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Determination of 3-dimensional deformations of the alveolar sac during simulated breathing

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Determination of 3-Dimensional Deformations of the Alveolar Sac During Simulated Breathing

by

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A Thesis Submitted in Partial Fulfillment of the Requirement for the Master of Science In Mechanical Engineering From The Kate Gleason College of Engineering

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Abstract

Mechanical properties of the parenchyma of the lung are currently unknown and difficult to quantify. Creating a computer model with valid property values will allow researchers to further investigate particle mixing in the lung during inhalation and exhalation. One challenge with modeling the material of the lung is the intricate geometry of the alveolar sac. Researchers are currently trying to model particle deposition within the lung using computational fluid dynamics. However, the mechanical properties of alveolar sac structure are currently undetermined.

Due to the complexity of the physical structure of an alveolar sac, it has been a challenge to model fluid-structural interactions during breathing. To assist in quantifying these interactions, computer aided finite element models are a necessity. These models will allow for calculation of the deflections and deformations of the physical structures of fluid containing membranes. The focal point of the project was to determine mechanical properties of a series of materials. There is currently no process for determining these properties and this was a major accomplishment of this research. The process of finding these properties can be applied to other materials in the future, even on a micro-scale, such as real alveolar tissue materials. These properties were applied to a series of finite element models, predicting deflection.

Mechanical properties were determined by using different test specimens to collect data and fit to a Mooney Rivlin model. The results were then applied to a series of finite element models, one for each test specimen and one for a spherical boiling flask. The boiling flask tests showed promising outcome for future research, with a determined material model nearly 40% increase in accuracy from prior research.

The tests were able to be replicated for a second surrogate material, showing that the process works for more than just a single material and allowing the process to be used with a new material in the future.
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Chapter 1: Introduction

1.1 Research Overview

The lungs are a complicated structure but when simplifying the organ down to its basic function, we can concentrate on the alveolar sacs within. These minute parts are responsible for the gas exchange into the blood stream. Oxygen is brought into the alveoli where it enters the blood stream through a network of capillaries. In different situations, such as metered inhaled medication or smoking, there may be particle deposition within the alveolar sacs. Researchers are interested in both aspects.

The research was being completed in support of research into both micro particle behaviors in a biological system and investigations on carcinogenic dosimetry inhaled during second hand smoking. One focus for this work is to determine how fluid-structure interactions contribute to particle deposition, both where and how the particles deposit within the alveoli. The contribution from the work will be presented in this thesis to develop an experimental approach for identifying material properties of materials used in lung modeling, from surrogate polymer materials to actual alveolar tissue.

1.2 Existing Research

Techniques of measuring the pathways of particles as they moved through a fluid field, known as particle image velocimetry (PIV), were outlined in a previous study [23] that discussed the ability to track fluorescent particles moving through a fluid network. The fluid was contained within a molded membrane, shaped as a simplified alveolar sac. The
simplified shape was similar to a grape sac, containing 13 alveoli, made of Ultraflex. The mold was created by a senior design team and was a scaled version of an alveolar sac for the purpose of testing if recirculation within the alveoli occurred due to the walls of the structure. A computational model was created using a computational fluid dynamics program, (CFD), COMSOL. The results, however, did not take in account the structural material, Ultraflex. Instead, the structure was made of a linear elastic material with an elastic modulus on the order of 100 kPa; a typical Young’s modulus of an elastomer-like Ultraflex would be on the order of magnitude of 10-100 kPa, but would also exhibit non-linear elastic characteristics. The mold material is rubber-like but details of its makeup and mechanical properties were unknown, especially after the melting/molding process. The prior work done in this thesis provided adequate information about the Ultraflex and a process to measure future materials that may be used in subsequent testing using PIV [23].

Figure 1.1 The 13 bulb alveolar model containing fluorescent particles for PIV.

1.3 Significance of Exploration

Both testing and simulation were completed for surrogate materials, allowing for validation of the mechanical property models. The process required the determination of mechanical
properties of Ultraflex using a membrane characteristic test stand able to collect load and displacement data.

The methodology, the processes and the theory behind determining the mechanical properties of surrogate materials has been outlined and documented within this thesis. The knowledge gained through this research will allow the mechanical properties of surrogate alveolar sac materials used in future PIV testing to be quantified and properly represented in CFD analysis.

Several different tasks needed to be completed to properly represent characterize the mechanical behavior of the surrogate lung materials:

1. A preliminary FEA model was created to analyze and validate a polymer figure in a shape that matched the sample in the membrane test machine. The material modeled first was the medium Ultraflex and the data collected from the characterization test stand was applied to the FE model.

2. A second FE model was created, in the shape of a boiling flask. The boiling flask was a simplified version of an alveolar sac, essentially a small balloon. The model was able to predict displacement data that was compared to experimental data of a physical molding of the boiling flask.

3. A scaled representation of an alveolar sac was modeled to display how the different chamber-like entities of the sac inflate and deflate. A FE model of the more complex alveoli was created, using the same 13 bulb model used in prior research. Both FEA data and experimental data was then compared and
validated. The processes are ready to be applied to future research in combining both the FEA and CFD results into one advanced model.

4. A second hyperelastic material was characterized. Firm Ultraflex was tested with data collected from a membrane characterization test stand. Experimental data was collected and applied to an FE model. A second FE model was created with Firm Ultraflex material properties. The model was able to predict displacement data that was compared to experimental data of a uniaxial tensile test.
Chapter 2: Preliminary Research and Experimentation

2.1 Literature Review

A literature search was performed to identify current methods being used to characterize and model membranes. Descriptions of effort to characterize mammal tissues, other organic materials, and polymers were found and are summarized here, along with an overview of different material models that might be appropriate for the polymers being characterized for the present study. The focus of this work is characterization of Ultraflex, but the published work reviewed may give insight for future investigations into other materials as well.

This chapter also includes background information on several pieces of custom equipment designed and built at RIT. The function and relevance of the equipment to the present study are both described.

2.1.1 Characterizing Materials and Testing

Characterization of lung tissue properties was a motivation for this present study. In the literature there was a lack of tissue-level properties for the lungs and only papers that characterized bulk level properties were available [17, 32, 28, 13]. As a result of the micro scale size of an alveolus, simulated models have been created of the entire lung parenchyma working together. The stress distribution in the alveolar septa was simulated [17] based on uniaxial tensile measurements done on alveolar septal tissue from the human lungs [32]. Uniaxial test data is not ideal to try to represent something under biaxial loading, so the material was assumed to be isotropic. Bulk properties of lung, heart, stomach, and lung
human tissues have also been tested using compression and simple shear testing [28]. There have been attempts to model and simulate elastin and collagen connective tissue fiber bundles in the alveolar walls [13]. The shear modulus for the model is represented by a linear relationship with transpulmonary pressure, however, this theory falls apart at large distortions and high initial pressures. The same simulation was used to analyze the viscoelastic behavior of the alveolar duct [12].

Researchers have used a variety of different test methods to determine mechanical properties of other thin elastic membranes found elsewhere in the human body. Uniaxial tensile testing has been used to characterize human tympanic tendons [10], anterior and posterior ocular lenses [19,20] and poly(glycerol sebacate) [9]. While the tests themselves are relatively simple to perform, creating a sample where edge effects do not influence results can be challenging.

Transversely loaded membranes have been used – both point loads and pressure loads. Point load membrane testing was performed on uncured silicone elastomers [3], silicon and silicone-based elastomers [30], nonlinear membranes (theoretical only, no experimental validation)[35, 4], human tympanic membrane [11], and other viscoelastic membranes [15]. Pressure loading has been performed on bovine cornea [7], elastomer membranes [34], and viscoelastic membranes [33]. The strength of these techniques is the removal of edge effects from data collection.
Correlation of data collected from these types of tests was the next step in the research. A relationship to evaluate the membrane load/displacement data has been developed [3, 30] for a Neo-Hookean Solid material model (Equation 2.1).

\[
\frac{\delta}{R} = \left( \frac{a}{R} \right)^{3/4} \left( \frac{16}{9\pi} \frac{P}{EhR} \right)^{1/3}
\]  

Equation 2.1

As will be shown in Section 2.4, the material under consideration for this research did not fit the Neo-Hookean model.

