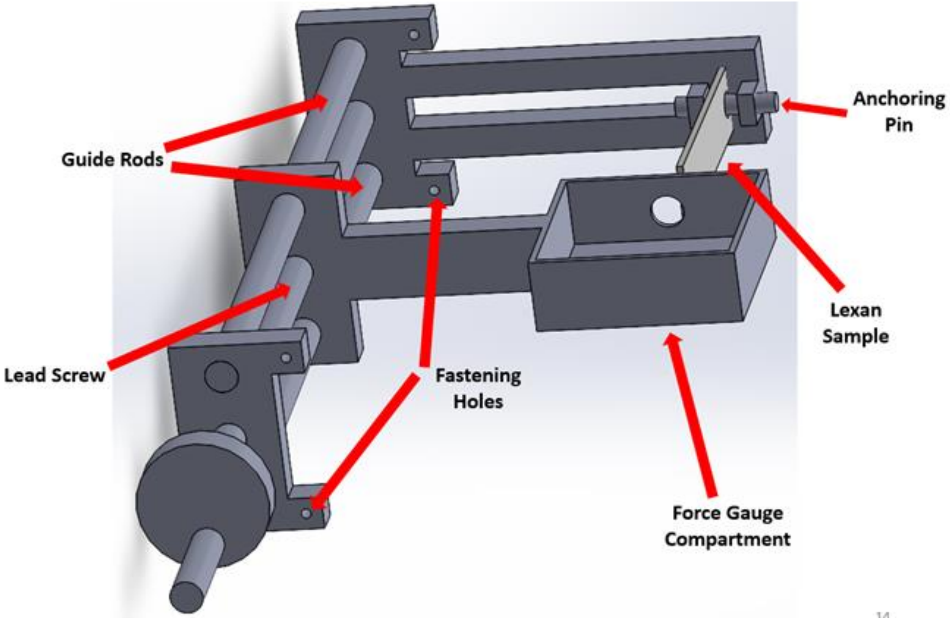

Figure 4.4. Conceptual Load Applying Mechanism Design

The final design for the load applying mechanism is shown in Figure 4.5. The frame is designed to slide into the polariscope. The device applies tension loads to samples using a threaded rod and adjustment knob. The force gauge is supported by steel bars on its underside with its hook passing through a hole in the frame to attach to the sample. The frame is constructed of ½ inch square steel tubing.

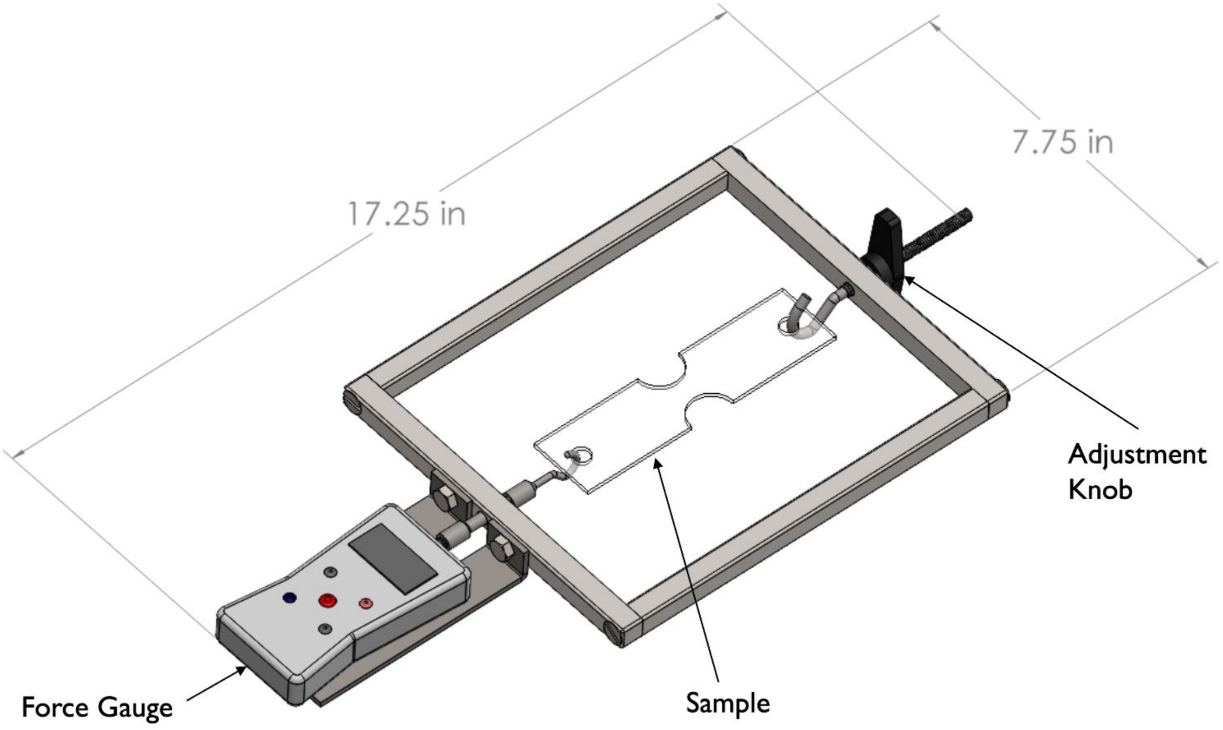

Figure 4.5. Model of Load Applying Mechanism Final Design

As shown in Figure 4.5, the final design of the load applying mechanism slides into the polariscope using c-channel aluminum as rails. The light will pass from the bottom of the polariscope, through the lower linear polarizer, through the lower quarter-wave sheet, through the loaded birefringent sample, through the upper quarter-wave sheet, through the upper linear polarizer and onto a wall, see Figure 4.6 to see the set up for a better understanding. The linear polarizers and quarter-wave sheets can easily be removed and reinstalled to modify the configuration to be a linear polariscope or circular polariscope.

