Shear Stress Sensor Design

EML 4551C-Senior Design- Fall 2012

FINAL DESIGN REPORT

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Executive Summary

The senior design project, *Shear Stress Sensor Design,* is a project sponsored by Dr. Benjamin Dickinson at Eglin Air Force Research Laboratories. The purpose for the project is to design a sensor that has the capabilities to decouple pressure and shear force and be affordable for mass production. There is a need for an accurate shear stress sensor because the shear force is directly related to the drag on an air vehicle. With the ability to know the shear forces being applied on the vehicle, an adjustment can be made to lessen the drag; which saves fuel consumption for the aircraft. Current shear stress sensors have issues in which their practicality is only in lab use, i.e. debris causing error and complexity of calculation, or not cost effective for mass production. Cholesteric crystals will be used to perform the task of measuring shear force because of their visual properties. When a force is applied to cholesteric crystals the pitch of the crystals changes, thus changing the color that is reflected.

To create a pure shear force, a linear servo is used to transmit motion to a shear block which then applies the force to cholesteric crystals. Since the shear block will need to be in contact with the liquid crystals, a light emitting diode (LED) will be required at the base to reflect light through a slot in the baseplate. To collect all of the data from the reflected light, a fiber optic cable connected to a USB spectrometer will determine the wavelengths of the reflected light, and then display a graph on a computer. Once experiments are completed, a relation will be found between the voltage applied and wavelength received. The voltage from the load cell can be converted to the force applied by the servo motor, which can be used to determine the shear stress applied to the specimen. If the experiment is successful in correlating the shear force to wavelength, further experimentation on a polymer cholesteric crystal will be performed. The reasoning behind testing a polymer is because the liquid crystal has the ability to be displaced with motion.

The testing procedure and testing apparatus concept was created by a graduate assistant over the summer but never completed. To complete the design a holder is required for the LED and fiber optic cable, a shear block, and a method to measure angles for the LED and fiber optic cable. After preliminary experimentation with the LED and fiber optic cable, it was found that the angle between the two is important because the spectrometer can only read the crystals when the LED's light is reflecting directly into the spectrometer.

All parts have been machined and ordered. As previously stated some of the preliminary testing has been conducted like the calibration of the load cell and spectrometer/LED calibration.

For the upcoming spring semester, testing and analysis of the project will be carried out to see how the liquid crystals are affected by the shear forces.

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Introduction

There currently isn't a small, inexpensive, and accurate method of measuring shear stress. The current methods aren't able to decouple the normal force from the shear force. It is hypothesized that normal and shear forces can be decoupled by measuring the light emitted from cholesteric crystals attached to a body undergoing a shear force. The project topic was thought up by Dr. Oates of Florida State University. Dr. Dickinson of Eglin Air Force Base realized that this is a very important problem that needed to be solved and offered to finance our project. The current testing apparatus, created by Dr. Oates and his research assistant Matt Worden, is partially completed and needs to be completed before any testing can begin. Once we complete the apparatus we can begin research on whether cholesteric crystals can accurately measure shear stress better than the other methods existing today.

Project Scope:

Needs Assessment:

A testing apparatus for cholesteric crystals is required to determine if the crystals are able to be used as a consistent visual meter for shear stress.

Problem Statement:

There currently isn't a shear stress sensor that only measures shear stress. The current methods unintentionally measure part of the normal component of pressure on the body as the shear stress. The current methods are also large and expensive. The cholesteric crystals attributes indicate that they might be able to only measure the shear component of stress; decoupling the shear from the normal stress. The cholesteric crystals can also be modularly attached to materials and measured with only a fiber optic spectrometer. This would make it possible to cheaply measure shear stresses outside of the lab environment.

Background:

The liquid crystals are not a new item, but they have never been used to find shear stress. Dr. Dickinson from Eglin Air Force Base is our sponsor providing us with the funds for the project. However our faculty advisor Dr. Oates will be providing most of the background information along with a lab and materials. The physical design will be to create a testing apparatus, but the data collected during experiments will be the bulk of our effort. The data collected will show how cholesteric crystals react to shear stress under various conditions. Eglin and Dr. Oates both hope to use this data to determine if this method of testing shear stress is viable for use on aircraft, underwater applications, robots, and other equipment. There are currently other shear stress sensors existing, but there isn't a method that is widely used and simple. There currently isn't much research in regards to using liquid crystals for sensing shear stress but there is a patent for the cholesteric crystals in the form of a polymer.

Previous Technology:

In the past few years, skin friction has become an important parameter in the aircraft industry because a reduction in drag directly correlates to a reduction in fuel consumption. As a result, many techniques for measuring shear stress have risen; but scientists are still having challenges with them. Some can only be used just in laboratories while others are very expensive. In the upcoming section different methods for measuring shear stress will be presented along with their advantages and disadvantages.

MEMS-based techniques

Microelectromechanical systems (MEMS) are, by definition, devices that have been fabricated using silicon micromachining technology. In general, it allows high resolution, time-resolved and quantitative fluctuating turbulence measurements in a controlled wind tunnel environment. However, the open nature of these sensors is not well suited for dirty environments in which debris may be trapped in the sensor gaps.

The three types of MEMS sensors are direct sensors, thermal sensors and laser based sensors. An example of direct sensors is shown in the figure below. In this case, the displacement of the floating element is a function of wall shear-stress. Therefore, it can measure the integrated force produced by the wall shear stress on a flush movable "floating" element.

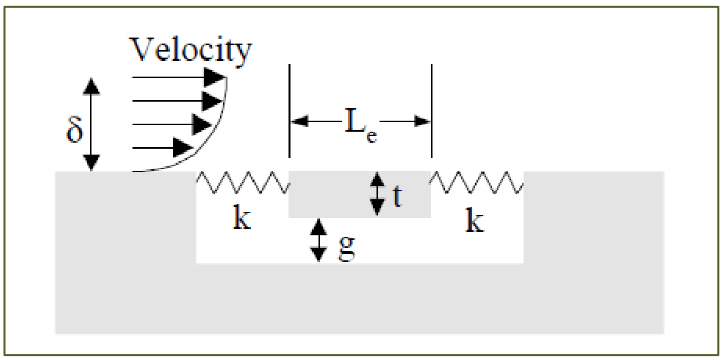


Figure 1- MEMS Direct Sensor (Naughton)

Thin-Oil-Film techniques

Thin-oil-film is a quasi-direct means of measuring skin-friction where the motion of the oil film is sensitive to shear-stress, gravity, pressure gradients, surface curvature of the oil and surface tension. As fluid passes over the model, the oil thins. To quantify the thinning rate of the oil, the oil thickness "h" is measured, normally via interferometry. It is possible to correlate the measurement of the oil thickness to local skin-friction using a form of the thin-oil-film equation.

The figures below show the interference fringes in interferometry and a schematic of an image-based oil-film technique. The common components of the measurement apparatus are the light source, a detector camera and a suitable model surface.

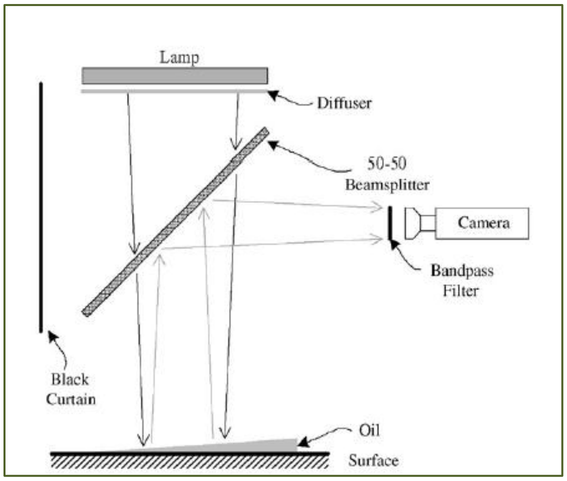


Figure 2- Schematic of image based oil film technique (Naughton)

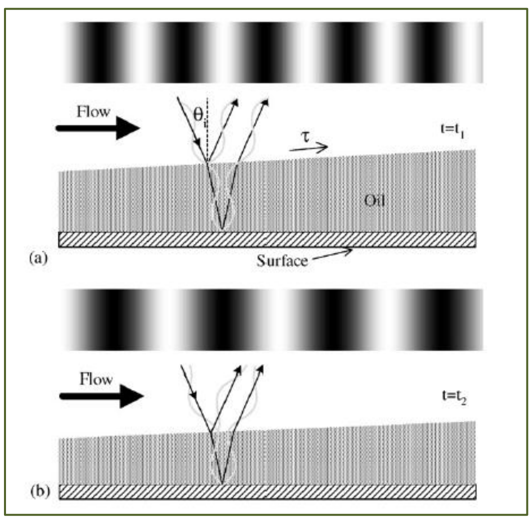


Figure 3- Interferometry finges (Naughton)

Single points, line, 1D and 2D techniques are examples of Thin-oil-film shear stress measurement. The advantages vary depending on the method selected, but the main limitation is the optical access required.

Liquid crystals coating techniques

Liquid crystals are a group of substances that display characteristics of both liquids and solids. When a shear stress is applied to the crystals, there is a change in the birefringence and also a selective reflection of light from the liquid crystal layer. The major classifications are isotropic, pneumatic and chiral/cholesteric. From these cholesteric is the material with more important properties to changing forces.

One of the advantages is that, as it does not need electricity, it can be used in dirty environments. However, some limitations such as the color dependence on illumination and observation angles, as illustrated in the figure below, constitute a problem for scientists who want to apply this technology outside the laboratory. As a result, the optical access, calibration and accuracy have to be considered before its use.

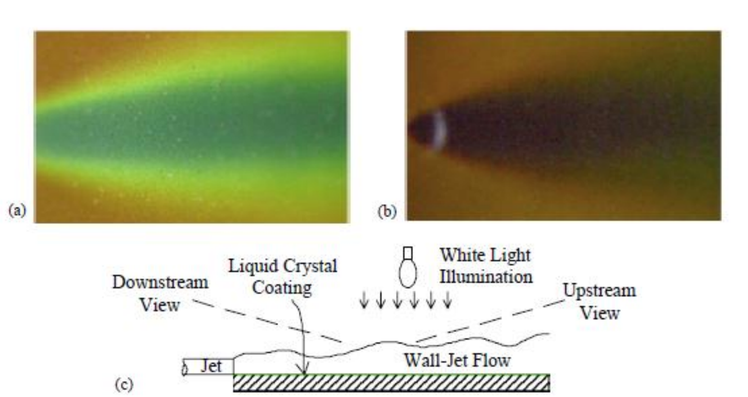


Figure 4- Viewed from different points, distinct change in color is observed (Naughton)

Devices for the measurement of light reflected from the crystal as the following have been developed. Figure 5 shows a patent scheme based on a laminate structure of a crystal polymer substrate attached to a test surface of an article.