Shear tests have been done on multiple tissues samples (stomach, heart, liver and lung) [28] to determine a bulk response on the organ. Shear testing of the lung did not focus on tissue level properties.

Research into pressure-expansion test fixtures was an alternative test procedure. A test fixture of this nature existed at the beginning of the research [23], but it was necessary to determine if a pressure-expansion fixture could be used within ANSYS. Unfortunately, the data collected was inconsistent with what the ANSYS curve fitting data required. ANSYS required pressure and volume data of a compressible material, such as a foam, and could not be used for the Ultraflex material that was nearly incompressible.

Biaxial tensile testing has been done on arterial elastic material [18], human lung parenchyma [16] and rubber-like elastomers [6]. The sample was stretched along two axes and the strain was determined by a series of images taken by a camera that showed deformations. The elimination of edge effects and effects from the grips/constraints was done through the images. They were taken at a centralized area on the test sample.
Several researchers have implemented image analysis in order to track displacements and strains during materials characterization testing [6, 18, 15]. To make the image analysis work, a camera was focused on the center of a test specimen. Images were analyzed either in real time [6] or captured and evaluated later [18, 15]. Software would then determine strains from drawn dots or points of interest that were on the sample prior to testing.

2.1.2 Constitutive Models

Various models were considered to represent the material properties of the surrogate materials, in particular, the Neo-Hookean and Mooney-Rivlin material models. It is noted within the literature that it is hard to determine a relationship for hyperelastic materials because there are so many different ways to explain the same stress-strain relationships [5]. However, all hyperelastic models follow three basic rules:

- The stress-strain relation is specified by the function $W = W(F)$, where $W$ is the strain energy density and is a function of the deformation gradient tensor $F$.
- The material is assumed to be isotropic or independent of material orientation.
- Formulas for stress are calculated in terms of differentiated strain energy density functions and are in terms of strain.

Neo-Hookean and Mooney-Rivlin models can be based on the generalized polynomial rubber elasticity potential:

$$
\bar{U} = \sum_{i+j=1}^{N} C_{ij} \left( T_1 - 3 \right)^i \left( T_2 - 3 \right)^j + \sum_{i=1}^{N} \frac{K_i}{2} (J - 1)^{2i}, \quad N = 1
$$

Equation 2.2
where \( \overline{U} \) is the strain energy density function; the shear modulus, \( \mu \), is represented by \( 2 \sum_{i+j=1}^{N} C_{ij} \); \( \overline{T}_i \) and \( \overline{T}_2 \) are invariants of the strain tensor \( B \); the bulk modulus, \( K \), is represented by \( 2 K_i \); and \( J \) represents the Jacobian (determinant) of the deformation gradient. The surrogate materials were assumed to be incompressible and therefore, the Jacobian was equal to 1. \( \overline{T}_i \) and \( \overline{T}_2 \) can both be represented with the term, \( \lambda \), a representation of stretch ratios. In equibiaxial testing both \( \overline{T}_i \) and \( \overline{T}_2 \) are equal to \( 2 \lambda^2 + \lambda^{-4} \). In a material that is nearly incompressible, \( K \) is a very large value, on the order of \( 10^5 \) MPa.

When generalizing the equation to a Neo-Hookean Solid model, \( i=1 \) and \( j=0 \), resulting in Equation 2.3:

\[
\overline{U} = C_{10} \left( \overline{T}_1 - 3 \right) + \frac{K_1}{2} (J - 1)^2
\]

Equation 2.3

Alternatively viewed as:

\[
\overline{U} = \frac{\mu}{2} \left( \overline{T}_1 - 3 \right) + \frac{K_1}{2} (J - 1)^2
\]

Equation 2.4

Where the shear modulus is represented by \( \mu = \mu_1 = 2(C_{10}) \) and \( 2K_1 \) is the bulk modulus.

The Neo-Hookean Solid model is a special case of the Mooney-Rivlin model, in which the material exhibits a constant modulus of elasticity (\( E \)) for the initial deformation. However, the Mooney-Rivlin model is a more general approach to curve fitting. It, too, is based on the generalized polynomial rubber elasticity potential, but with more parameters. There are four Mooney-Rivlin models available within ANSYS: 2-parameter, 3-parameter, 5-parameter, and 9-parameter. The 3-, 5-, and 9-parameter models are generally not used, as it is hard to
correlate the parameters of the actual experimental data. The 2-parameter model can be represented using Equation 2.2, where \( i+j=1 \) and therefore, \( i \neq j \):

\[
\overline{U} = C_{10} \left( I_1 - 3 \right) + C_{01} \left( I_2 - 3 \right) + \frac{K_1}{2} (J - 1)^2 
\]

Equation 2.5

Alternatively viewed as:

\[
\overline{U} = \mu_1 \left( I_1 - 3 \right) + \mu_2 \left( I_2 - 3 \right) + \frac{K_1}{2} (J - 1)^2 
\]

Equation 2.6

Where the shear modulus is represented as \( \mu = \mu_1 + \mu_2 = 2(C_{10} + C_{01}) \).

Other models considered were the Ogden material model, as well as the Arruda-Boyce model. The Ogden material model contains variables that are temperature dependent [10]. Temperature was not thought to have significant effect on the material in the present study. Therefore, the Ogden model was not considered for this work. The Arruda-Boyce model was another alternative model that represented a material, as it is stretched to a moderate length. When some hyperelastic materials are stretched far enough, they experience non-Gaussian behavior, or a varying elastic modulus, and models such as the Arruda-Boyce and Mooney-Rivlin take into account this effect [8]. Although the Arruda-Boyce model could have been used, there was not enough supporting literature to apply it to the application of the membrane indenter, which was originally assumed to be the proper material characterization stand.

However, representing the models in the form of strain energy density was not the problem. When data is collected during any type of test, it is typically collected in terms of load and
displacement data. Understanding how to represent the load, depending on the way it was being applied, and developing a stress relationship, required further investigation.

As the material was originally assumed to be Neo-Hookean, the load-displacement equations for a spherical indentation of a freestanding circular membrane [3] were used (Equation 2.1).

However, when these equations were applied to preliminary test data, the result was not Neo-Hookean (Figure 2.1), since E is clearly not constant for small strains.

![Figure 2.1: Preliminary results of Ultraflex fit to a Neo-Hookean Solid Material Model](image)

The more general Mooney-Rivlin material model was then pursued and became the focus of the work. This still left the issue of being able to correlate stress-strain data. This is described in more detail in Section 2.4.
2.2 Prior work on expanding alveolar sac model

The syringe pump test fixture was developed by a senior design team [1]. The machine was used to expand and contract balloon-like samples. The machine (Figure 2.3) consists of a container (1), filled with glycerin, to house a test sample (2). The test sample itself is also filled with glycerin to avoid any effects of gravity. The syringe pump (3) to the right controls the pressure (vacuum) of the apparatus. As the syringe is pulled out, it draws the glycerin from the container, causing a pressure drop and expansion of the sample inside.

Two sensors are used in the system. One sensor at the top of the graduated cylinder (4) measures the flow rate of the apparatus. The other sensor near the bottom of the container (5) measures the pressure differential as the syringe is pulled out or pushed in. The pressure sensor was calibrated using a column of water. At various heights of water, voltage readings were recorded. A linear curve fit was applied and the curve allowed for a calibration factor to be determined in order to change volts to pressure. The manufacturer claimed this factor should be 1055 Pa/V. In the calibration testing, the resulting slope was 1016 Pa/V, on the same order as the manufacturer’s data sheet.

The sample inside normally contains glycerin with fluorescent particles. These particles would aid in particle image velocimetry (PIV). The glycerin was used because it had a refractive index that would not change the path of a laser as it shines through the fluid and the balloon-like structure. The overall goal of the test fixture was to study recirculation within the molded sample by shining the laser on the particles while taking pictures of the
sample expanding and contracting. The images would then be analyzed and the individual particles could be tracked and their pathways could be traced.