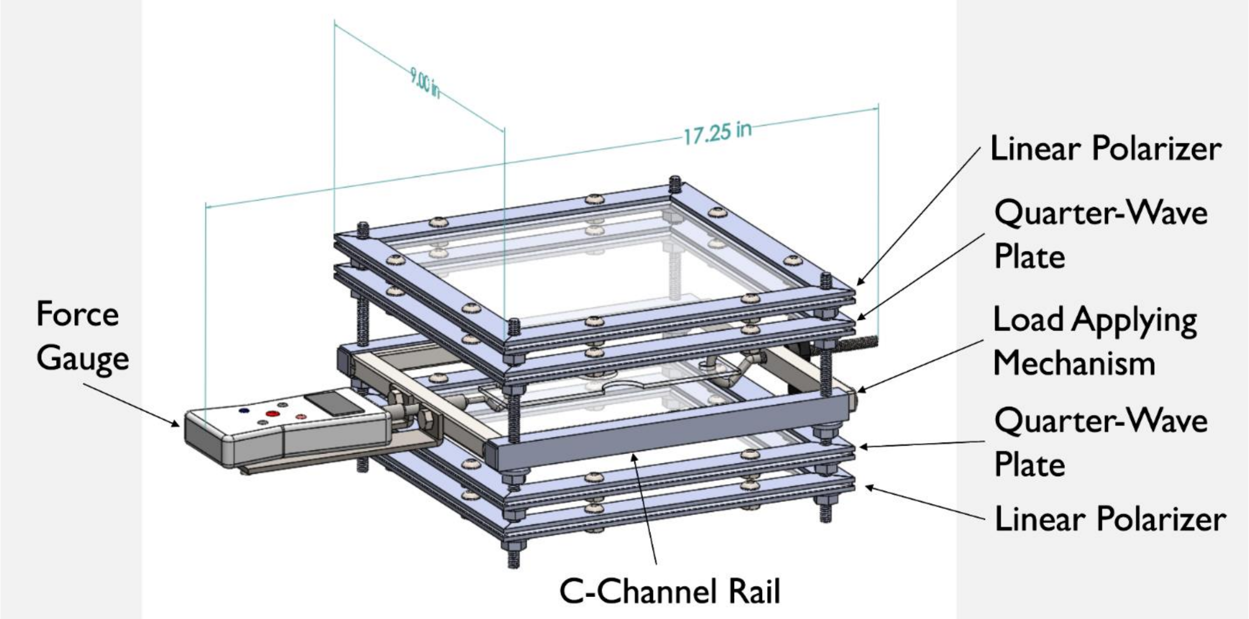

Figure 4.6. Circular Polariscope Model

The team ran a simulation on the frame of the load applying mechanism to verify that the applied transverse force caused by tension on the sample would not cause the mechanism to yield, seen in Figure 4.7. The deflection shown in the image is greatly exaggerated. The simulation was based on a force of 60 pounds applied transversely to the center of the bars on each end of the frame. The factor of safety was found to be 1.766, so an applied force of 60 pounds will not cause the mechanism to yield. The force gage can only read up to about 110 pounds of force.