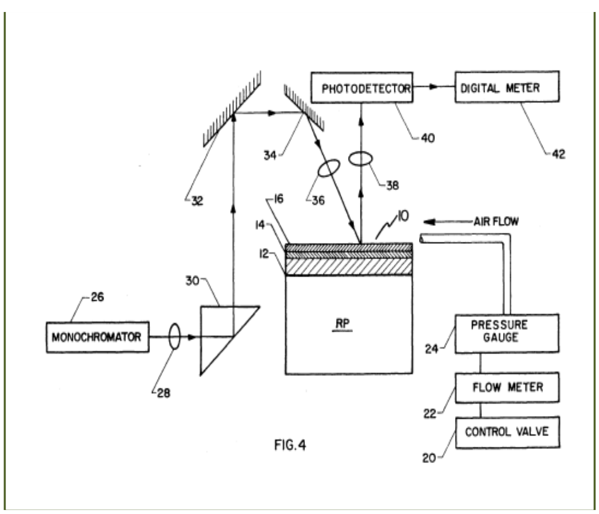


Figure 5- Patent 5223310 – Shear stress measurement apparatus (Singh)

THEORY

To model the problem described, two kinds of loads were studied. For the first one, which is constant through the domain x, the plane theory can be applied. For the second, represented by oscillating load, the Timoshenko equations and boundary conditions are more appropriate. Both distributions can satisfy the real case, depending on the way in which the experiment is executed.

Constant Load

The problem that will be analyzed can be simplified applying the plane strain theory when a constant load is applied. In this case, the strain normal to the x-y plane ε_z, and the shear strain $\varepsilon_{xz}$and ε_{yz} are assumed to be zero. This assumption can be done because the dimension of the structure in one direction (z), is very large in comparison with the dimensions of the structure in the other two directions (x and y coordinates axes).

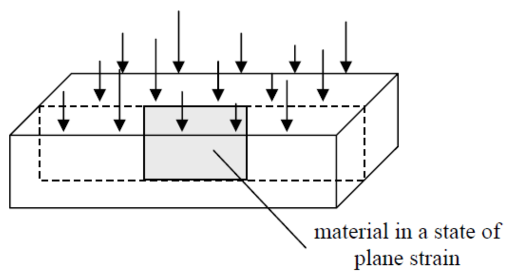


Figure 6-Section of the structure in Z direction. Material in a state of plane strain

The strong form for solid mechanics problems is set below:

Equation 1

$$\rho f_x + \left(\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y}\right) = \rho\, \ddot{u}_x$$

Equation 2

$$\rho f_y + \left(\frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y}\right) = \rho\, \ddot{u}_y$$

Where σ is the stress, u is the displacement, ρ is the density and f is the problem function. As in this case the problem is stationary, $\ddot{u}$ is zero. In addition, f is also zero. Recalling the equations for the Hook's Law,

Equation 3

$$\varepsilon_{xx} = \frac{1}{E}\left(\sigma_{xx} - \nu\left(\sigma_{yy} - \sigma_{zz}\right)\right)$$

Equation 4

$$\varepsilon_{yy} = \frac{1}{E}\left(\sigma_{yy} - \nu\left(\sigma_{xx} - \sigma_{zz}\right)\right)$$

Equation 5

$$\varepsilon_{zz} = \frac{1}{E}\left(\sigma_{zz} - \nu\left(\sigma_{xx} - \sigma_{yy}\right)\right)$$

Equation 6

$$\varepsilon_{xy} = \frac{1}{2G}\sigma_{xy}\varepsilon_{xz} = \frac{1}{2G}\sigma_{xz} \quad \varepsilon_{yz} = \frac{1}{2G}\sigma_{yz}$$

Where ε is the strain and σ the stress. The x, y and z corresponds to the axes. To solve the problem, the simplifications described must be applied to these equations. Another characteristic of this assumption is that the loads are uniformly distributed with respect to the large dimension and act perpendicular to it, as shown in Figure 7. The quantitative value of both pressure and shear loads is 0.5 Pa, which represents a real experimental value. Figure 7 shows a scheme of the problem. The value for c is related to the thickness and L, to the length. The thin film modeled is subjected to a constant pressure and shear load.

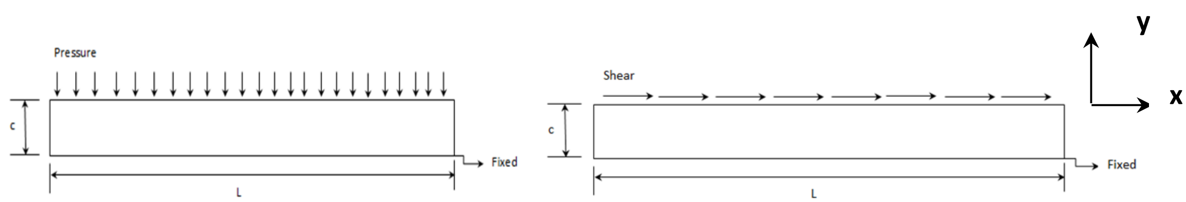


Figure 7-Scheme of the physical system of a thin film

Oscillating Load

For an oscillating load, the Timoshenko equations must be applied. These equations were developed based on the plane strain theory, but with a sine and cosine boundary conditions. For both, stress and shear, the equations are shown below.

Equation 7

$$\sigma_x = \sin\alpha x[C_1\alpha^2\cosh(\alpha y) + C_2\alpha^2\sinh(\alpha y) + C_3\alpha(2\sinh(\alpha y) + ay\cosh(\alpha y)) \; + \; C_4\alpha\left(2\cosh(\alpha y) + \alpha y\sinh(\alpha y)\right)$$

Equation 8

$$\sigma_y = -\alpha^2\sin\alpha x[C_1\cosh(\alpha y) + C_2\sinh(\alpha y) + C_3 y\cosh(\alpha y) \; + \; C_4 y\sinh(\alpha y)$$

Equation 9

$$\tau_{xy} = -\alpha\cos(\alpha x)[C_1\alpha\sinh(\alpha y) + C_2\alpha\cosh(\alpha y) + \; C_3\left(\cosh(\alpha y) + \alpha y\sinh(\alpha y)\right) + C_4\left(\sinh(\alpha y) + \alpha y\cosh(\alpha y)\right)$$

Where $\alpha=(4\pi/L)$, and L is the film length.

Constants C depends on the boundary conditions of each load distribution. For the pressure load, the values for the top and bottom are:

Equation 10

$$\boldsymbol{For\ y = \ +c}$$

$$\sigma_y = -B\sin(\alpha x)$$

Equation 11

$$\boldsymbol{For\ y = \ -c}$$

$$\sigma_y = -A\sin(\alpha x)$$

For the equations above, the unit normal has to be considered when implemented in the FEM software.

Consequently, the resultant constants are:

Equation 12

$$C_1 = \left(\frac{A+B}{\alpha^2}\right)\frac{\sinh(\alpha c) + (\alpha c)\cosh(\alpha c)}{\sinh(2\alpha c) + 2\alpha c}$$

Equation 13

$$C_2 = \left(\frac{A+B}{\alpha^2}\right)\frac{\cosh(\alpha c) + (\alpha c)\sinh(\alpha c)}{\sinh(2\alpha c) - 2\alpha c}$$

Equation 14

$$C_3 = \left(\frac{A-B}{\alpha^2}\right)\frac{(\alpha)\cosh(\alpha c)}{\sinh(2\alpha c) - 2\alpha c}$$

Equation 15

$$C_4 = \left(\frac{A-B}{\alpha^2}\right)\frac{(\alpha)\sinh(\alpha c)}{\sinh(2\alpha c) + 2\alpha c}$$

Similarly, for the shear load, the values for the top and bottom are:

Equation 16

$$\boldsymbol{For\ y = +c}$$

$$\tau_{xy} = -Bcos(\alpha x)$$

Equation 17

$$\boldsymbol{For\ y = -c}$$

$$\tau_{xy} = -Acos(\alpha x)$$

For the equations above, the unit normal has to be considered when implemented in the FEM software.

Consequently, the resultant constants are:

Equation 18

$$C_1 = \frac{(A-B)(c)\sinh(\alpha c)}{\alpha(2c\alpha + \sinh(2c\alpha))}$$

Equation 19

$$C_2 = -\frac{(A+B)\,(c)cosh(\alpha c)}{\alpha(-2c\alpha + \sinh(2c\alpha))}$$

Equation 20

$$C_3 = \frac{(\mathrm{A+B})\sinh(\alpha c)}{\alpha\,(-2c\alpha + \sinh(2c\alpha))}$$

Equation 21

$$C_4 = -\frac{(\mathrm{A-B})\cosh(\alpha c)}{\alpha(2c\alpha + \sinh(2c\alpha))}$$

Figure 8 shows a scheme of the problem. The value for c is related to the thickness, L to the length and A, to the load amplitudeof an oscillating pressure and shear load.

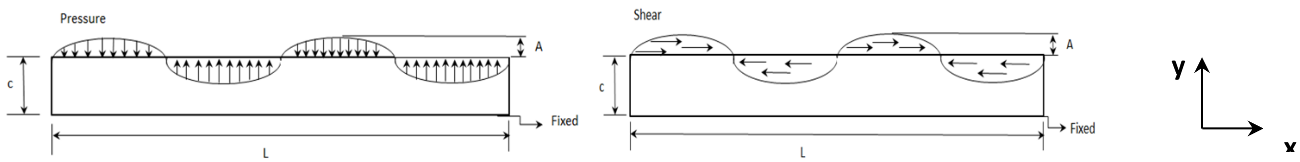


Figure 8-Scheme of the physical system of a thin film

COMSOL

One of the methods for shear stress measurement is executed through a liquid crystal thin film. This material has properties that allow a correlation between the load applied and the wavelengths reflected. However, one of the problems of this method is that the load applied at the top may not correspond to the load at the bottom, where the spectrometer is located. As a result, if it happens, the correlation will not provide accurate information. To ensure that the experimental results of the correlation correspond to the applied load, in this section will be studied a liquid crystal thin film FEM model. In addition, will be compared the stress through the domain x considering a constant and an oscillating load.

Starting from the strong form in Equation 1 and Equation 2, after integrating by parts the final weak form can be written as

Equation 22

$$\int_{\Omega} \left[\left(-\frac{\partial w_1}{\partial x}\sigma_{xx} - \frac{\partial w_1}{\partial y}\sigma_{yy}\right)\right] dV + \int_{\Gamma} w_2(\sigma_{xx}n_x + \sigma_{xy}n_y)dS = 0$$

Equation 23

$$\int_{\Omega} \left[\left(-\frac{\partial w_2}{\partial x}\sigma_{xy} - \frac{\partial w_2}{\partial y}\sigma_{yy}\right)\right] dV + \int_{\Gamma} w_2(\sigma_{xx}n_x + \sigma_{yy}n_y)dS = 0$$

Where $w_1$andw_2 are the weight functions for x and y and $n_x$and n_y are the normal vectors. The final matrix for the thin film problem considering the plane strain theory is set below:

Equation 24

$$\varepsilon_{zz} = \varepsilon_{xz} = \varepsilon_{yz} = 0$$

$$\sigma_{xz} = \sigma_{yz} = 0$$

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{bmatrix} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} (1-\nu) & \nu & 0 \\ \nu & (1-\nu) & 0 \\ 0 & 0 & \left(\frac{1-2\nu}{2}\right) \end{bmatrix} \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{xy} \end{bmatrix}$$

Another form to write this matrix is

Equation 25

$$\sigma_{xx} = c_{11}\varepsilon_{xx} + c_{12}\varepsilon_{yy}$$

Equation 26

$$\sigma_{yy} = c_{12}\varepsilon_{xx} + c_{11}\varepsilon_{yy}$$

Equation 27

$$\sigma_{xy} = c_{66}\varepsilon_{xy}$$

Where $c_{11} = 6.73\ x\ 10^8 (Pa)$, $c_{12} = 2.88\ x\ 10^8\ (Pa)$ and $c_{66} = 1.92\ x\ 10^8\ (Pa)$ for liquid crystals.