Figure 2.3: Syringe Pump Test fixture with Alveolar Sac Mold Sample inside, the following parts are noted:

For this thesis, the machine was used without the laser and fluorescent particles, since the focus is on the deformation of a sample as it expands and contracts. The pump was normally controlled by a LabVIEW program that sent the pump a signal to move based on breathing curve data collected by the senior design team. This gave continuous sampling but provided excessive data that was not relevant to this research. Instead, the pump was controlled by the user and was manually moved to either remove or replace glycerin. As the pump was
manually controlled, the pressure sensor voltage was read through the Measurement and Automation software provided by LabVIEW. At each incremental movement of the pump, a picture was taken to track the displacement of the sample.

This pump was used for verification of the predicted behavior of an inflating balloon-type sample after material properties were determined. The pump data was compared to 3D models created in ANSYS to verify the accuracy of the material properties. Images, such as Figure 2.4, can be taken using the syringe pump apparatus. The images were analyzed using ImageJ, image analysis software provided by the National Institute of Health [25].

![Figure 2.4: Sample picture of boiling flask expansion within the syringe pump apparatus. The red circles represent areas of interest that were measured for experimental data, further discuss in section 5.1.2.](image)

ImageJ allowed for tracking of pixel movements as a sequence of images was advanced from one from to the next. This allowed for the generation of the displacement of various points that would correspond with pressure readings collected from the differential pressure sensor.
Diameter measurements were taken in the middle to determine the side deflections. Diameter displacements were then divided by two to give radial displacements of that point.

2.3 Existing materials characterization hardware and software

First efforts on characterization of Ultraflex were completed using existing hardware. The test device was a combination of a miniature tensile stage built by a 2003-04 senior design team [26] and a membrane indenter test fixture developed by a 2005-06 senior design team [29] and built during a 2005-06 independent study done by a member of the 2005-06 design team.

2.3.1 Miniature tensile stage

The original machine was created by a senior design team that developed a tensile stage that could test miniature steel hourglass specimens. The intent was for education and instructional purposes allowing for research on metal structures using a scanning electron microscope. Due to the sizing constraints of the SEM, within a vacuum chamber, this machine was created as a micro-scaled tensile machine similar to a screw-driven uniaxial tension machine. The machine’s displacement is controlled using Anaheim Automation software [31].

The load frame (Figure 2.5) consists of a stepper motor that is attached to a gear box with a high gear ratio to create enough torque to break a steel test specimen. The apparatus provides 2000lbs of tensile force. The radial motion from the motor (not shown in the figure) is converted to linear displacement through a gearing system (1) that is set up to move two
oppositely threaded lead screws (2). A moveable steel block (3) is attached to the lead screws and as they turn, the test specimen (4) stretches.

![Figure 2.5: Load Frame without motor and gearbox. 1. Gears driven by motor/gearbox (not shown), 2. Lead screws, 3. Moveable Block, and 4. Test specimen](image)

The velocity of the system is considerably reduced by the large gear reduction from the gearbox. The motor upper speed threshold is 1500 steps/min. However, this speed is significantly reduced from the transfer of power between the motor and the gearbox and 1500 steps/min resulted in only 0.0533 inches/min of linear displacement.

LabVIEW is used to control the machine and the VI operated similar to the manufacturer’s software, in which the user can send a desired position signal to move the apparatus or allow the machine to move in a closed loop until stopped by the user. Load and displacement data is collected using a Matlab interface.
2.3.2 Membrane indenter

To convert this machine over into a membrane indenting test stand (Figure 2.6), the moveable block received an adapter that housed a ruby tipped spherical indenter with a diameter of 1 mm. On the stationary end of the test machine is the adapter that locked the membrane in place. The membrane mounting adapter is based on literature that discussed the indentation of thin plastic films using a spherical indenter, as discussed in section 2.1.1. The point load created by the indenter presses down on the membrane material but, rather than leaving a permanent indentation on the sample like a hardness test, the indenter only elastically deforms the membrane, stretching it in what is assumed as equibiaxial loading.

The free end moves forward, at a constant displacement rate, allowing the indenter to come in contact with the membrane, applying a point load in the center of the sample, similar to the method outlined in Scott [2] (Figure 2.6).

![Figure 2.6: Spherical indenter in contact with thin film membrane](image)

The load is measured using a 2lb s-beam load cell.
The data collected is stored as load and displacement data. The data will be used in ANSYS but the raw data needs to be converted into stress and strain data in order to be useful. The linear displacement is converted to a change in the circular membrane’s radius and then converted into a strain ($\Delta r/r$) (Figure 2.8).

Figure 2.7: Load frame converted into Membrane Indenter 1. Ruby Tipped Indenter attached to adapter for load cell (not shown), 2. Membrane clamp/housing, 3. Membrane sample, and 4. Motor and gearbox

Figure 2.8: Estimation of displacement in z-direction to achieve the desired elongation of the radius
1. Undeformed membrane, $r_0$, 2. Deformed Membrane after 6.7% elongation of radius, 3. Spherical Indenter

$z = 0.372 r_0$

$r_f = 1.067 r_0$
It became apparent during a trial and error testing period and through literature investigation [3, 30], that establishing the stress correlation would not be trivial and another approach would need to be taken. This is discussed further in section 2.3.4.

2.3.3 Software

The software to run the machine is a combination of ideas from the initial design team’s LabVIEW program [21], software provided by Anaheim Automation and LabVIEW interfaces created by Professor John D. Wellin. The programs are written in a LabVIEW interface and split into two programs, one that controlled the motor’s movement and another that read results from a load cell and a motor encoder. The motor control program allows the user to control linear displacement of the indenter and the data collection program allows the user to determine load and displacement information and store it in a spreadsheet format.
2.3.4 Failures of the Membrane Indenter

During the testing to see if the material experienced viscoelastic effects over specified time frame, it was shown that the material had significant viscoelastic effects. Further examination of the test specimen revealed that the indenter had penetrated the membrane and the effect being seen was due to a hole being generated. This penetration was a significant source of error. It was later proven with another testing method that the material did have a negligible effect from viscoelastic characteristics.

Correlating the load readings and displacement data into the proper stress-strain relation was very difficult. Although there were mathematical models representing a Neo-Hookean Solid model, the data collected for the Ultraflex simply did not fit. Other attempts at correlating the load-displacement data were pursued. It was assumed that a central portion of the circular membrane was determining the load readings and therefore, the stress should be calculated using a portion of the total area. The calculation of stress this way was applied into the ANSYS curve fitting application but with no success.

![Figure 2.11: Membrane sample cross section. Hashed Section shows cross sectional area.](image)
As the indenter moved down in the z-direction, the membrane was stretched radially and circumferentially (Figure 2.11). The cutout section in Figure 2.11 shows the cross sectional area used in calculating the stress. There was no material model that remotely followed the stress-strain relationship created. The machine was designed to pull apart aluminum tensile specimen. It was geared down to have a large amount of torque to be able to stretch the metal sample while displacement was measured using a motor encoder. It was able to measure an optical signal as the shaft of the motor turned. Converting the machine over to be able to indent a soft elastomeric membrane resulted in very slow tests and some inaccuracies in the displacement readings. The motor encoder output data in bits and the bits were used to determine the displacement. There were points where the encoder overshot the number of bits it was supposed to read, giving higher displacement readings than those that were actually occurring.

In general it was clear that that with the available literature on fitting material models to rubber-like tissues would not be accomplished using a membrane indentation test stand and an alternative approach was needed.
Chapter 3: Experimental and Test Methods

3.1 Biaxial Tension Machine

A second material characterization test stand was developed to obtain accurate results that would work properly with ANSYS. The machine was created as a senior design project [14], spanning over a six month period with a budget of $1500.

Prior to construction, the team had to determine how much sample deflection was necessary in order to generate enough stress/strain data to represent the full inhale/exhale range. Under this investigation, it is noted that inhaling during respiration causes around a 30% increase in the volume of a lung [23]. If the lung were simplified into a sphere then Equation 3.1 and Equation 3.2 would determine how the radius, and therefore, the circumference, would increase. The increase represents a single-direction elongation.

\[ V_o \times 1.30 = V_f \]

Equation 3.1

Where \( V_o \) is the initial volume and \( V_f \) is the final volume. Expressing this in terms of initial and final radius (\( r_o \), \( r_f \)) gives:

\[ \frac{4}{3} \pi r_o^3 \times 1.30 = \frac{4}{3} \pi r_f^3 \]

Equation 3.2

Solving the above equation results in a radius or circumference change of 6.7% from the beginning to the end of a 30% volume expansion. This can be equated to a 6.7% biaxial elongation for a planar biaxial tension specimen.
During biaxial tensile testing, samples were elongated approximately 15%. The 15% elongation was decided just for enough data collection instead of having data for the elongation only to 6.7%. This allows for enough data in case further elongation is done in the future.