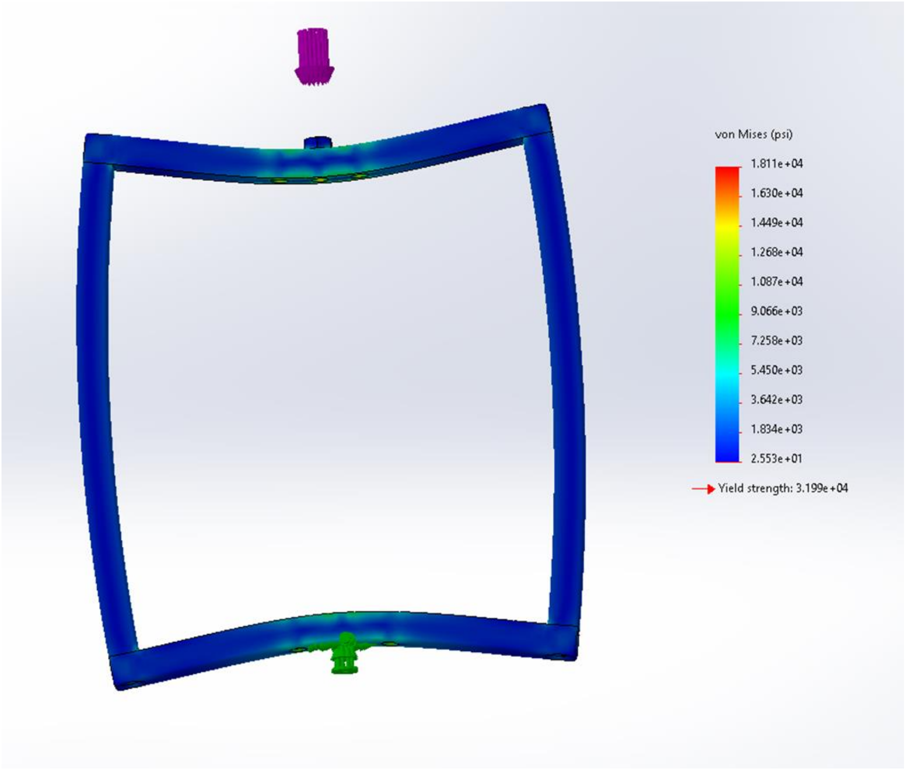

Figure 4.7. Solidworks Simulation on Frame

The team ran a simulation on one of the samples to verify that it will not yield under a tension load of 60 pounds, seen in Figure 4.8. Out of the 10 samples, the sample shown in the image was found to have the highest level of stress under a tension load. This sample was found to have a factor of safety of 3.234 meaning the sample will not yield under a 60 pound tension load. Because this sample has the highest level of stress given some tension load, all other samples will also avoid yielding when placed under a 60 pound tension load. The deflection shown in the image is greatly exaggerated.

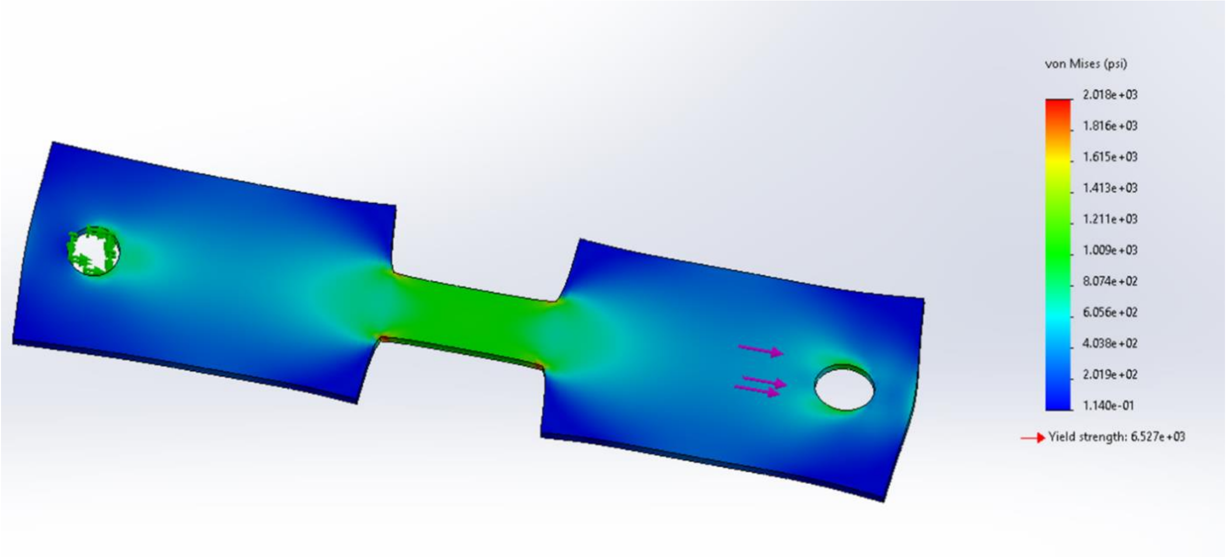

Figure 4.8. Solidworks Simulation on Sample

The system hierarchy is shown in Figure 4.9. The system is divided into three subsystems according to their operation. The structure breaks down into the load applying mechanism, frame, and optical components. Every part required to build the polariscope is included in the system hierarchy.