After setting up the equations, the model was implemented in the COMSOL software. The geometry used was a rectangle of $8.56\ x\ 10^{-4} m\ x\ 2m$, and liquid crystal was selected as a material. Figure 9 shows the boundary load and the fixed constraint in the geometry. Figure 9Figure 10 shows the liquid crystals properties.

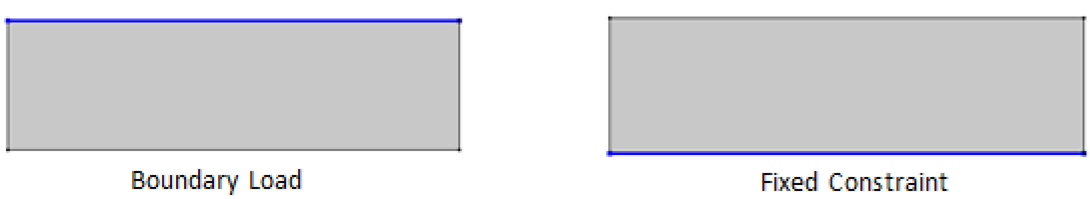


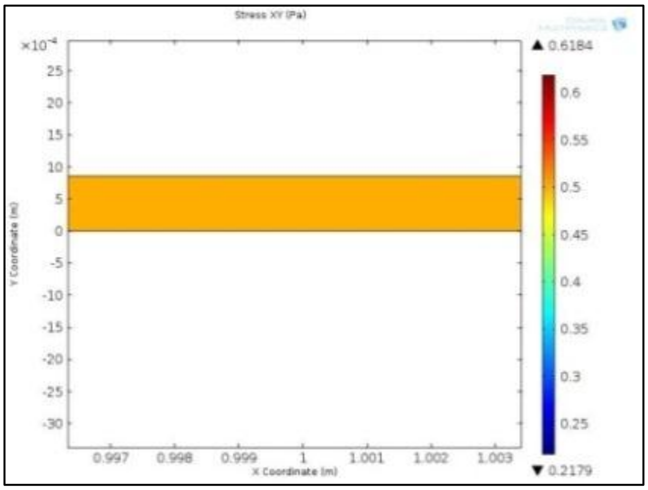
Figure 9-Boundary load and fixed constraint in the geometry selected.

Material	v	E (GPa)
Liquid Crystals	0.3	0.5

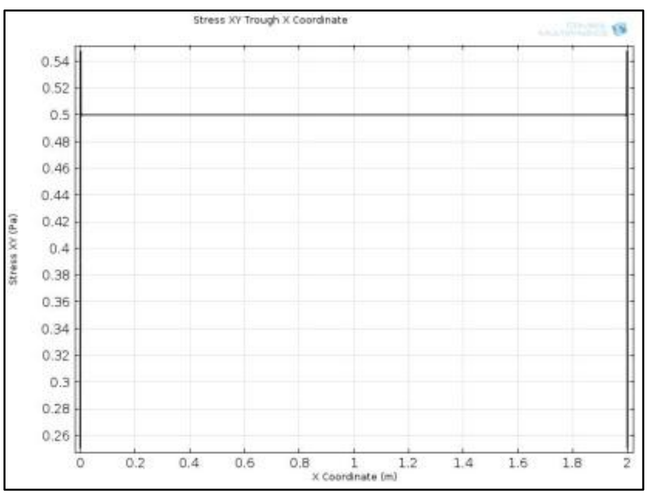
Figure 10- Liquid Crystal Properties

Regarding to the boundary load, was considered a load of -0.5 (Pa) (pressure) and 0.5 (Pa) (shear) in the constant load problem simulation. In addition, for the oscillatory problem, the boundary conditions in the Equation 10, Equation 11, Equation 14 and Equation 15 were applied for pressure and shear respectively. The value assumed for A and B constants were 0.5.

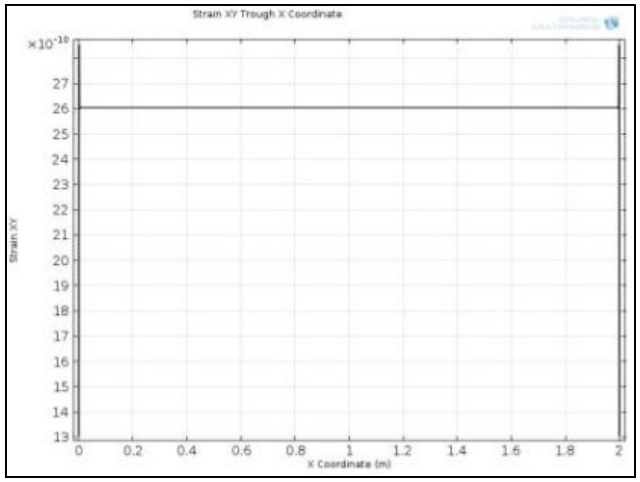
The results for a shear load of 0.5(Pa) are shown below. The curves plotted correspond to strain and stress in XY through the domain x. The verification can be done substituting the materials properties and the numerical value for the middle point of the geometry in Equation 27. The stress calculated must be equal to the FEM stress in the simulation.



(a)



(b)



(c)

Figure 11- FEM simulation of a shear load of 0.5(Pa).

The geometry is a rectangle with 8.56 x 〖10〗^(-4) m x 2m . (a) Stress distribution in 2D. (b) Stress XY distribution through the domain (x, 8.56 x 〖10〗^(-4)). (c) Strain XY distribution through the domain

Verification through the surface – Recalling Equation 27,

$$\sigma_{xy} = c_{66}\varepsilon_{xy}$$

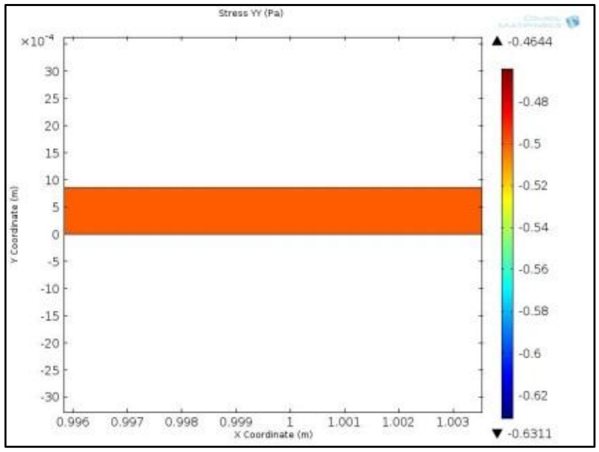
$$\varepsilon_{xy\ numerical} = 26x10^{-10}$$

$$\sigma_{xy\ analytical} = (1.92x10^{8})\ (26x10^{-10}) = 0.4992 \text{ Pa}$$

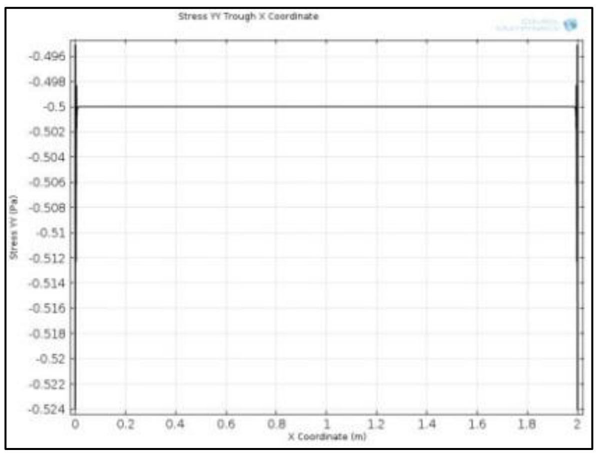
$$\sigma_{xy\ numerical} = 0.5\ Pa$$

$$\sigma_{xy\ numerical} \simeq \sigma_{xy\ analytical}$$

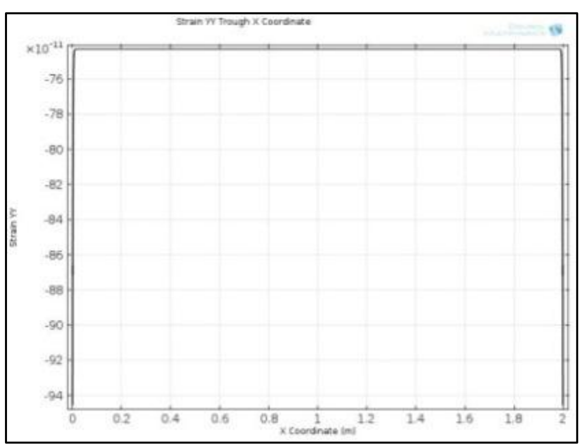
Similarly, for a pressure load of -0.5 Pa, the resultant graphics for YY component are shown below. The verification can be done substituting the materials properties in Equation 26.



(a)



(b)



(c)

Figure 12-FEM simulation of a pressure load of -0.5Pa.

The geometry is a rectangle with 8.56 x 〖10〗^(-4) m x 2m. (a) Stress distribution in 2D. (b) Stress YY distribution through the domain (x, 8.56 x 〖10〗^(-4) m). (c) Strain YY distribution through the domain.

Verification – Recalling Equation 26

$$\varepsilon_{xx\ numerical} = 1.0\ x\ 10^{-11}$$

$$\varepsilon_{yy\ numerical} = -76.9x10^{-11}$$

$$\sigma_{yy} = c_{12}\varepsilon_{xx} + c_{11}\varepsilon_{yy}$$

$$\sigma_{yy} = (2.88\ x\ 10^{8})(1.0\ x\ 10^{-11}) + (6.73\ x\ 10^{8})(-76.9x10^{-11})\ Pa$$

$$\sigma_{yy\ numerical} = -0.514\ Pa$$

$$\sigma_{yy\ numerical} \simeq \sigma_{yy\ analytical}$$

Analyzing the oscillating load, comparing the simulation to the Timoshenko Equation 7, Equation 8, and Equation 9, the results for the shear are shown below.

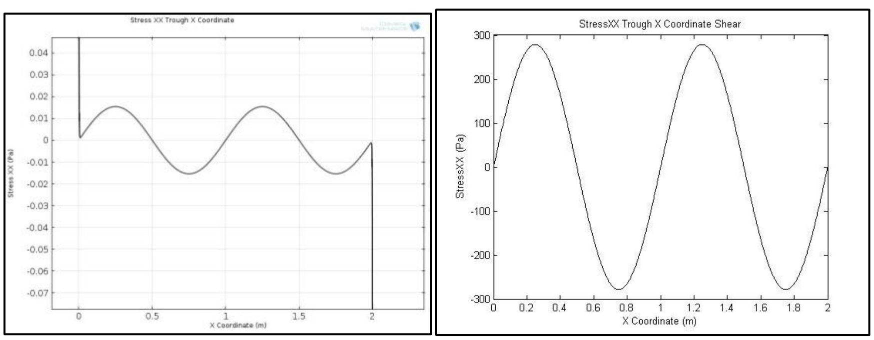


Figure 13-FEM simulation of an oscillatory shear load

Stress xx through the domain (x, 8.56 x 〖10〗^(-4) m).