### 3.1.1 Design and Development

The focal point of conceptualizing the machine was benchmarking between biaxial loadings and volumetric/pressure loading. Volumetric/pressure loading was ruled out because of the expense that came with the building of the machine and fact that the data collected could not be used with ANSYS to fit mechanical properties. ANSYS uses volume/pressure data for compressible materials such as a sponge or foam while Ultraflex is a nearly incompressible material.

Initial biaxial device design concepts included a pulley system that would be operated by two motors, stretching the membrane sample evenly, and a twin screw-dual motor set up that would run similarly to the SEM uniaxial tester. The idea of the biaxial load system was the most logical step but a system that was more efficient and accurate was needed. With further investigation, the design team came across a paper [20] describing a biaxial adapter used with an Instron uniaxial test stage to measure stress-strain behavior of a rubber-like material. This design concept was pursued because it was the most feasible design for the given budget. Other designs required more parts such as multiple motors, to create them. From what was shown in the paper, it seemed the biaxial adapter could be made into a single biaxial tensile machine that could provide equibiaxial tension.
### 3.1.2 Machine Design

The biaxial tension machine is based on a uniaxial test stand with the addition of intricate linkages that allow for horizontal motion as well as vertical.

![Conceptual Design of Biaxial Load Stand](image)

In Figure 3.1, the linkage can be seen and parts are annotated. Figure 3.2 shows the motion as the motion goes from start to finish. In Figure 3.2a, the test machine is at its initial position. As the crosshead (2) is driven up, the slides (6) follow the 45 degree angle created by the angled rod (9). As the slide travels up, the horizontal motion rods (5) travel through the pivot link (8). In Figure 3.2b, the final position of the machine can be seen. The motion arms (7) have changed from a 20 to 45 degree angle and the machine is fully extended. As a result of the 45 degree angle rod (9), there is a 1:1 ratio in x:y motion, which makes this an equibiaxial test stand. Other ratios can be achieved with different angles of rod 9.
3.1.3 Test Specimen

The test specimen used in the biaxial test machine is a cross-shaped specimen (Figure 3.3). The minimum size of the sample was 1” arms to allow for a minimum of a 1” x 1” central section. The thickness of the sample could be up to 5 millimeters. In order to eliminate the edge effects from where the material was clamped and from the corners of the cross, a central diamond region was on the focus of all strain measurements [20].
3.1.4 Operation

The machine included two load cells to collect the load data, one in the x-direction and one in the y-direction. Strain data was collected using a camera. Pictures were taken of the central diamond region, as shown in Figure 3.3, and as mentioned earlier, this approach was shown to eliminate the effect of what was happening where the material was constrained.

3.1.5 Software and Control

To control the motion of the machine, software from Anaheim Automation [31], the supplier of the motor controller, was used. The software controlled the stepper motor. The motor was sent a signal to move 50 steps, equating to a 0.635 mm displacement of the crosshead. The setup read load data using LabVIEW, and then a picture was taken using software provided from the camera [22]. All control was done manually. This process was repeated until the motor moved 1300 steps. The same process was completed while returning the crosshead back down to its initial position.
3.2 Experimental Methods

The focus of the following experimentation is on the biaxial tension machine. Information on testing the syringe pump and creating the boiling flask/alveolar bulb models can be found in prior published studies [23].

3.2.1 Creation of Specimen

Ultraflex comes in a rectangular aluminum pan. To prepare it for the biaxial test machine it needs to be melted and molded into a cross. The cross shape was created by making an aluminum mold. Melted Ultraflex was poured into the mold and allowed to cool. The mold was machined to allow for a sample that had a 1” x 1” central region with 1.20” long arms. To create a cross shape sample the following steps were used:

- Cut Ultraflex into small cubes
- Place cubes into a beaker
- Add heat from a hot plate. Ultraflex melts at 375°F.
- Once completely melted, pour Ultraflex in cross shape mold and allow to cool

3.2.2 Mounting Specimen

Mounting the sample took some finesse. The tackiness of the material made mounting the sample difficult as the operator could not simply slide the sample around in order to align it on the clamp. A test was done to measure how much error was created by remounting a sample three separate times and running a biaxial tension test on each mounting. The maximum resulting error was approximately 3-5% (Figure 3.4); however, when the target maximum error between experimental and analytical results was 5%, error stacks up quickly.
The clamp fully constrained the arm of the sample. Figure 3.5 shows the clamp and its tightening screw. The clamp allowed for zero slip in the sample.

3.2.3 Execution of Testing

Before testing began, the load cells were calibrated. The two load cells were calibrated by Maxwell Bennett Associates, the supplier. To ensure that the calibration was what the
supplier reported, known weights were applied to the load cells; 100g, 200g and 500g masses. The vertical load cell had a linear relation of 0.843 N/V and the horizontal read 0.870 N/V.

During initial testing, the weight of the clamps was shown to bend the horizontal rods (numbered 5 in Figure 3.1) down a bit. To avoid this occurrence, weak linear compression springs were added to provide enough stability to level out the rods. Once the machine had moved enough, the springs were no longer in contact and provided no additional force. The rods overcame the weight of the clamps as they moved out over the test cycle. This was verified by looking at x vs. y load data before and after the compression springs were added and verifying that the ratio of motion went from 1:2 down to around 6:7. Ideally, the ratio should be 1:1.

The tests were run using the process described in sections 3.1.4 and 3.1.5. A signal was sent to the motor to move 50 steps. Each time the motor moved the crosshead of the machine; an image was taken of the central region and stored to the computer. A LabVIEW VI was executed as well, collecting load readings for both the horizontal and vertical load cells and were stored into a text file.

### 3.2.4 Data and Image Analysis

The initial data collected was in volts, which were converted to Newtons. Using the Equation 3.3 for engineering stress:

\[
\sigma = \frac{F}{A}
\]

Equation 3.3
Where the area represented the cross sectional area of the cross sample, the thickness of the sample multiplied by the width of the sample arm.

The pictures were collected and then analyzed using Nation Instruments Vision [24] to measure displacement of patterns added to the test sample. This software has the ability to track contrast changes in a family of pictures and record the coordinates of the moving particles. Vision was used to track the moving edges of a four dots imprinted in a diamond shape upon the membrane cross sample (Figure 3.5). In order for the program to work, four template images were created. Each template image was an image representing a dot location; top, bottom, left and right. These images were created from the undeformed sample picture or the first picture of each data set. The template images are saved as portable network graphic (PNG) files. The series of images were stored in separated folders and named in sequential order containing a series of tagged image file format (TIFF) files. The Vision VI takes three inputs: image series location, template 1 location, template 2 location, all referring to the location where the files are saved on the computer.

![Image Analysis VI with Vision Assistance](image.png)

Figure 3.6: LabVIEW Image analysis VI with Vision assistance, show example of distinct images used for the image processor as template images
When the VI is started it cycles through the images from a designated folder and determines where the template images are and how they move throughout the image set. The green box surrounds the top template image and the red surrounds the bottom template image. The software effectively measures the displacements of the boxed images and establishes a distance from center to center of the images. As the image is stretched through the testing, the program is able to establish extension distances as each load step is completed. The VI runs twice for every image set, once for the vertical deflections and a second time for the horizontal deflections. Table 3.1 illustrates the sample output.

<table>
<thead>
<tr>
<th>Vertical</th>
<th>Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence Number</td>
<td>Displacement (pixels)</td>
</tr>
<tr>
<td>0</td>
<td>156.5</td>
</tr>
<tr>
<td>1</td>
<td>157.6</td>
</tr>
<tr>
<td>2</td>
<td>158.7</td>
</tr>
<tr>
<td>3</td>
<td>159.8</td>
</tr>
<tr>
<td>4</td>
<td>161.4</td>
</tr>
<tr>
<td>5</td>
<td>162.5</td>
</tr>
<tr>
<td>6</td>
<td>163.6</td>
</tr>
<tr>
<td>7</td>
<td>164.6</td>
</tr>
</tbody>
</table>

Table 3.1: Sample output from Image Processing VI. Displacements are later converted into millimeters and then strains are calculated.