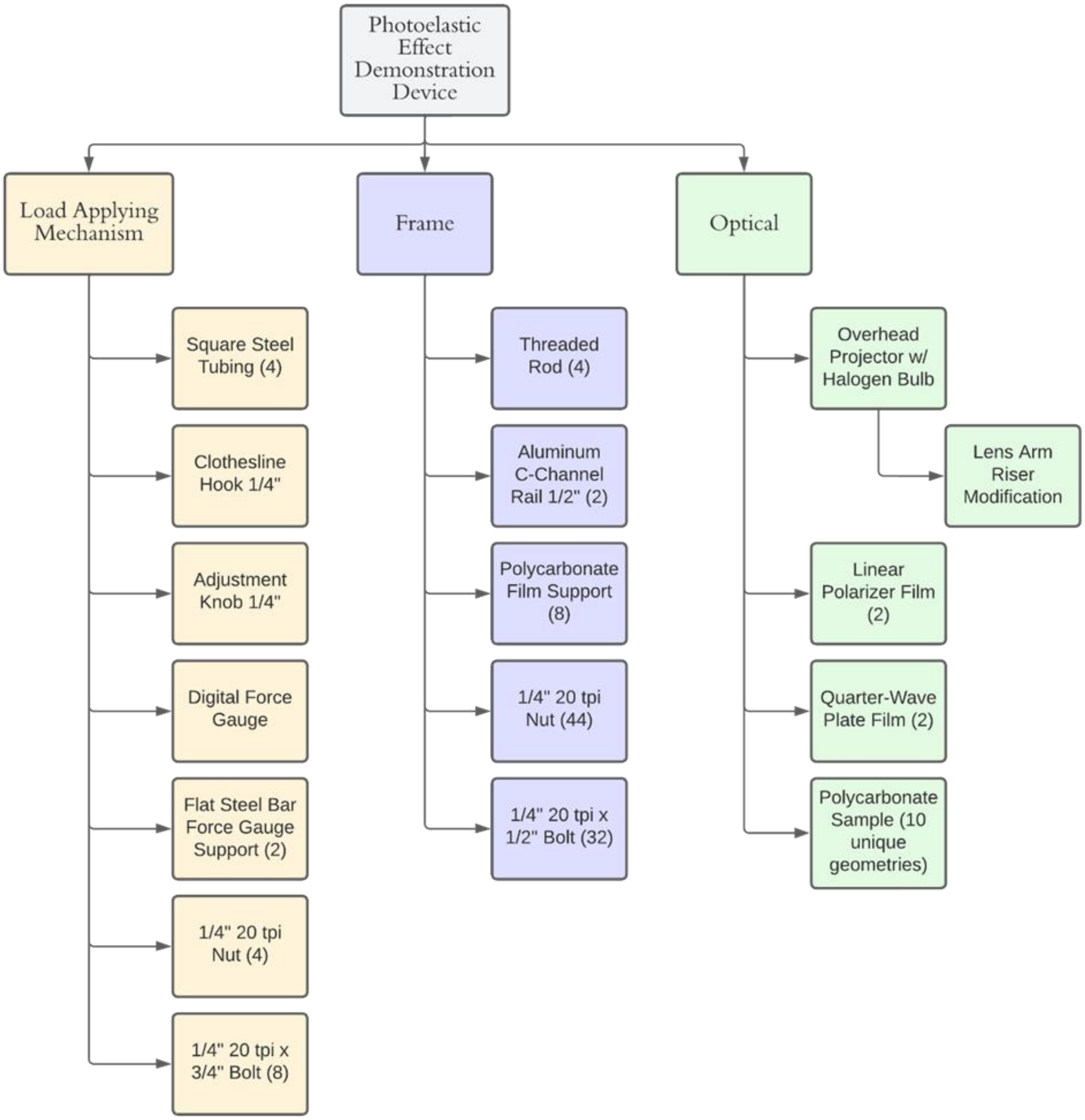

Figure 4.9. System Hierarchy

5 Results

Below shows all the results from the polariscope the team built. All the samples were under about 40 pounds of tension. The left side of the picture shows the sample that is being tested, the middle of the picture shows the sample in a linear polariscope, and the right side of the picture shows the sample in a circular polariscope.

Figure 5.1 shows the sample with no added stress concentrators. This can be considered the control sample for this device. The image shows the effect that the mounting holes have on the stress patterns of the samples. Each end of the sample is severely affected by these stress concentrators, so any patterns seen in this area on any of the other samples must be ignored. The middle of the sample is unaffected by the stress concentrations created by the mounting holes.

Initially the mechanism that is used to apply tension would also apply torque to the samples. This happened because the hook with the knob was not supported on the sides and would turn with the handle causing a torque to occur. The team made a couple of supports to go on either side of the hook, made of steel, so the hook would not turn but would run into these supports keeping the hook vertical with no torque acting on the samples. These supports also made it easier to turn the knob and add higher tensile loads.