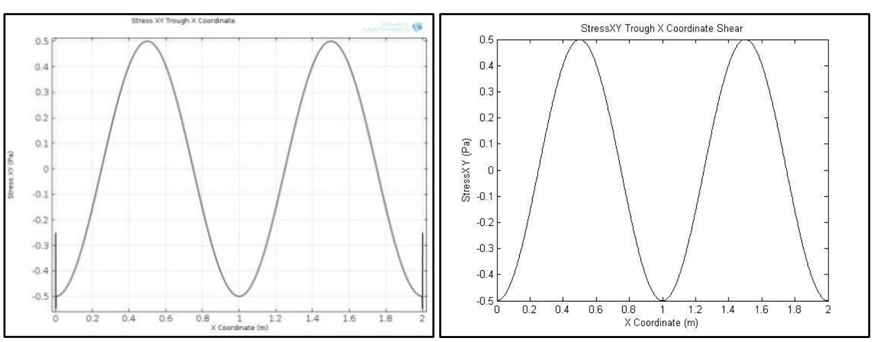


Figure 14-FEM simulation of an oscillatory shear load

Stress xy through the domain (x, 8.56 x 〖10〗^(-4) m).

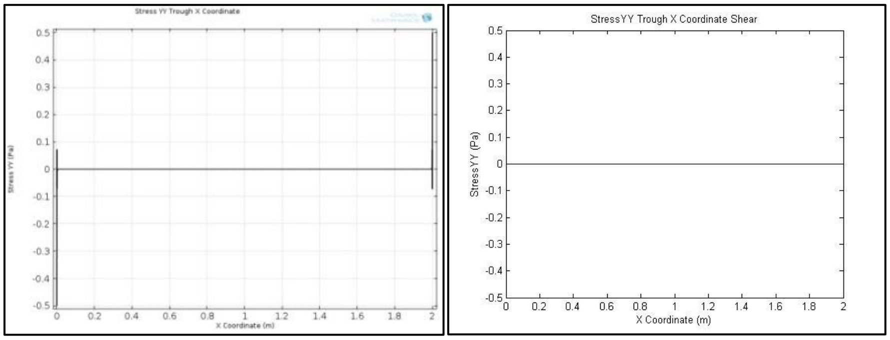
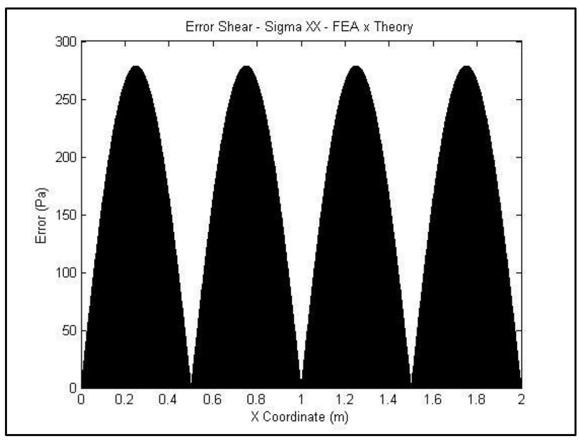


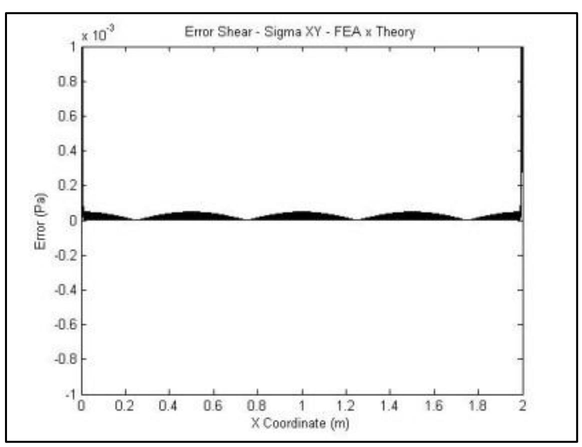
Figure 15- FEM simulation of an oscillatory shear load.

Stress yy through the domain (x, 8.56 x 〖10〗^(-4) m).

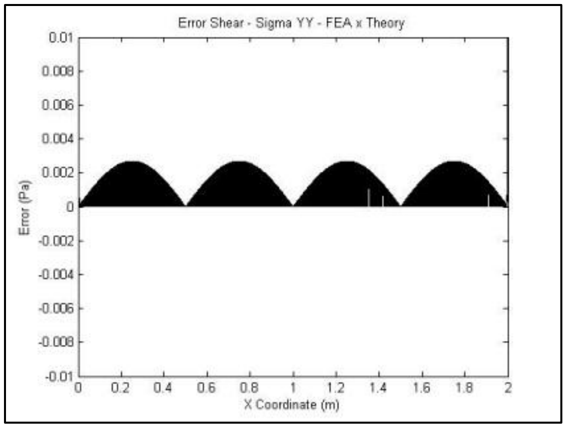
The error between the simulation and theory is shown in the following figure.



(a)



(b)



(c)

Figure 16-Verification error for pressure load. (a) Stress xx. (b) Stress xy (c) Stress yy

Similarly, for the pressure load, the graphics are plotted below.

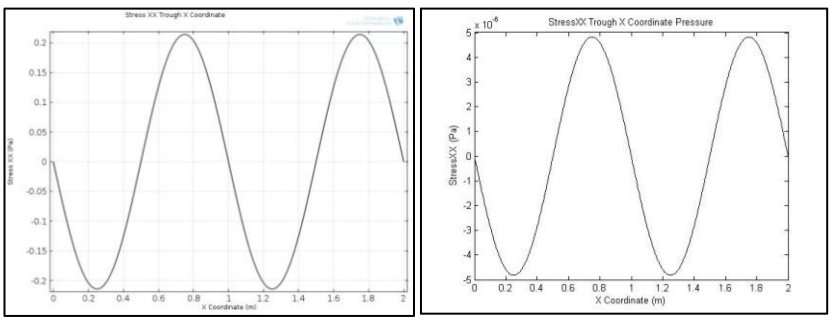


Figure 17-FEM simulation of an oscillatory pressure load.

Stress xx through the domain (x, 8.56 x 〖10〗^(-4) m).

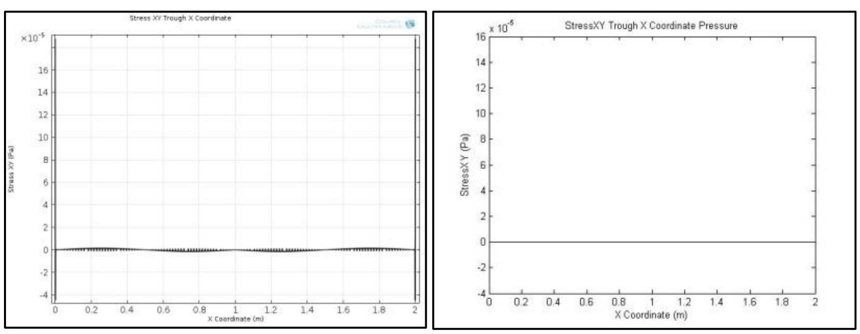


Figure 18-FEM simulation of an oscillatory pressure load.

Stress xy through the domain (x, 8.56 x 〖10〗^(-4) m).

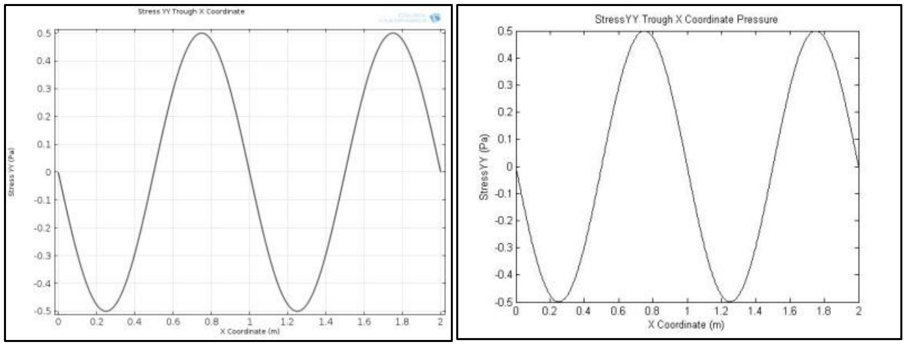
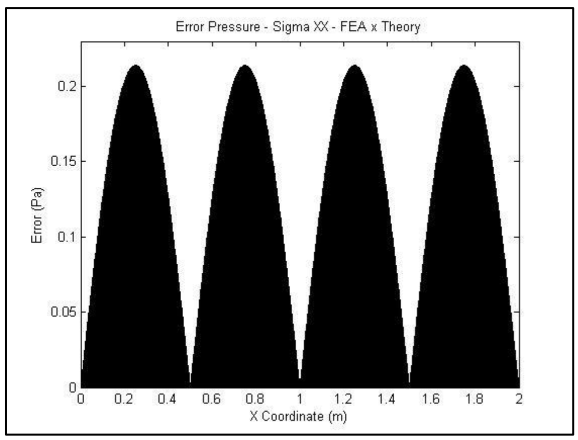


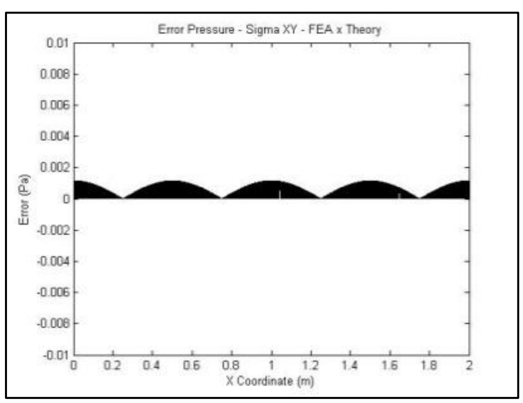
Figure 19-FEM simulation of an oscillatory pressure load.

Stress yy through the domain (x, 8.56 x 〖10〗^(-4) m).

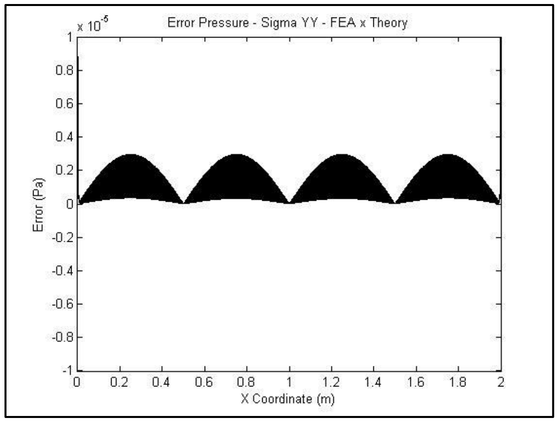
The error between the simulation and theory is shown in the following figure.



(a)



(b)



(c)

Figure 20-Verification error for pressure load. (a) Stress xx. (b) Stress xy (c) Stress yy

Comparing the plane strain theory with the numerical values, the results are very close when a constant load is applied. However, considering the oscillating load, the results for the xx stress didn't match the Timoshenko equations. In addition, the simulation showed that the stress through the film is constant when constant or oscillatory load is applied. This ensures that accuracy is achieved experimentally since the spectrometer will collect the correct data. The next studies will concentrate more on the oscillating theory to see if the solution converges when the boundary conditions are changed.