The data can be processed to determine the percent elongation of the central section of the membrane. The central section starts at around 8.97 millimeters and elongates on average 15%. Due to the small concentrated displacement, it is necessary to have significant resolution for the pictures. The original images for the initial data sets were acquired using a 1.3 Megapixel camera with a zoom lens. The pixel concentration was 140 pixels/mm$^2$ or 11.8 pixels/mm. This was not accurate enough because of the small displacements with displacements less than 100 microns per load step. Use of a high zoom lens with a magnifying lens insert was added, effectively raising the level of pixel concentration from
140 pixels to 1600 pixels (40 pixels/mm), allowing more accurate tracking of particles and more definitive displacements.

### 3.3 Other Considerations

Certain aspects of the material properties were neglected to help simplify the experimentation and the ANSYS models that followed. However, it had to be verified that the assumptions made were valid.

#### 3.3.1 Hysteresis Effect

Raw data was collected from the biaxial test fixture using three cycles of testing on each of three samples, each including a loading and unloading process. A plot of the correlated data showed that the surrogate materials experience minimal hysteresis damping, meaning that the loading path and the unloading path were relatively identical. It was initially a concern that two separate FEA models would be needed to analyze the loading and unloading stages.

![Test For Hysteresis Effect](image)

**Figure 3.7:** Biaxial Test Stand, Loading & Unloading, to illustrate hysteresis effect.
The data at very small stain values between the loading and unloading phases begin to vary a bit from one another. This can be explained by the machine coming back in contact with the weak springs, causing a slight difference in displacement from beginning to end.

### 3.3.2 Viscoelastic Considerations

As mentioned in Chapter 2, the material was assumed to be viscoelastic but it was also assumed that the viscoelastic effect had minimal affect over the duration of the test time cycle. To make sure this assumption was valid; the cross shape membrane was loaded into the machine and stretched to 750 steps. After the initial stretching an image and a load reading were collected. The material was allowed to sit for one minute and another picture and load reading were taken. The process was repeated for four minutes. This yielded a result that showed insignificant effect, an average force reading of 1.861 N with a standard deviation of 1.17E-4 N, caused by the viscoelastic properties of the material and therefore, the assumption to neglect the viscoelastic effect was valid.
Chapter 4: Finite Element

4.1 Finite Element Modeling Methods

The ultimate goal of the FEM for this thesis is to be able to predict nodal displacements of an alveolar sac model. This chapter describes the process of creating the finite element model including material properties, model geometry and boundary conditions for a series of models with increasing complexity. Results were validated with actual experimental data.

4.1.1 General FE Process

There were a few steps to follow in order to create the finite element models. It started with deciding the element type. The SHELL element was chosen for the models because of the hollow shape of the molds and the ability for the elements to accommodate membrane behavior. There are many SHELL elements within ANSYS, however, only three of them allow for membrane stiffness. A material that exhibits membrane characteristics lacks transverse stiffness and therefore collapse under its own weight. This eliminated many element types leaving SHELL elements as one of the remaining options. The four SHELL elements viable for the model creation were SHELL181, SHELL281, SHELL208 and SHELL209.

SHELL181 and SHELL281 are very similar. All of the element options are the same; however, SHELL181 uses 4-Node quadrilateral elements while SHELL281 uses 8-Node quadrilateral elements. SHELL281 allows for analyses involving composites that feature nonlinear stabilization. SHELL208 and SHELL209 are similar to SHELL181 and SHELL281 with the difference lying in the model creation. SHELL208 and SHELL209 are
limited to 2-D axi-symmetric models for representing 3-D shapes, unlike SHELL181 and SHELL281, which are full 3-D elements.

<table>
<thead>
<tr>
<th>Element Type</th>
<th>Hyperelastic</th>
<th>Membrane</th>
<th>3-D</th>
<th>Complex Geometry</th>
<th>Other Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHELL181</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Only 4-Node elements, not ideal for curved surfaces</td>
</tr>
<tr>
<td>SHELL281</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>8-Node elements, for curved surfaces</td>
</tr>
<tr>
<td>SHELL208</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes, Axi-symmetric</td>
<td>No</td>
<td>2 Node Elements</td>
</tr>
<tr>
<td>SHELL209</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes, Axi-symmetric</td>
<td>No</td>
<td>3 Node Elements</td>
</tr>
</tbody>
</table>

Table 4.1: SHELL elements considered for modeling and their characteristics

SHELL281 was finally chosen because it allows for nonlinear geometry. In other words, for any rounded or filleted shapes, an 8-node element was more appropriate.

After the element was chosen, the geometry of the model was created. Due to an issue with importing a CAD model with a finite thickness that needed to be meshed as a 2-D surface element, all models were created with ANSYS using the modeling section in the preprocessor.

One special consideration was the use of substeps. Substeps help control the solver when the element reaches nonlinearity. The routine will incrementally increase the applied load or displacement based on the size of the substeps. For example, if the maximum number of substeps is 50, the nominal is 25 and the minimum 10, and then if a severe nonlinearity occurs in the solution, the solver can cut the applied displacement into 50 increments, thus allowing for the calculation to move at a finer step size making solution convergence more
likely. Conversely, if the solution shows little nonlinearity, the solver will use 10 load or displacement increments. Using substeps also allows for Time History plot generation to see how the sample deforms as the applied load or displacement is ramped up.

4.1.2 Biaxial Test Sample

The cross-shaped biaxial tensile sample model was simulated in ANSYS to support the data found using the characterization test stand. The data collected from the test stand, converted to stress and strain data, was imported into ANSYS. The coefficients for a Mooney-Rivlin 2-parameter model were generated and used in the model.

The model was created using a SHELL281 element. SHELL281 elements allow for hyperelastic materials with membrane characteristics. This element type is a plane element with a defined thickness, meaning the z-dimension (thickness) is small compared to the in-plane (local x-y) dimensions. Also, all the loading occurs in the local x-y plane. The cross-shaped sample lacked transverse stiffness and therefore collapsed under its own weight when not supported. The elements were defined with a thickness of 1.19 millimeters (real constant), and to behave with membrane stiffness only (keyopt1=1), as opposed to membrane and bending stiffness. In order to create an accurate model and to ensure that results would be available for specific points of interest to compare with experimental data, the model was split into 13 areas (Figure 4.1) and a mapped mesh was applied (Figure 4.2).
_mapped meshing allows for a tighter concentration of elements at certain specified areas, for example, where a stress raiser may occur. When the mesh needed refinement, it was easier to refine at the area of the stress raiser, rather than the entire model. This allowed for fewer elements and nodes while maintaining the accuracy of the model. Mesh convergence tests were performed to ensure that the points of high stress were not skewing the accuracy of the model. Mesh convergence simply implies that the mesh was refined to the point where the...
results of each subsequent model refinement, was less than 5% off from the other. Table 3.3 summarizes the results of mesh convergence tests, where “Mesh Iterations” describes the number of times the model was refined to achieve an accurate solution (within 5%), “Result” is the Von Mises stress at a certain node within the model, “%Difference” is the error from mesh iteration, and finally “Nodes” is the number of nodes in the model after each refinement.

![Figure 4.3: Mapped Meshing of Biaxial Elements](image)

<table>
<thead>
<tr>
<th>Mesh Iterations</th>
<th>Nodes</th>
<th>Results (MPa)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mapped Mesh</td>
<td>2892</td>
<td>0.06422</td>
<td>N/a</td>
</tr>
<tr>
<td>Refinement #1</td>
<td>4572</td>
<td>0.07244</td>
<td>11.35</td>
</tr>
<tr>
<td>Refinement #2</td>
<td>9042</td>
<td>0.07352</td>
<td>1.47</td>
</tr>
</tbody>
</table>

Table 4.2: Mesh Convergence of the Biaxial Sample.