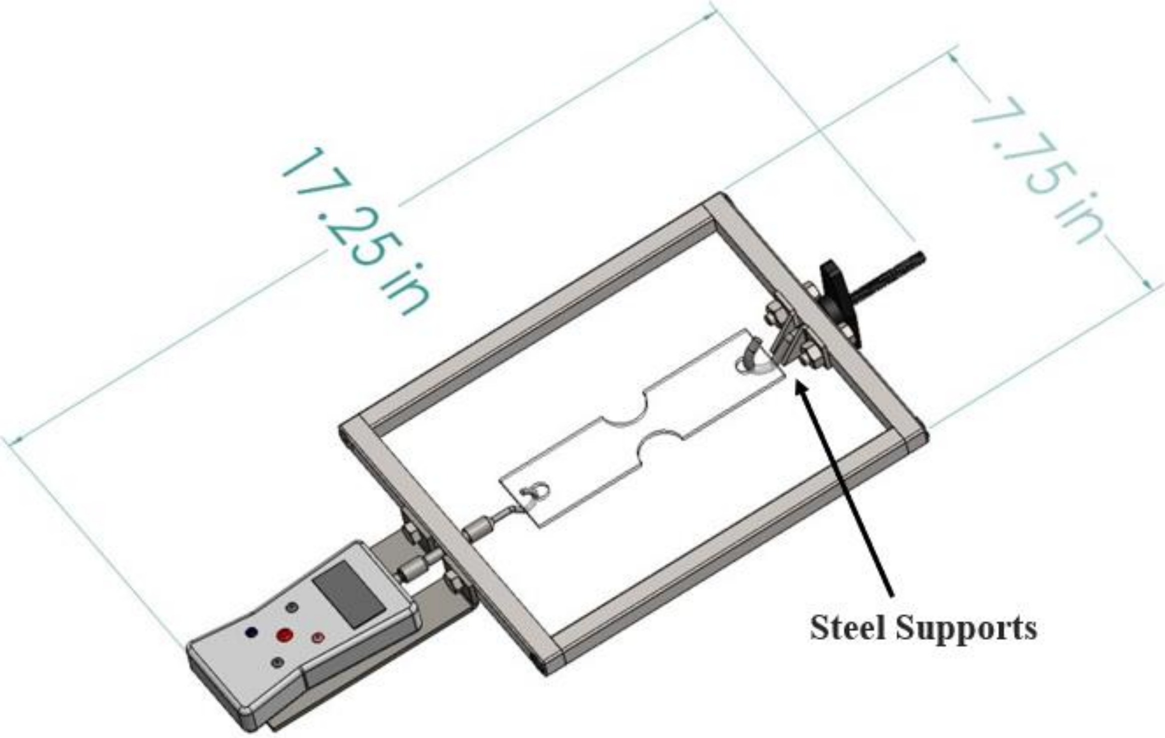

Figure 5.1. Steel Supports for Hook

Figure 5.2. Control Sample with No Added Stress Concentrations Under 40 Pounds of Tension

Figure 5.3. Sample with Notched Radius of 0.125 in. Under 40 Pounds of Tension

Figure 5.4. Sample with Notched Radius of 0.25 in. Under 40 Pounds of Tension

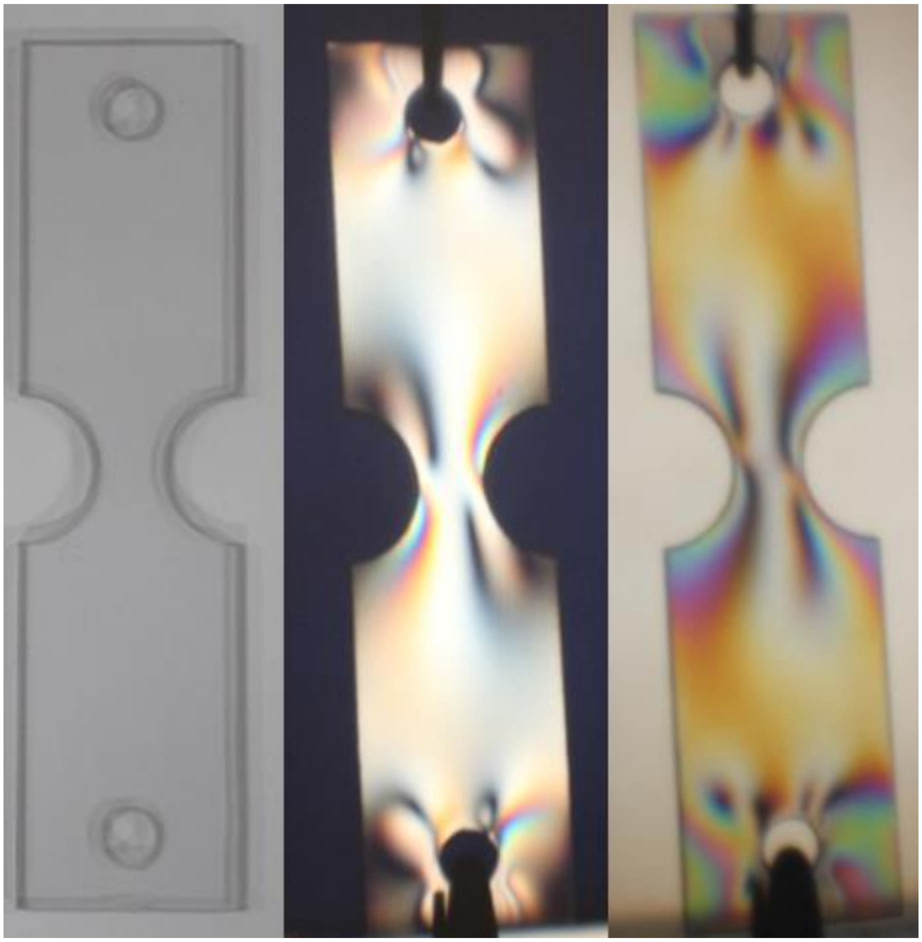

Figure 5.5. Sample with 0.5 in. Radius Half-Circle Cutouts Under 40 Pounds of Tension

Figure 5.6. Sample with 1 in. Radius Half-Circle Cutouts Under 40 Pounds of Tension

Figure 5.7. Sample with 0.5 in. Diameter Hole in Center Under 40 Pounds of Tension