Previous Design Work:

This project was started by a graduate assistant over the summer. We received the testing apparatus, as shown in Figure 21Equation 21, at the beginning of the semester and were told to proceed. In addition to the apparatus, we have been given a linear servo motor, a linear load cell, a fiber optic light sensor, and a ProEngineer model of the baseplate. The reason that the shear stress is being measured this way is because the material being tested is in a liquid form, since the material is in a liquid form it can't be tested in a wind tunnel or in a liquid such as water. The glass slide is where the cholesteric liquid will be subjected to the shear stress. The servo motor will be mounted on the opposite side of the baseplate and in between the glass slide and motor is where the load cell will be. With the baseplate already created and a clear plan of how to mount the components that will be creating the load on the cholesteric crystals, only a few components need to be designed.

Figure 21- Previous design apparatus

Improvements on Previous Work:

The given apparatus, motor, and load cell have given the group a good starting direction. To complete the project, adjustments from the previous design needed to be made. The first change that needed to be made was to the block holding the motor. The motor block was improperly dimensioned but was still a good design. So the only change was to the engineering drawings to give the motor block correct dimensions. To improve the design the following would need to be redesigned: shear block with the ability to heat the material, a support for the shear block, a connecting rod that would join the load cell and the shear block, a light sensor holder that would be able to vary the angle of observation, a variable angle light holder, and longer legs.

Objectives:

Our first objective is to design, machine, and assemble the testing apparatus. A LabVIEW visual interface will be created to control the experiments and record data. Once this phase is complete, we will collect as much data as possible which will be the main product of this project. The first phase of testing will be for the cholesteric liquid crystal. The liquid crystal will be used to characterize the cholesteric material and provide a proof of concept for using cholesteric crystals as a shear stress sensor. We then expect to determine how the material reacts under static and dynamic shear stress along with how the material reacts to different temperatures, light sources, and measurement angles. We also want to find the maximum and minimum shear values that the materials can record, if the material has an endurance limit, and the materials sensitivity to shear. Once we have characterized the liquid crystal, a polymerized form of the cholesteric crystals will be ordered and the same experiments will be run on the polymer. The polymer is very expensive and takes a significant amount of time to make; which is why there first needs to be a proof of concept with the inexpensive liquid crystal. With time permitting we will indicate what type of applications the material is suited for, and design a "sensor package" that could be reproduced for future tests.

Constraints:

Some design constraints were imposed because of the fact that the testing apparatus was inherited. The first main constraint is space. The baseplate that was passed down by the previous design group was 12" by 4.5". The size of the baseplate can be changed but additional measures will need to be taken if a larger baseplate is needed. The light sensor is about 3" long and its cable isn't able to bend well. When the cable is bent at 90 degrees it needs about 6" of vertical length to bend. This means that the legs for the apparatus need to be at least 9" long. The light sensor must also be able to view the material form any angle from 20 to 90 degrees. The light that is going to be used must be white so that it contains the highest wavelength distribution across the visible color spectrum. The light must also be adjustable like the spectrometer. The heat source for the experiment will be able to generate temperatures up to 300°F and needs a 28V power source capable of supplying 10W of power. The range of load applicable is 0.5N due to the given load cell.

The time available for the project development is a constraint. When the first set of experiments is completed, a more expensive polymer form of the cholesteric crystals will be ordered. This polymer takes a good deal of time and money to create and the procurement of the polymer will only occur if the first set of experiments is done on time and if the budget is kept low. The project budget to conceptualize and build the device is $2000. Since the project is mostly research based there aren't many constraints. The main goal is to find the constraints of the cholesteric crystals, such as; maximum and minimum stress measurements, endurance, and temperature limits.

Concept 1:

Figure 23 below shows the design for concept one with the design of the light and sensor holder along with the shaft support. The light and sensor holder are the same pieces except a flipped location for the light and sensor circular holder. The apparatus shown has the light/sensor bracket with a set screw on the top, so that the bracket can be easily moved or taken off of the apparatus' base plate. The reasoning behind the circular holder is for the ability of the holder to rotate along the bracket, thus giving the ability for the experiments to make the placement of the sensor/light a variable. Since the method of measuring shear stress with the cholesteric liquids is a new concept having the ability to see how the data is altered with the differing angles could be important to the project. For the shaft support, a U-shape is used to hold up the shaft as to reduce the chance of a rotating moment due to the length that the shear block is from the motor driver.

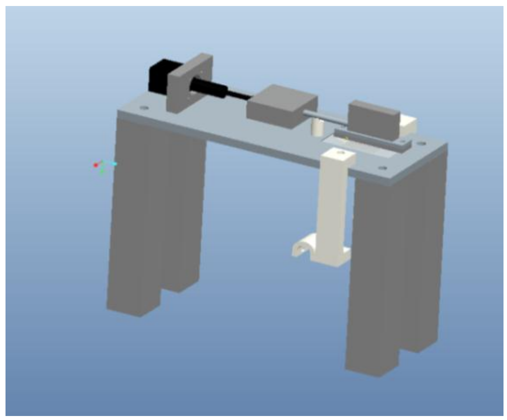


Figure 22- Concept 1- Dual Light Sensor Holder

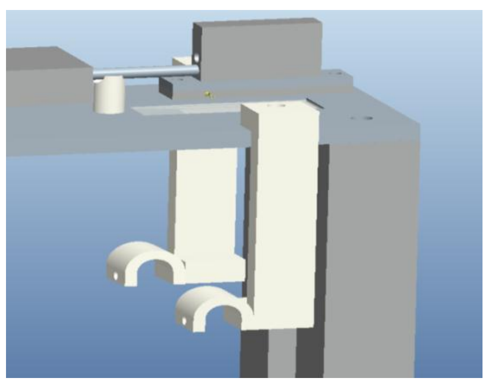


Figure 23- Close side view of holders and bracket to balance the shaft

Concept 2:

Shown in Figure 24 the fiber optic light sensor would be held in a rectangular block with a set screw. The rectangular block would then fit into a circular track and be bolted to the track. The angle of the block could be adjusted by sliding the block around the tack. The main problem with this design is that while the block is slid around the track, the axis of rotation of the sensor would change and point at a different point on the slide. It would be difficult to change the angle of the sensor so that the axis of rotation would stay the same as they previous position that the sensor was in.

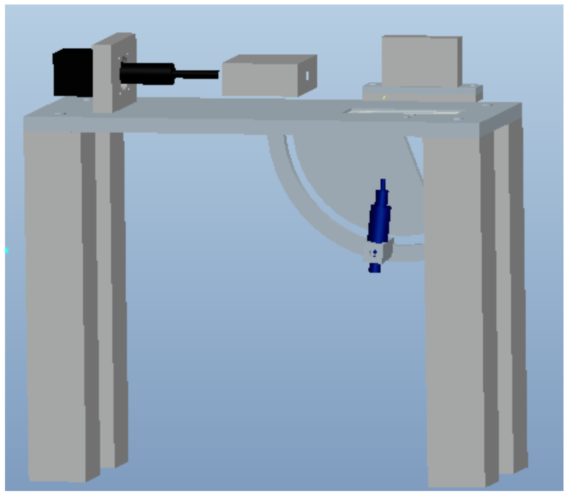


Figure 24- Adjustable sensor holder with degree indicating quarter disk

Concept 3:

Figure 25 shows the concept 3, based on a wheel for the fiber optic sensor holder attached to an arm. The desired angle could be adjusted by sliding and fixing the wheel. The simple design allows easy fabrication and cost reduction, as little material is required. However, the angle test range is lower than the others. In addition, this design is more susceptible to errors, as the fiber optic will not see the liquid crystals response throughout its range of motion.

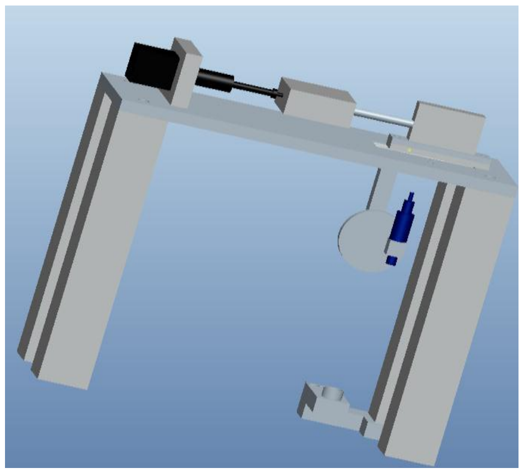


Figure 25- Concept 3- Wheel fiber optic sensor holder

Decision Matrix

Score Range (1-5) - Higher scores correlate to more ideal

		Concept 1		Concept 2		Concept 3	
	Weight	Score	Weighted	Score	Weighted	Score	Weighted
Ease of Use	0.20	2	0.40	4	0.80	4	0.80
Reproducibility	0.30	3	0.90	5	1.50	4	0.60
Accuracy	0.30	2	`0.60	4	1.20	1	0.30
Cost	0.15	3	0.45	2	0.30	3	0.45
Size	0.05	2	0.1	3	0.15	4	0.20
Total	1.00		2.45		3.85		2.35

Table 1-Decision Matrix of Design Concepts

Interim Design:

The decision matrix was used and along with the input from Dr. Oates and Matt Worden (Graduate Assistant), it was determined that it would be best to combine concepts two and three. Once discussing the light source with both Dr. Oates and Mr. Worden the ability for the light source to be another variable would not be ideal, so placing the light holder at the base of the apparatus without being able to move is theoretically more effective. The shear block support will be an elevated linear bearing, in which the shaft will be able to slide through. By using a linear bearing a minimal amount if friction will be generated and effectively supporting the load cell and shear block to stop the moment that would more than likely occur due to the length in which the shaft will have to translate. The location of the linear bearing is to be between the load cell and the shear block because of the limited area on the opposite side of the shear block. In the interim design (see Figure 26) the quarter measuring circle is used as the holder for the wavelength sensor, as to have an accurate form of measuring the degree and rotation of the sensor.