In the material characterization test stand (biaxial), the user can control the displacement of the sample. To better recreate this phenomenon in ANSYS, displacements were assigned to the model where they would be applied in the physical model.
To analyze the model, substeps were used. The maximum number of substeps was 12, minimum was 12 and the nominal substeps amount was 12 to force the solver to give 12 data points for graphing purposes.

4.1.3 3D Boiling Flask Model

The boiling flask model was used to confirm that the data collected from the biaxial test stand was indeed correct. The 3D bulb model was created to predict the displacements of its physical counterpart. As mentioned before, PIV studies were conducted using a test fixture with a molded balloon-like sac that was filled with glycerin and completely submerged in a glycerin bath, to eliminate gravity effects on the model. The PIV test stand was used to collect displacement and pressure data that could be compared to the predicted ANSYS information.

The model was created using the same SHELL281 element. However, the keyopt (1) was set to 0 this time, enabling both bending and membrane stiffness because the geometry provided some type of stiffness against bending. The shape did not completely collapse under its own weight. The thickness was defined through the real constant and the material properties were applied using the coefficients generated from the previous model for a Mooney-Rivlin 2-Parameter curve. The geometry was simplified into a sphere with a cylinder coming out of it. The two shapes were merged together into a single volume. Finally, to achieve the desired geometry the entire volume was deleted leaving only areas, lines, and key points behind, giving a hollowed model. The cylinder’s surface areas were removed leaving only the surface of the sphere with an opening on the top. The model is shown in Figure 4.2.
Mesh convergence was achieved after two iterations. Unlike the biaxial tensile sample model, mapped mashing was not required on this model since there are no stress raisers or other features of interest in the model. The mesh was refined to achieve an accurate solution.

<table>
<thead>
<tr>
<th>Mesh Size</th>
<th>Result (mm)</th>
<th>% Difference</th>
<th>Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smart Mesh (6)</td>
<td>2.691</td>
<td>N/A</td>
<td>572</td>
</tr>
<tr>
<td>Refinement #1</td>
<td>2.692</td>
<td>0.001</td>
<td>2250</td>
</tr>
</tbody>
</table>

Table 4.3: Mesh Convergence for Boiling Flask
As shown in the biaxial convergence table (Table 4.2), the only change to Table 4.3 is that the result column is the displacement very bottom node of the boiling flask. Note that Smart Mesh (6) is a mesh sizing option within the ANSYS meshing tool.

Displacement constraints were applied to the line at the opening in the boiling flask. All degrees of freedom were set to zero to represent the way the sample is mounted in the pump fixture. A negative pressure of 300 Pa is applied to all nodes of the model, as would be seen in the fixture. To establish a ramping of the pressure, substeps were used again. The solver was forced to solve using 100 increments to ensure that there would be small enough increments to generate substantial data tables for comparison purposes.

![Figure 4.6: Boiling Flask Boundary Conditions](image)

Time plots were collected by writing all the substeps from the analysis to produce a displacement curve as the pressure ramps up. This curve will be compared to the data collected from the test fixture in Chapter 5.

**4.1.4 13 Bulb Alveolar Sac**

The 13 bulb alveolar sac model was created in a manner similar to the 3D Boiling Flask. 13 spheres were merged with a cylinder. The physical model of the alveolar sac cast used for the
PIV test fixture has ellipsoid bulbs. The CAD model used to create the cast used equally sized spheres; however, more distinct intersections between the spheres were created using a DREMEL tool as well as polishing of the sphere surfaces. This happened in the course of the previous research to try to encourage more fluid recirculation within the alveolar sac, as would be seen in real alveoli. The problem with using the DREMEL tool to modify geometry is that it results in the creation of irregular features. No two bulbs were the same dimensions and the added intersections were all different depths. As a result, the creation of a model that looked like the actual casting was nearly impossible, so the model was kept simplified.

Model creation procedure was similar to the boiling flask. The same elements, same real constant and keyopts were all used. The creation of the model followed the same exact process as creating the boiling flask model. The mesh convergence could not be achieved because the model solution would not converge and will be further discussed in the results chapter.
The stress raisers were at the intersections of the spheres. Initially, area fillets were added to try to alleviate this occurrence. However, due to the way the casting was modified, there was no way of determining the size or true shape of the fillets added.

Displacement constraints were applied to the top opening. All degrees of freedom are set to zero to represent the way the sample is mounted in the pump fixture. A 300 Pa pressure was applied, as in the physical model.

<table>
<thead>
<tr>
<th>Element Type</th>
<th>Thickness</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHELL281</td>
<td>1.5mm</td>
<td>Membrane and Bending</td>
</tr>
</tbody>
</table>

**Boundary Conditions:** Zero displacement at top. Ramping Load up to 300Pa to entire area

**Validate:** Displacement results at the middle and bottom of model

Table 4.4: Element/Model inputs for 13 Bulb Alveolar Sac Sample

To establish a ramping of the vacuum, substeps were used again. The solver was forced to solve using 10,000 increments to ensure that there would be small enough increments to
generate substantial data tables for comparison purposes. The increased number of
increments was also needed because of the geometric interactions between the spheres as
mentioned earlier.

4.1.5 Uniaxial Sample

The uniaxial sample was created just as the biaxial sample was. The only change was that the
model was a single strip. The model was created using a SHELL281 element.

Table 4.7 shows the constraints and boundary conditions that were applied. The bottom line
of the sample was constrained to not move in any degree of freedom. The top line was
constrained to not be able to move in the x or z directions and was assigned a 6.35mm
displacement in the y-direction.

Table 4.7 shows the constraints and boundary conditions that were applied. The bottom line
of the sample was constrained to not move in any degree of freedom. The top line was
constrained to not be able to move in the x or z directions and was assigned a 6.35mm
displacement in the y-direction.

![Figure 4.9 Uniaxial Boundary Conditions](image_url)
Mapped meshing was used even with the simple geometry. Area partitions and map meshing may not have been necessary but were used regardless.

<table>
<thead>
<tr>
<th>Mesh Iterations</th>
<th>Result (MPa)</th>
<th>%Difference</th>
<th>Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mapped Mesh (Edge Length 10)</td>
<td>0.0159</td>
<td>N/a</td>
<td>781</td>
</tr>
<tr>
<td>Mapped Mesh (Edge Length 4)</td>
<td>0.0158</td>
<td>0.63</td>
<td>4173</td>
</tr>
</tbody>
</table>

Table 4.5: Mesh Convergence of the Uniaxial Sample.
Mesh iterations describes the number of times the model was refined to achieve an accurate solution, within 5%. The result column depicts the Von Mises stress at a certain node within the model. The Difference column shows the error from mesh iteration and finally the nodes column displays the increase in the number of nodes after each refinement.

Substeps were used to generate data for the Time-History plot. The maximum number of substeps was 12, minimum was 12 and the nominal substeps amount was 12 to force the solver to give 12 data points for graphing purposes.
Chapter 5: Results

This chapter summarizes the results of all testing using the biaxial tension machine and all predictive modeling done to validate the mechanical property model.

The first material tested for the thesis research was medium Ultraflex. Material data was collected using the biaxial tensile machine. Due to inaccuracies of the machine, only the y-direction results were used because of the 45 degree angle rod that controls the 1:1 ratio movement for the x-direction. A slight change in the angle of the rod can cause up to 15% strain difference in the x-direction.

Figure 5.1: Example of Biaxial Tension Machine comparison of x vs. y Stress-Strain data

Figure 5.1 shows how the 45 degree angle affects the equibiaxial test. The x-direction strains around 15% while the y-direction strains to 17.5%. This is nearly 15% difference in the strains. Figure 5.2 shows the relation of the x and y loads based on the machine moving to
15% elongation in the y-direction. Y is set to the x-axis because the y-direction displacement is being controlled by the crosshead moving and x-direction displacement is a result of that.

Instead of a 1:1 x-y relation, the machine has become a 6:7 relation. Each degree that the rod is off from 45 contributes to a 3.5% difference in the overall strain amount. The machine was assumed to still be accurate in the y-direction and this assumption is later proved to be correct.