Figure 5.8. Sample with 1 in. Diameter Hole in Center Under 40 Pounds of Tension

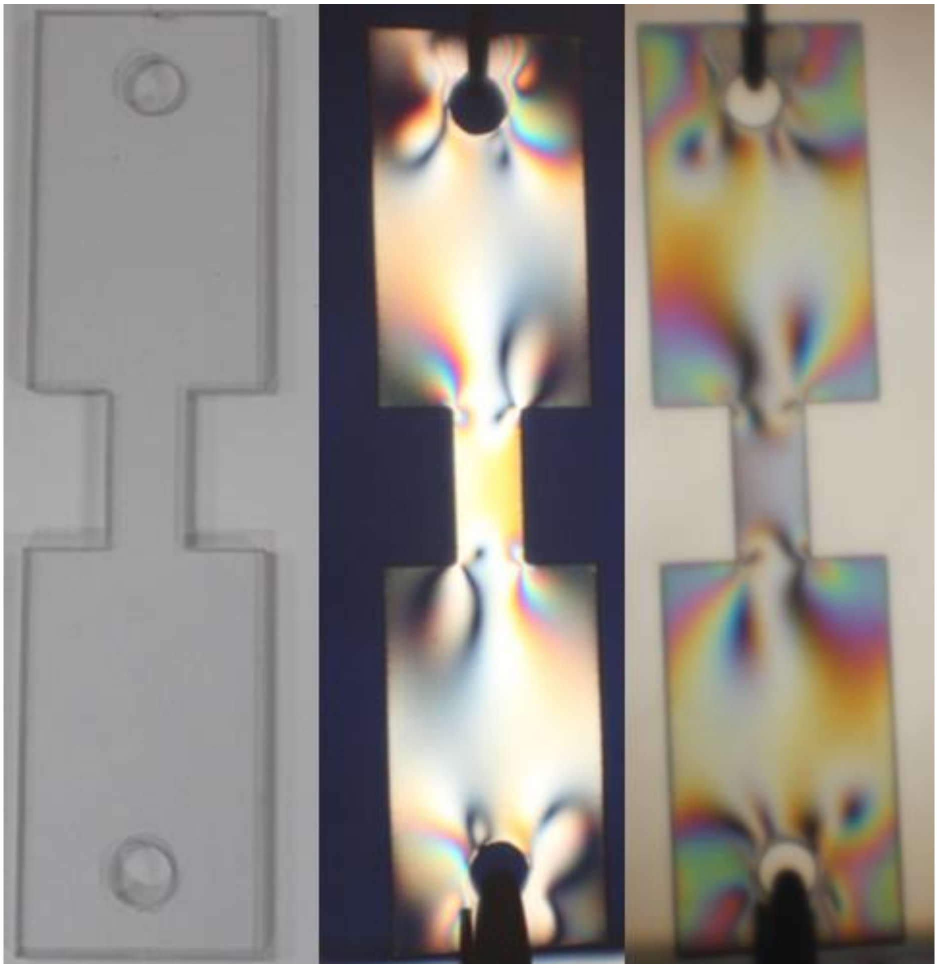

Figure 5.9. Sample with 1 in. x 0.5 in. Rectangular Cutouts Under 40 Pounds of Tension

Figure 5.10. Sample with Triangular Cutouts Under 40 Pounds of Tension

6 Conclusion and Lessons Learned

An engineer can model and predict stresses and strains using complicated equations, but by using the photoelastic effect anyone can see the true strains and stresses no matter how small. Using the photoelastic effect would be a great teaching device for people, especially engineering students, to visually see the stresses and strains in objects in tension or compression. Birefringence in an object will impose two different refractive indices on light passing through. This is caused by anisotropic properties of the material or caused by the stresses in transparent materials [2]. Photoelasticity uses light to shine through a transparent material with birefringent properties and uses a polarized film to display the principal strains and stresses by showing colorful strands in the material. The photoelastic effect can sometimes be used to measure the stresses and strains on the surface of a part [3].

By executing this project, the team learned that the device is sensitive to loadings other than tension. Specifically, torque creates a very colorful effect, but it removes any possibility of the force gauge getting an accurate reading. The force gauge is only intended to read the amount of tension being applied to the sample. It is unable to account for any other type of loading. As such, it was found necessary to design a system to mitigate the possibility of torque being applied to the samples.

As seen in some of the imagery, the circular polariscope seems to be much more colorful than the linear polariscope. The camera struggles to focus on the circular polariscope projection because the light is much more intense than that of the polariscope. When photographing the photoelastic effect, it may be beneficial to use a linear polariscope rather than a circular polariscope.

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APPENDICES

APPENDIX A

Table A.1. Project Schedule

Date	**Event**
14-Jan	Advising Meeting
19-Jan	Advising Meeting
26-Jan	Advising Meeting
2-Feb	Advising Meeting
9-Feb	Advising Meeting - Critical Design Review (Delayed)
11-Feb	Acquire Materials - Purchase Projector and Materials for Frame Construction
14-Feb	Inspect Projector - Make Sure Light Source Functional
16-Feb	Advising Meeting - Critical Design Review
17-Feb	Cut Samples at AEC
23-Feb	Advising Meeting
25-Feb	Cut Acrylic and Polarizers, Prepare Frame Materials (DELAYED)
2-Mar	Advising Meeting (ZOOM)
4-Mar	Construct Frame (DELAYED)
9-Mar	NO MEETING - Spring Break
16-Mar	Advising Meeting, PURCHASE REQUEST
18-Mar	Construct Load Applying Mechanism and Test Fit (DELAYED)
23-Mar	Advising Meeting
24-Mar	Parts Delivery Expected

29-Mar	Construct Frame and Load Applying Mechanism (AEC)
30-Mar	Advising Meeting
1-Apr	Design Presentation Review
6-Apr	Cut Film Clamps (AEC), Quarter-Wave Films Expected Arrival, Advising Meeting
7-Apr	Complete Construction and Confirm Operability, Finish Report First Draft
8-Apr	Report First Draft Due
13-Apr	Advising Meeting
17-Apr	Finish Report Second Draft
20-Apr	Advising Meeting, Report Second Draft Due
22-Apr	Final Presentation Due
27-Apr	Advising Meeting, Finish Report for Final Submission
28-Apr	Final Report Due and Poster Session
6-May	Semester Ends