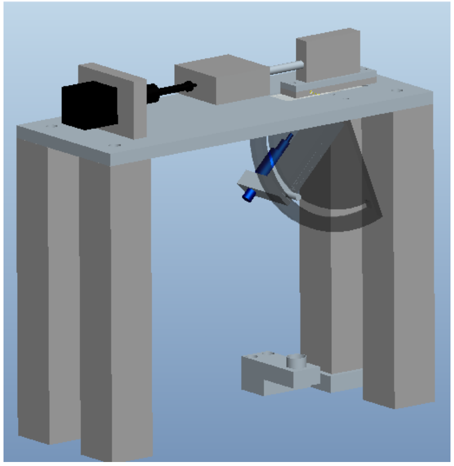


Figure 26- Final design concept after the recommendations from Matt W. and Dr. Oates

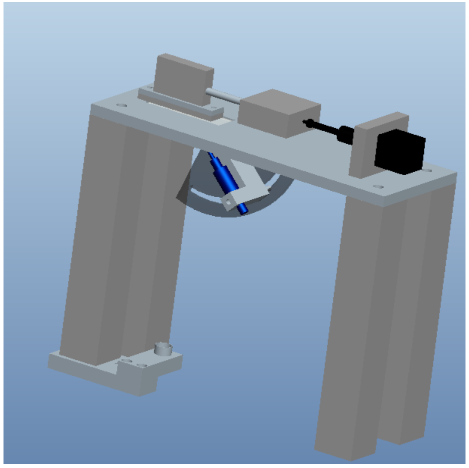


Figure 27- Angle of final design to show the light source holder

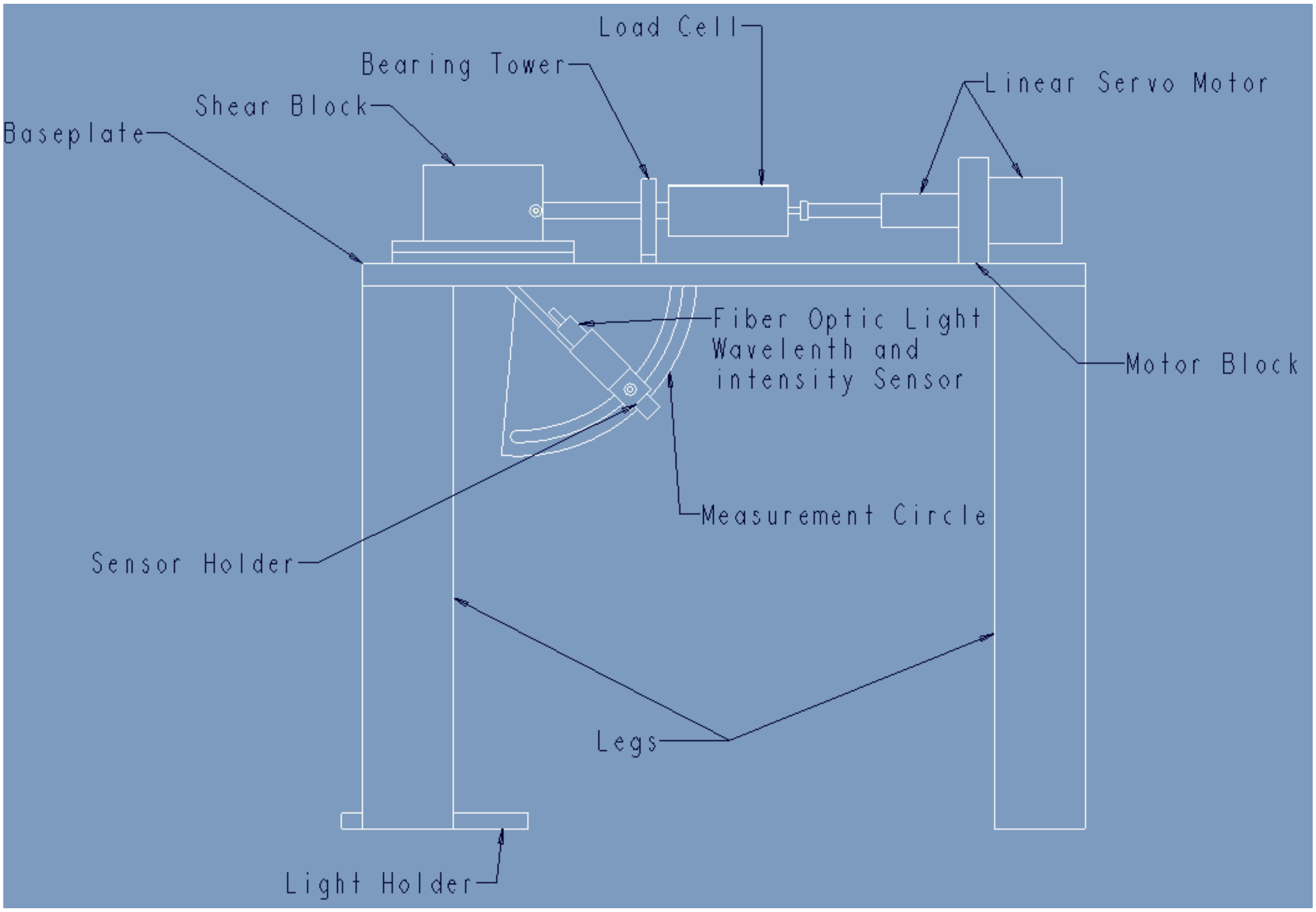


Figure 28- Interim Design Drawing

Shear Block Design:

The shear block is designed to house a heating pad and apply a shear force caused by the linear servo motor. The shear block is made out of three rectangular pieces of aluminum. For the upper face of the bottom section an area has been milled out to allow room for a .007" heating pad and insulation. The heating pad is placed in the milled area between the aforementioned bottom piece and a similar piece of aluminum on top. Another piece of aluminum is placed perpendicular to the surface of the top piece holding the heating pad. The perpendicular piece is meant to reduce the moment caused by the lateral force of the servo motor. If an L-type bracket were used, the end of the shear block would be forced into the material while the side closest to the motor would be forced up. This would result in a nonlinear distribution of force across the material and cause the readings to vary across the glass slide. Also the bottom section of the shear block has been modularized as to have variable thickness of the cholesteric crystals and to display how the crystals react. Along with having the variable thickness the bottom sections have particular attributes in the U-shape and extended shape (see Figure 29) to contain the cholesteric crystals, so there will be minimal amount of thickness change due to motion.

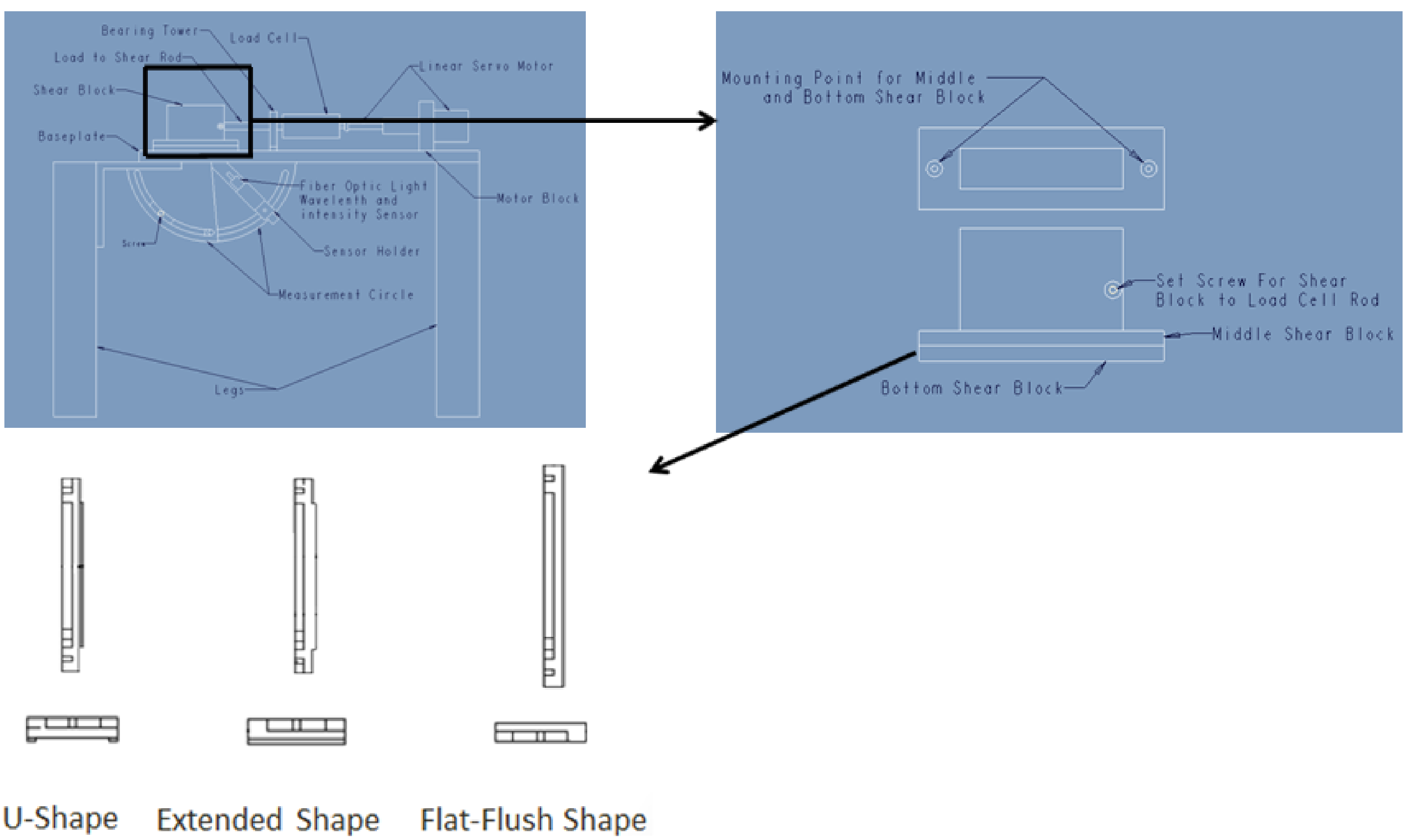


Figure 29- Shear Block Enhanced

Final Design:

The final design is a slight variation of the interim design. The only improvement was the movement of the light holder. The light holder was moved because it was found through experimentation that the light holder and spectrometer work best when the reflection of light off the crystals hits the spectrometer directly. In any other orientation the signal from the spectrometer is weak or nonexistent. When the light source is orthogonal to the cholesteric crystals, like in the previous design, the light reflects directly back at the light source. This means that the spectrometer must be orthogonal to the cholesteric crystals to get the best reading. It also means that the spectrometer can't be moved otherwise the reading degrades. Based on the laws of reflection the best configuration between the spectrometer and light source is most likely to be a mirror of each other across the plane orthogonal to the crystals. As a result the spectrometer and the light source must be adjustable to test different angles of the spectrometer and the crystals. To make the light source adjustable the measurement circle idea was adapted to fit the light source. Both the light source and spectrometer will travel on a fixed track that will ensure accurate positioning. Since the baseplate is relatively short the legs had to be extended off of the baseplate to make room for the additional measurement circle and light source holder arm.