5.1: Machine Validation

The tests were performed on the Ultraflex using the biaxial tensile machine. The tests were done to elongate the test sample to approximately 15%.
The load data was first converted from V to N. Then a stress correlation was made by using the simple stress relation shown in Equation 3.3, where the area was simply the cross sectional area of the sample; the width multiplied by the thickness. The displacement data was converted from pixel displacements to measurements in millimeters using a calibration factor, as outlined in section 3.2.4. Finally, the displacement was converted into strain measurements using the following strain equation:

$$ e = \frac{\ell_i - \ell_o}{\ell_o} $$

Equation 5.1

where $\ell_i$ is the instantaneous length of the sample and $\ell_o$ is the original, unstrained length.

Figure 5.3 shows the stress-strain data for medium Ultraflex.

![Figure 5.3: Biaxial Tension Machine results of data converted over to Stress/Strain data. Material Tested: Medium Ultraflex](image)

A curve fit within ANSYS using this data resulted in the following Mooney-Rivlin 2-Parameter Coefficients (Figure 5.4):
• $C_{10} = 1.27 \times 10^{-2}$ MPa
• $C_{01} = -3.02 \times 10^{-3}$ MPa
• $d = 0$

Figure 5.4: Mooney-Rivlin Curve fit from within ANSYS for Medium Ultraflex using data collected by the Biaxial Tension Machine.

It was discovered through analyzing the data and comparing biaxial experimental data to biaxial ANSYS data that a problem had arisen. The assumption that stress at the grip where the load cell was located was the same as the strain in the central diamond region was not valid. This assumed that stress was uniform throughout the sample from top to bottom. Unfortunately, this was not the case. From this point on, material properties were determined from uniaxial tensile tests and were compared to those of the biaxial tensile tests. This will show the process is still valid but a different approach to measuring stress is necessary when using biaxial samples. There is a comparison on the uniformity of stress between the biaxial sample and the uniaxial sample in Figure 5.5.
The contour values of the biaxial sample (left) vary from 0.012-0.018 MPa, or a 33% variation. The uniaxial sample (right) vary from 0.0024 to 0.0026, or 7.5% variation. As a result of the lower variation in the uniaxial sample, the previously described assumption was more valid for this sample geometry. The uniaxial data was collected and correlated just like the biaxial data.
A curve fit within ANSYS using this data (Figure 5.6) resulted in the following Mooney-Rivlin 2-Parameter Coefficients (Figure 5.7):

- \( C_{10} = -3.52 \times 10^{-3} \) MPa
- \( C_{01} = -7.79 \times 10^{-3} \) MPa
- \( d = 0 \)

![Figure 5.7: Mooney-Rivlin Curve fit from within ANSYS for Medium Ultraflex using data collected by the Uniaxial tension.](image)

**5.1.1: Biaxial Sample**

The first verification for the collected data was to apply it into an ANSYS model that represented the biaxial tensile machine. Using the processes described in Chapter 4, the model was solved and the resulting stress-strain data is shown in Figure 5.8, along with ANSYS models solved with both the uniaxial and biaxial Mooney-Rivlin coefficients.
The comparison between ANSYS and experimental stress/strain data shows moderate error in the stress values. The ANSYS biaxial model overestimates the amount of stress required to strain the sample while the uniaxial underestimates. Due to the nature of the uniaxial test, the results are not ideal for the loading scenario seen in a biaxial test [8].

The same comparison was done with the uniaxial tensile test of Medium Ultraflex (Figure 5.9). In this test, the ANSYS model run with uniaxial Mooney-Rivlin coefficients predict the experimental results to within 2%. The biaxial data is off as a result of what was described before with the assumption of a uniform stress distribution.
Due to the nature of the fabrication process for the boiling flask model, non-uniform sample thickness occurred frequently. To investigate the effect of thickness on the behavior of the samples, three different biaxial samples with three different thicknesses were tested. The following load-strain data was collected using the biaxial tension machine. Figure 5.10 notes the thickness of each sample and shows the effect on the reaction load at the clamps and how it varies with thickness. Thicknesses are based on the three thicknesses of the three samples used for testing. As the strain increases above 6%, the thickness of the material has notable effect on the amount of force needed to stretch the material. At approximately 14% strain, there is approximately 10% difference in load due to thickness related effects.
To properly recreate the conditions in the biaxial tensile machine during testing, the ANSYS model needed staggered displacements between x- and y-directions. Ideally, the displacement in the x-direction would be equal to that in the y-direction but because this was not the case with the machine, the x-direction was forced to displace 10% less than the y-direction in the ANSYS model. Figure 5.11 shows how the difference in displacement can affect the results of the simulations.

The Y-direction stress begins to drop as there is less x-direction pulling to overcome and as a subsequent result, the sample strains more. The nominal region of the difference between x- and y-direction would be around 1:1.12. All biaxial models were completed using a 1:1.12 ratio.
5.1.2 Boiling Flask

The boiling flask validation was critical. A successful validation would demonstrate that the biaxial tension material characterization could be applied to the type of loading experienced in an inflating balloon-type shape similar to an alveolar sac.

Deflection data was collected at the 6:00 and 3:00 positions on the boiling flask (A and B in Figure 5.12).
The data was collected with a sample from the syringe pump fixture. It had a thickness of 1.1mm. However, there were areas of non-uniformity. As the boiling flask is made and cooled, the material is able to collect more at the bottom of the flask than at the top. In these tests, a thinner wall on the sample would allow for greater deformation than that with a thicker wall. It could be a source of error in the results.

The following graphs depict the experimental data collected from the pump fixture compared to the ANSYS model at the two points as described earlier.

The results from the boiling flask comparison show the progression of results over time. Oakes’ model [23] is based on a linear elastic modulus and it can be seen that the new process of testing and using hyperelastic material models is progressively getting closer to the experimental results. The results are not the 5% difference that was targeted, but this work can be seen as a move in the right direction for further analysis.
Significant error is introduced by the pressure sensor in the Syringe Pump Test Stand. This error is large enough that it alone could be responsible for the difference when predicting
model behavior (Figure 5.14 and 5.15). This will be discussed in further detail in section 6.2.3.

Figure 5.14: Experimental and ANSYS data for the 6:00 position on the boiling flask, with error bars. Material Tested: Medium Ultraflex

Figure 5.15: Experimental and ANSYS data for a point at the 3:00 position on the boiling flask, with error bars. Material Tested: Medium Ultraflex
The 3rd data point in both figures is an outlier and this could be an effect of the variation in the thickness in the real sample as opposed to the uniform model created in ANSYS. Also, inaccuracies within the syringe pump system such as a fluctuation in the pressure sensor voltage reading can very easily contribute to large error. Along with those error points, nodes from the ANSYS models do not exist at the exact points measured from the images from the experimental data. The nearest node to its corresponding experimental point was chosen. The assumption was made that the boiling flask should act as a symmetric model because simplistically, it is a sphere with an opening on top. Aside from minor variation in thickness from side to side, the data collected from the 3:00 position should be the same as the 9:00 position. The same type of assumption was made earlier when discussing the use of two load cells on the biaxial machine. The machine was assumed to pull equally from right to left and from top to bottom [23].

5.1.3 13 Bulb Alveolar Sac

Various issues arose in work on the 13 bulb alveolar sac model. When testing the model experimentally, the cast used for the mold has a great deal of variation from bulb to bulb, making it very hard to create in ANSYS. The ANSYS model was created using equally sized spheres, merged with a cylinder, as they would look on the injection mold. A common occurrence during the solving process of ANSYS was an error from an unconverged solution due to excessive loads. To eliminate that in the other models, the load was split up into more substeps. After using over 10,000 substeps, the solution would still not converge correctly. With the material properties being used, when the model was expanded, random areas detached from the model and displaced hundreds of millimeters away from the actual 13 bulb model. The model was recreated multiple times yet the same errors still existed.
As mentioned earlier, even with the ANSYS model working correctly, the comparison between experimental data and ANSYS data could be greatly skewed due to the actual geometry of the mold casting. As a result, this modeling work was not pursued further.

5.2 Firm Ultraflex

To establish that the method of determining material properties through the use of ANSYS model curve fitting was generally applicable, a second surrogate material was used. Firm Ultraflex was used to satisfy this requirement. Firm Ultraflex has a Shore A hardness of 15 compared to that of medium Ultraflex, with a Shore A hardness of 7.