APPENDIX B

Table B.1. Project Budget

Photoelastic Effect Demonstration Device Parts Budget					
Supplier	**Part Descprition**	**Item Number**	**Price**	**Qty**	**Subtotal**
Edmund Optics	8.5" x 15" Linear Polarizing Film	19-292	$ 53.50	1	$ 53.50
Edmund Optics	300 x 300mm, λ/4 Retarder Film (WP140HE)	88-253	$ 97.50	2	$ 195.00
Home Depot	1/2 in. W x 1/2 in. H x 96 in. L Aluminum C-Channel with 1/16 in. Thick	802657	$ 10.98	1	$ 10.98
Home Depot	3/4 in. x 36 in. Plain Steel Flat Bar with 1/8 in. Thick	801767	$ 3.76	2	$ 7.52
Home Depot	1/4 in.-20 tpi x 36 in. Stainless-Steel Threaded Rod	802477	$ 6.40	1	$ 6.40
Home Depot	1/4 in. - 20 Thru Knob (5-Pack)	QNB3001	$ 9.99	1	$ 9.99
Home Depot	1/4 in. x 4-1/4 in. Steel Clothesline Hook	807116	$ 1.31	1	$ 1.31
Amazon	500N Force Gauge	VTSYIQI	$ 95.99	1	$ 95.99
AEC	1/2 in. x 1/2 in. x 48 in. Plain Steel Square Tube		$ -	1	$ -
AEC	1/4 in.-20 tpi x 1 in. Socket Head Screw		$ -	4	$ -
AEC	1/4 in.-20 tpi Polymer Insert Lock Nut		$ -	10	$ -
AEC	1/4 in.-20 tpi x 1 in. Hex Head Bolt		$ -	2	$ -
AEC	1/8 in. x 48 in. x 20 in. Lexan		$ -	1	$ -
USI	3M Overhead Projector		$ -	1	$ -
Subtotal for Complete Polariscope with Samples					
			N/A	N/A	$ 380.69

APPENDIX C

Instruction Manual

1. Place the overhead projector about 3 feet - 12 feet from the wall or screen.
2. Plug the 120 V overhead projector into an outlet or extension cord if needed.
3. Place the polariscope on top of the overhead projector if it is not already on there and then on the overhead projector using the orange on and off switch on the front of the projector.
4. Decide if you would like to use a linear or circular polariscope.
5. If you would like to use a linear polariscope ensure only the two black linear polarizers are on the frame, one above the tension mechanism and one below.
   a. Make sure they are rotated 90 degrees from each other. It will look dark and let little to no light through. All films have a marking indicating their axis.
6. If you decide to use a circular polariscope ensure you have all the films on the frame, one of each below and above the tension mechanism.
   a. Make sure first you have a linear polarizer, then a quarter wave film rotated 45 degrees from the linear polarizer, then the tension mechanism, then another quarter wave film rotated 90 degrees from the first quarter wave film, finally put the last linear polarizer on top rotated 45 degrees from the quarter wave film and in line with the bottom linear polarizer. All films have a marking indicating their axis.
7. Pull the tension mechanism out of its channel and insert a sample onto the hooks and turn on the force gage.
8. Use the knob on the head of the projector to move it up and down until the image is in focus.
9. Apply a minimum of 20 lbs. of tension or a maximum of about 100 lbs. of force using the black knob by turning it clockwise.
10. Observe the image.
11. When done with the demonstration turn the black knob counterclockwise to relieve the tension.

12. Pull out the tension mechanism and take out the sample or swap out a sample for another. Then turn off the force gage if you are done and place the mechanism back into slots.

13. Turn off the projector using the orange switch on the front of the overhead projector.

14. Unplug the overhead projector and return it to its storage area.

APPENDIX D

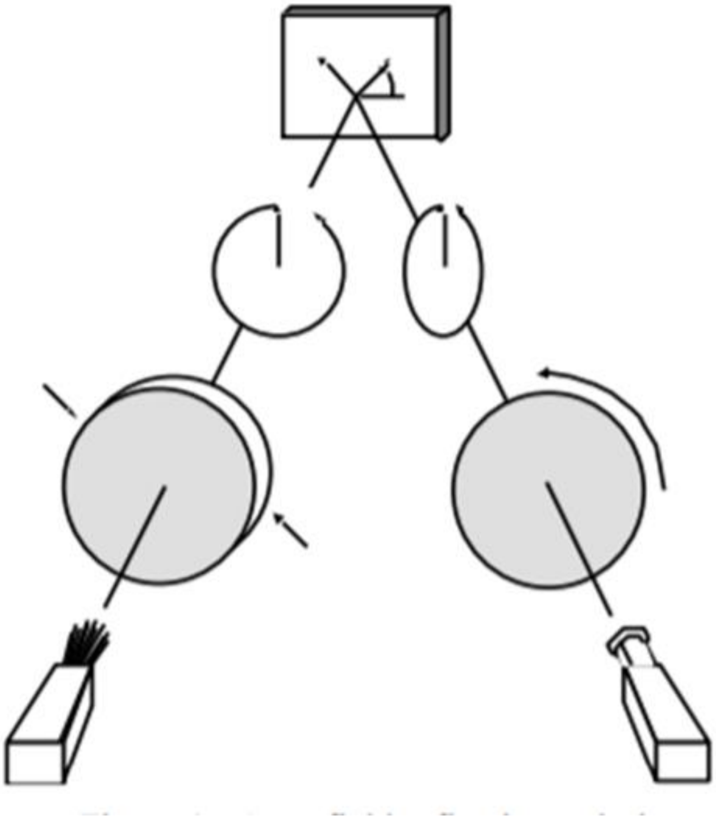

Figure D.1. Grey-field reflection polariscope [4]