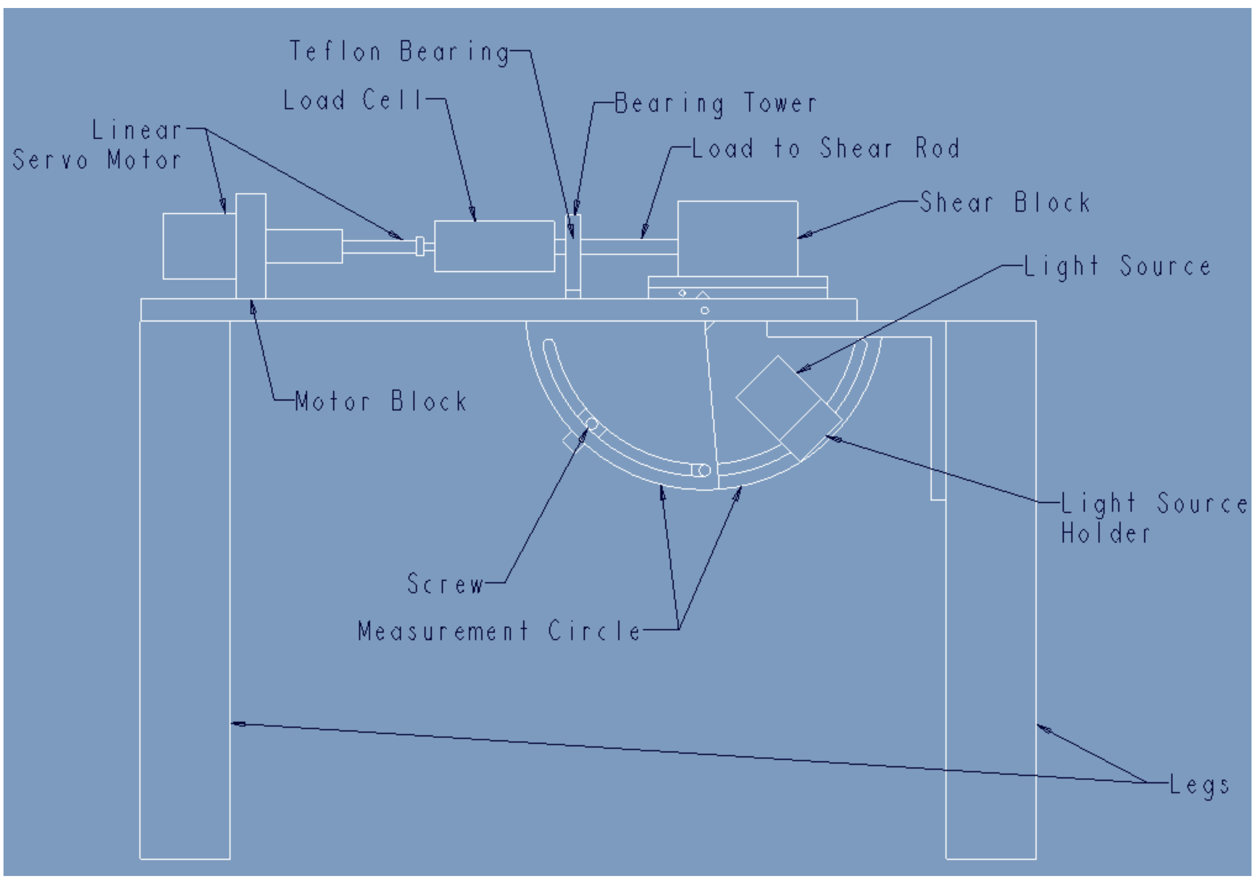


Figure 30-Final Design

Light Source Selection

It was determined that the light source for the experiment should be an LED because of its small size and power requirements. A wide band light source and a blue light source were both tested to see if a large or small spectrum distribution would make it easier to see the cholesteric crystals against the noise of the light source. When the blue LED was used, the only data that appeared was the light source. This is most likely because the blue light washed out the small reflection of the crystals. A wide band white LED was also tested and the liquid crystal's reflection was a strong peak above the original white light as seen in Figure 31.The intensity is not important but the shape of the spectrum is. The large peak around 560nm is the cholesteric crystals. This data shows that a wide band white LED would be best for the experiments.

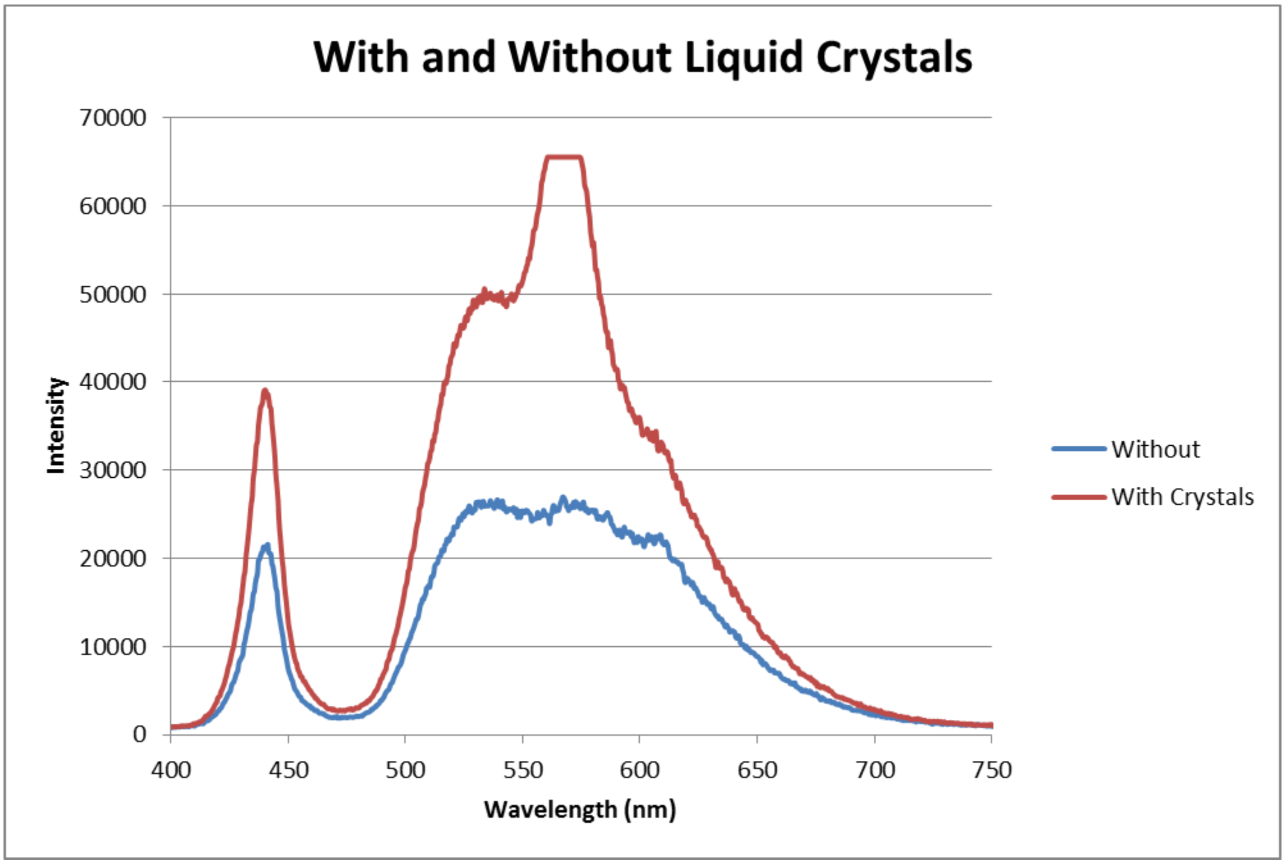


Figure 31-White Led With and Without Red Liquid Crystals

Components

Spectrometer

The use of a spectrometer will allow the collection of light in the correct intensity and range. This equipment consists of a fiber optic cable attached to a 2MHz analog to digital converter and outputs the signal via USB. The sensor is able to detect light between 200nm and 1100nm. The maximum resolution possible is 0.35 nm. Consequently, it is perfect for applications where fast reactions need to be monitored.

Load Cell

The load cell is used to measure the shear force exerted on the cholesteric crystals. It is attached between the linear servo motor and shear block. The output of the load cell is in volts and must be calibrated before use. The load cell works in tension and compression and is rated to 0.5N with and is overload protected to 2.5N.

Linear Actuator

The linear actuator is needed to apply the shear force on the crystals. Its linear characteristic allows the movement in just one axis. The motor is a stepper motor, which means that the speed and distance that the actuator moves can be regulated through programming. This is ideal for accurately changing the force that is applied to the crystals.

Environmental and Safety Issues

The current project contains only a limited amount of materials including a load cell, linear servo motor, spectrometer, aluminum apparatus, glass slides, and cholesteric liquid crystals. The cholesteric crystals are the only of the aforementioned components that pose a threat to the environment or its handlers. There do not appear to be any environmental hazards posed by the crystals. The material safety data sheet shown in the appendix only indicates to dispose of the crystals according to state guidelines. The safety sheet also indicates that the crystals may cause irritation if they come in contact with the skin or eyes and irritation if they are ingested or inhaled. The solution for contact with the skin and eyes is to flush with water. If inhaled and irritation occurs, medical attention is advised. Medical attention is also advised if ingested. When combusted the crystals will emit the toxic fumes carbon monoxide, carbon dioxide, and hydrogen chloride. The crystals aren’t carcinogenic and aren’t considered hazardous by any of the government agencies listed in the material safety data sheet. The materials that make up the cholesteric crystals are cholesterol, oleycarbonate, cholesterol nonanoate, cholesterol chloride, cholesterol dichlorobenzoate, cholesterol benzoate, and cholesterol propionate. All of these chemicals are used in cosmetics as for color and aren’t considered hazardous.

Cost Analysis

Eglin Air Force Research Laboratory has donated $2000 to the design of the shear stress sensor using liquid crystals. After purchasing materials and parts from McMaster-Carr, LED Supply and Pressure Chemical Company the project has come to a total of $369.10 which is well under budget and the cost for travel per the FAMU & FSU College of Engineering mileage reimbursement of $170 ($.44/mile traveled) the project is still under the budget set by Eglin AFRL. There are components that are being used by the senior design group in the Optics Lab of the Aero-Propulsion, Mechatronics and Energy Center (AME), if the components in the lab were to be purchased the budget would be exceeded. For the pricing and listing of the components used in the Optics Lab Table 3 in the Appendix displays all of the information. Also if the testing of the liquid cholesteric crystals is successful a polymer cholesteric crystal will be purchased for more testing as to see how the testing will affect a polymer form. The purchase of the polymer form will not be from the budget set by Eglin AFRL, but graciously by Dr. Oates the faculty advisor on the project.

Part	Unit Price	Quantity	Price
Teflon Bearing	$3.11	1	$ 3.11
Insulation	$9.03	1	$9.03
Heat sheet	$38.90	1	$38.90
Fasteners	- -	- -	$21.84
LEDs	$23.74	3	$71.22
Liquid Crystals	$75.00	3	$225.00
	Total		$369.10

Table 2- Purchased Parts

Specials Thanks

We would like to thank the FSU-FAMU College of Engineering for providing us the opportunity to work on this senior design project. In addition, we thank Dr. Oates, our academic advisor, for the support during each weekly meeting and for keeping us on track as well. We'd also like to thank Dr. Dickinson and Dr. House, our project sponsors, who motivated us on our trip to Eglin Air Force Base, showing the engineering applications that our project was tied to. Thank you Matt Worden, our graduate assistant, who taught and helped us with the experimental and simulation studies. Finally, we would like to thank Dana Edmunds, Jeremy Phillips, Marshall Lewis and Keith Larson from the machine shop for manufacturing the components for our apparatus.

Appendix

Environmental and Safety

MATERIAL SAFETY DATA SHEET

Pressure Chemical Co.

Item Number: LC Kit
Chemical Name: Pressure Chemical LC Kit

••

1. Chemical Product and Company Identification

CHEMICAL NAME: **This MSDS is for a combination of Liquid Crystal (LC) products. These products include the following:**

Chemical Name	Synonym	CAS Number	PCC Item No.
Cholesterol oleylcarbonate	None	17110-51-9	L193
Cholesterol nonanoate	Cholesterol Pelargonate	1182-66-7	L170
Cholesterol chloride	3-Chloro-Cholest-5-ene	910-31-6	L050
Cholesterol 2,4-dichlorobenzoate	None	32832-01-2	L078
Cholesterol benzoate	None	604-32-0	L010
Cholesterol propionate	None	633-31-8	L230

MANUFACTURER:
Pressure Chemical Co.
3419 Smallman St.
Pittsburgh, PA 15201
412-682-5882
FAX 412-682-5864
email: service@presschem.com

EMERGENCY TELEPHONE NUMBERS:
For Chemical Emergency, Spill, Leak,
Fire, Exposure, or Accident Call
CHEMTREC - Day or Night 800-424-9300
or 703-527-3887 outside USA

Pressure Chemical 24 Hour Emergency Number: 412-565-1190

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2. Composition / Information on Ingredients

HAZARDOUS INGREDIENTS

None of the components in this kit are considered as hazardous under the OSHA Hazard Communication Standard.