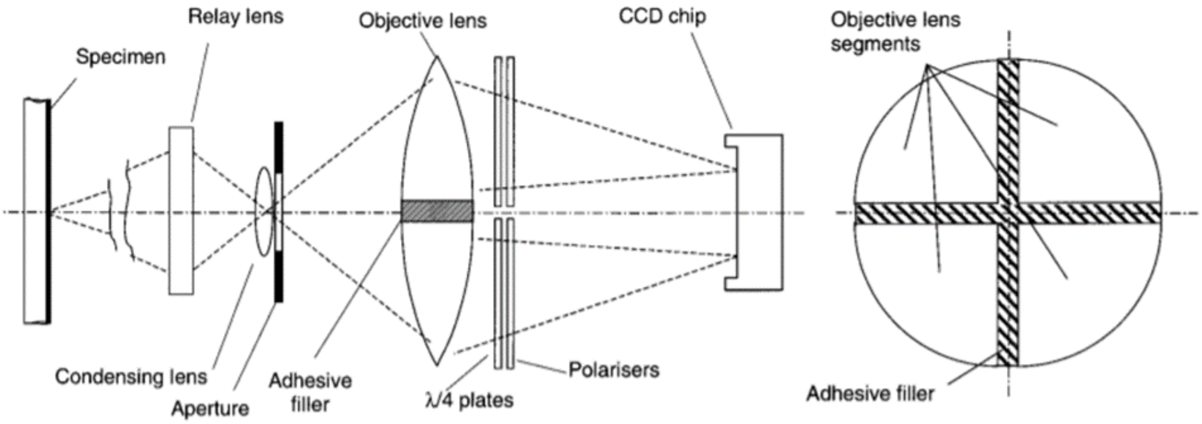

Figure D.2. Poleidoscope [5]

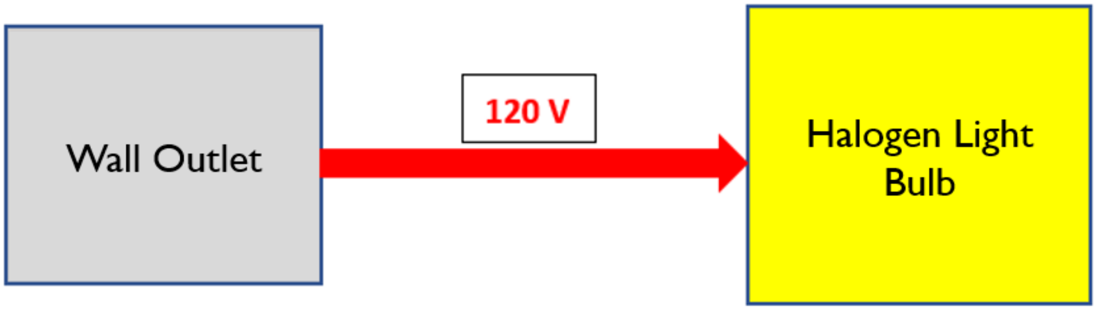

Figure D.3. Functional Block Diagram

Figure D.4. Polariscope on Overhead Projector (Angle 1)

Figure D.5. Polariscope on Overhead Projector (Angle 2)

APPENDIX E

Table E.1. Failure Modes and Effects Analysis

Item	**Failure Modes**	**Cause of Failure**	**Possible Effects**	**Likelihood**	**Level**	**Possible Action**
Frame	Cannot be Assembled	a. Miscalculations in design b. Production errors c. Damaged parts during transportation d. Ordered parts have delayed delivery	Project not functional to end user	middle	critical	Teammates will check all calculations to reduce errors in design. Inspection of parts before assembly.
Frame	Tensile Failure	a. Frame members are overloaded b. Crack Propagations on frame members	Physical harm to end user, destruction of project	low	critical	Carefully design frame with adequate factor of safety. Inspect all parts before assembly for damage.
Light Source	Insufficient Output	a. Dirty lens b. Not enough power	Effect may be difficult for user to see	low	moderate	Ensure all components are clean. Make calculations for required light before purchasing parts.
Lens	Fracture	a. Damage during shipping b. Improper handling c. Stresses applied	Result may be distorted or impossible to see	low	moderate	Order parts ahead of time if possible. Check for damage when received.
Load Mechanism	Compressive Failure	a. Components are overloaded b. Damaged Components c. Poorly Designed Mechanism	User will be unable to apply stresses to test samples	middle	moderate	Simulate motion of the mechanism before assembly. Inspect components for damage.

APPENDIX N

Table N.1. Design Factors Considered

Design Factor	Page number, or reason not applicable
Public health safety, and welfare	45, instructions for safe operation
Global	Not applicable, has no global effect
Cultural	Not applicable, has no cultural effect
Social	Not applicable, has no social impact
Environmental	Not applicable, has no environmental impact
Economic	44, budget
Professional Standards	13, weight of device