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3. Hazards Identification:

POTENTIAL HEALTH EFFECTS:

ROUTE(S) OF ENTRY:
Inhalation: X
Skin/Eyes: X
Ingestion: X

EFFECTS AND SYMPTOMS OF OVEREXPOSURE:
May be harmful if swallowed, inhaled or absorbed through skin. Symptoms of exposure may include irritation.

EFFECTS OF INHALATION:
May cause irritation.

EFFECTS OF SKIN CONTACT:
May cause irritation.

EFFECTS OF EYE CONTACT:
May cause irritation.

EFFECTS OF INGESTION:
May cause irritation.

CARCINOGENICITY, as determined by:

NTP:	Not Listed
IARC:	Not Listed
OSHA:	Not Listed

MEDICAL CONDITIONS AGGRAVATED BY EXPOSURE:
None Known.

4. First Aid Measures:

FIRST AID FOR EYES:
In case of contact, immediately flush eyes with large quantities of water for at least 30 minutes. Assure adequate flushing of the eyes by separating the eyelids with fingers. Call a physician if irritation persists.

FIRST AID FOR SKIN:
In case of contact, immediately wash skin with plenty of soap and water for at least 15 minutes. Remove contaminated clothing and wash before reuse.

FIRST AID FOR INHALATION:
If irritation of the upper respiratory tract occurs, remove to fresh air at once. If not breathing, give artificial respiration. If breathing is difficult, administer oxygen. Seek medical attention immediately.

FIRST AID FOR INGESTION:
Seek proper medical attention.

NOTE TO PHYSICIAN:
None

5. Fire Fighting Measures:

FLASH POINT: Flash point only available for Cholesterol Oleylcarbonate FP: 113 deg C
METHOD USED: Closed Cup

FLAMMABLE / EXPLOSIVE LIMITS: Explosive Limits Not Determined

EXTINGUISHING MEDIA: Water spray, dry chemical, foam or carbon dioxide.

SPECIAL FIRE FIGHTING EQUIPMENT / PROCEDURES:
Use water to cool fire-exposed containers. Wear self-contained breathing apparatus and protective clothing to prevent contact with skin and eyes.

UNUSUAL FIRE / EXPLOSION HAZARDS:
Emits toxic fumes under fire conditions.

COMBUSTION PRODUCTS:
Carbon monoxide, carbon dioxide, hydrogen chloride.

6. Accidental Release Measures:

Absorb on sand, vermiculite, or clay and/or sweep up and place in closed containers for disposal.

7. Handling and Storage:

HANDLING AND STORAGE PRECAUTIONS:

Keep containers tightly closed.
Keep away from heat.

8. Exposure Controls / Personal Protection:

Respiratory Protection: If significant quantities of dust are generated, wear appropriate NIOSH/MSHA approved respiratory protection to eliminate inhalation exposure. Respiratory protection is not typically required under normal conditions of use.

Skin/Hand Protection: Wear chemical-resistant gloves and chemical resistant clothing.

Eye Protection: Wear safety goggles.

Avoid all exposure to eyes, skin and clothing. Avoid prolonged or repeated exposure. Wash thoroughly after handling.

VENTILATION REQUIREMENTS:
Use good industrial ventilation and local exhaust hoods if inhalation risk exists in use.

EXPOSURE LIMITS:
No exposure limits have been established.

9. Physical and Chemical Properties:

	Cholesterol oleylcarbonate	Cholesterol nonanoate	Cholesterol chloride	Cholesterol 2,4-dichlorobenzoate	Cholesterol benzoate	Cholesterol propionate
APPEARANCE	Opalescent Fluid or Solid	White Crystalline Solid	White to off-white Crystalline Solid	White to off-white Crystalline Powder	White to off-white Crystalline Powder	White to off-white Waxy Solid
ODOR	Negligible	Coconut	Negligible	Negligible	Negligible	Negligible
MOLECULAR FORMULA	$C_{46}H_{80}O_3$	$C_{36}H_{62}O_2$	$C_{27}H_{45}Cl$	$C_{34}H_{48}O_2Cl_2$	$C_{34}H_{50}O_2$	$C_{30}H_{50}O_2$
BOILING POINT	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
MELT POINT	10 °C	74 – 77 °C	92 – 93 °C	125 – 127 °C	149 – 151 °C	114 °C
SOLUBILITY IN WATER	Insoluble	Insoluble	Insoluble	Insoluble	Insoluble	Insoluble
SPECIFIC GRAVITY	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
VAPOR PRESSURE	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
VAPOR DENSITY	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
EVAPORATION RATE	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown

10. Reactivity:

STABILITY: Stable

HAZARDOUS POLYMERIZATION: Not expected to occur.

INCOMPATIBILITIES: Strong acids, bases, oxidizing agents and reducing agents

HAZARDOUS DECOMPOSITION PRODUCTS: Fire may release carbon monoxide and carbon dioxide, and hydrogen chloride.

11. Toxicological Information:

No toxicological information is available.

12. Ecological Information:

No ecological information is available for this chemical.

13. Disposal Considerations:

Observe all applicable local, state, and federal environmental regulations.

14. Transportation Information:

US DOT SHIPPING NAME: DOT NOT REGULATED

15. Regulatory Information:

OSHA HAZARDOUS: **NO**

TSCA LISTED: **Yes**

SARA TITLE III:

SECT. 302 EXTREMELY HAZARDOUS SUBST. TPQ (Lbs): N/A

REPORTABLE QUANTITY (RQ)(Lbs): N/A

SECTION 313 LISTED: No
LISTED MATERIAL/COMPOUND:

SECTION 311/312 HAZARD CATEGORIES:

Pressure:	N
Fire:	N
Reactivity:	N
Acute Health:	N
Chronic Health	N

STATE / INTERNATIONAL REGULATORY INFORMATION:

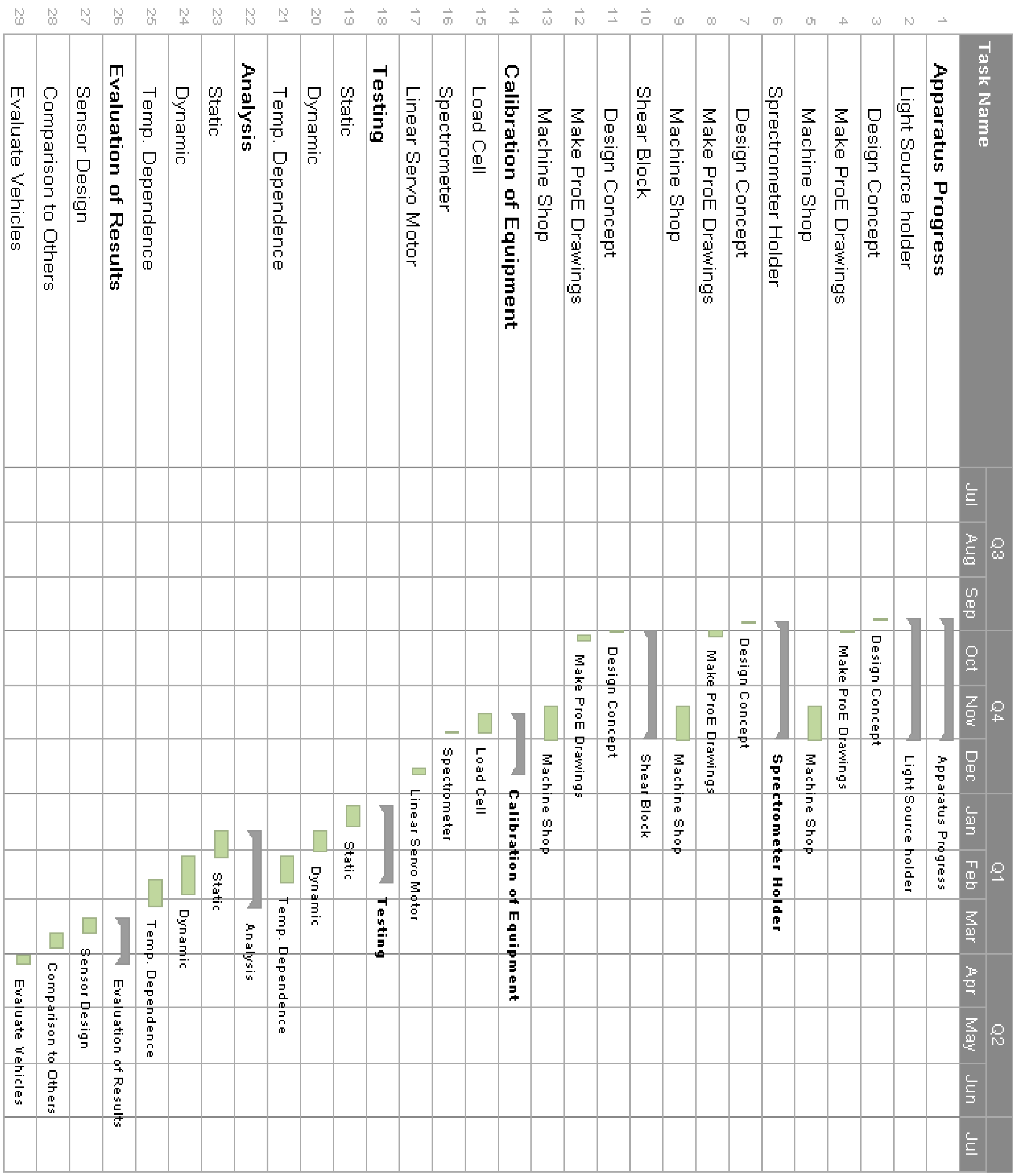
PENNSYLVANIA RIGHT TO KNOW.	**LISTED:** No
NEW JERSEY RIGHT TO KNOW:	**LISTED:** No
CALIFORNIA PROP 65.	**LISTED:** No
CANADA DOMESTIC SUBST. LIST	**LISTED:** No
EINECS	**LISTED:** No

16. Other Information:

REASON FOR ISSUE	: New MSDS
REVISION DATE	: November 20, 2006
SUPERSEDES DATE	: Not Applicable

Schedule

Figure 32- Schedule for Fall & Spring



Cost Analysis (Supplied Parts)

Part	Unit Price	Quantity	Price
Teflon Bearing	$3.11	1	$ 3.11
Insulation	$9.03	1	$9.03
Heat sheet	$38.90	1	$38.90
Fasteners	- -	- -	$21.84
LEDs	$23.74	3	$71.22
Liquid Crystals	$75.00	3	$225.00
	Total		$369.10

Table 3- Purchased Parts

Part	Quantity	Price
Aluminum	- -	$64
Load Cell	1	$935
Fiber Optic Spectrometer	1	$2771
Linear Servo Motor	1	$230
Software	1	$60
Total		$4,060

Table 4- Supplied Parts from Optics Lab

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