A curve fit within ANSYS using this data resulted in the following Mooney-Rivlin 2-Parameter Coefficients (Figure 5.17):

- $C_{10} = 3.46E-2$ MPa
• $C_{01} = -1.085 \times 10^{-2}$ MPa

• $d = 0$

Figure 5.17: Mooney-Rivlin Curve fit from within ANSYS for Firm Ultraflex using data collected by the Biaxial Tension Machine.

As a result of the ANSYS curve fit of the biaxial data being inaccurate, the uniaxial tensile data was used to generate the ANSYS coefficients for model prediction.

Figure 5.18: Uniaxial Tension results of data converted over to Stress/Strain data. Material tested: Firm Ultraflex
A curve fit within ANSYS using this data resulted in the following Mooney-Rivlin 2-Parameter Coefficients (Figure 5.19):

- $C_{10} = 1.514E-2$ MPa
- $C_{01} = 5.10E-4$ MPa
- $d = 0$

### 5.2.1 Biaxial Sample

In Figure 5.20, the ANSYS data predictions are the same as they were with Medium Ultraflex. The Uniaxial data underestimates while the biaxial data overestimates. The uniaxial prediction is around 10% off from the experimental data while the biaxial prediction is off by nearly 30%.
Once again, this shows that the process of material property determination as outlined in this study is viable and probable but refinement of the biaxial test needs to be further pursued.

5.2.2 Uniaxial Sample

The uniaxial tension model was also used to verify what was seen in the previous material, that the uniaxial data could still generate an accurate material model for an ANSYS representation. Unlike the other uniaxial comparison with Medium Ultraflex, the biaxial coefficients underestimate what happens experimentally. With the inaccuracies of the machine, the increased stiffness of the Firm Ultraflex and the mismatch of data, (using biaxial data for coefficients to predict a uniaxial test), the added variability of all these occurrences could cause such an underestimate.
Tests on the boiling flask model were not done using Firm Ultraflex. The supplier of the Ultraflex stated that firm Ultraflex is no longer available, meaning the firm Ultraflex remaining from initial testing was all that was left.

By analyzing the uniaxial data and the biaxial data for the firm Ultraflex, it can be assumed that the process of determining material properties through the use of the biaxial tensile machine and ANSYS curve fitting works for more than one material. The average error in the uniaxial data test was around 1% when comparing with uniaxial coefficients and 30% when comparing biaxial coefficients. The biaxial tensile stand requires some remanufacturing to improve test data. Given the limitation of the test fixture, the material properties determination process is ready for further research on geometry of the test sample. Any further refinements would require construction of new test equipment.
Chapter 6: Conclusion

6.1 Evaluation of the results

The application of using the biaxial tension machine to generate material properties of various hyperelastic materials has been proven a viable path for further research. It has been shown in this study that the shape of the test sample is important. This study showed that a cross shape tensile sample did not provide a uniform stress distribution necessary for estimating the stress happening where the strain data was being collected. Uniaxial test samples were tested originally for verification processes but they were later used to demonstrate that the process of experimental data collection used to for the purpose of ANSYS curve fitting to achieve material models was applicable. As a result of the shape of the uniaxial sample, the stress distribution through the sample was more evenly dispersed. In a further look into the literature, a square shape sample has been successfully used [34]. The stress distribution from where the sample was gripped to the center of the sample was even. Future research could focus on a new shape sample for testing.

Error from the machine itself was depicted in Chapter 5. These errors did not necessarily show a significant contribution to affecting the results; however, they do show the need for correction to the machine. Ensuring the machine has a 1:1 ratio of movement in the horizontal aspect of the machine would eliminate a large sum of possible error for future testing.
As suggested in the literature, the research supported that using one load scenario to represent another wasn’t ideal. For example, using the uniaxial data to generate coefficients and then creating a predictive model in ANSYS to represent the biaxial tensile tests. This just further supports corrective measurements need to be taken with the test Fixture as well as the test sample for future research.

The work completed for this thesis lays the groundwork for follow-on projects related to characterizing biological materials and surrogate materials that have nonlinear elastic behavior. Work currently under way as part of a separate project is aimed at looking into the characterization of materials to simulate lung tissue in healthy and emphysematous (loss of elastic characteristics over time) states. Other work could revolve around moving on to smaller scale material samples to eventually being capable to be able to quantify the material properties of a human alveolar sac.

6.2 Improvements

The results show data that is promising and close to target ranges. However, there are many improvements that can be made to the test fixtures and testing procedures that could eventually lead to greater accuracy and precision for future work.

6.2.1 Biaxial Machine

The biaxial machine has the ability to gather relatively accurate data. A few corrections to the machine build would make for a high precision material characterization test stand.
• Better manufacturing process: Have the machine made by a computer numerical controlled (CNC) machine. This would provide less variation from part to part and could eliminate a great deal of error and binding in the machine. The Brinkman Lab at RIT has the capability to do so. The job was submitted to be done on the CNC machines. However, after four weeks of trying to follow up and see the progress of the job, it was apparent that the job was not moving further in the queue and the work from the Brinkman Lab was abandoned due to time constraints. The machine needed to be completed and testing needed to begin.

• Control horizontal and vertical motion using two independent linear stages: Vertical motion was translated into a horizontal motion using angled rods at 45 degrees. The angled rods being off by just a single degree could have contributed significantly to the error between the vertical and horizontal data.

• Smoother motion: Linear bearings were used to provide smooth motion as the machine stretched the sample. The bearings bound up as the machine moved up and down. As a result, the data was collected in incremental steps. The linear bearings were relatively expensive but higher precision and accurate bearings are available with a higher price tag.

• Biaxial Test Sample Shape. A sample with square geometry as mentioned earlier would be a more appropriate test shape for more uniform stress distribution.

• Mounting the sample in the machine was challenging. To remount the sample, repeatedly, provided error in the data collection and redesigning a new mounting technique could greatly improve data collection repeatability from sample to sample.

• Better load cells: the load cells used for this project were accurate, but limited by the team’s budget. More accurate load cells are available for a higher price.
• Finer motion control: The motion from the stepper motion is very accurate, but the incremental displacements of a stepper motor are not small. For future research of micro-scale samples, a linear stage could be used. The suggestion was made during the design review for the biaxial tension machine. The stages were over budget, but the resolutions of the stages are available to 1.5µm. The stages are expensive but the concept of biaxial testing for material properties has been shown to work with relatively high accuracy, so stages could be implemented for smaller samples.

6.2.2 Image Analysis

The image analyses processes made a simple and seamless transition from images over to useable displacement data. However, modifications to the process would make it faster and easier to gain the images for analysis.

• The marking of Ultra Flex is incredibly difficult. The Ultra Flex is very tacky and most marking instruments wipe off with the touch of a finger. Permanent marker was used to apply a data pattern to samples; however, the tip of the marker sometimes would rip the sample.

• A smooth line was very hard to achieve because of the material tackiness and the size of the tip of the magic marker was rather large for the scale work being done. The displacement of the sample at the central area was at most one millimeter. The tip of a permanent marker is 0.3 millimeters.

• When using the µI Vision software, the bounding box used to capture the template image of the dots drawn on the sample could vary based on the size of a dot. Smaller
markers were tried. A 0.005mm marker was found, but unfortunately, the ink would not adhere to the material and just beaded up.

- A stencil was used to apply the dots in a diamond pattern on the biaxial samples. If the diamond was a tenth of a millimeter larger in the horizontal direction than the vertical direction, the strain measurement would be greater in the horizontal. It was seen that as strain was measured through an axis, the farther from the center that the strain was measured, the greater the strain percentage was. When dealing with such small strains as millimeters, this can cause a great deal of inaccuracy. Developing a better way to mark the samples could help with variation in strain measurements from sample to sample and even from dot to dot.

- Using ImageJ can introduce some error into analysis. With the boiling flask images, when a data point was chosen, a (x-y) location was recorded. When trying to record that same location, it was easy to miss that data point by almost 4 pixels. This could be quantified into a 0.3 mm difference. Trying to incorporate the boiling flask image analysis into the NI Vision program, the data could be more precise.

6.2.3 Syringe Pump

The syringe pump had the ability to gather information for the inhalation and exhalation testing. However, the sensors within the pump lacked precision and accuracy. Also, mounting a sample in the pump was very tedious and took multiple attempts and models to finally run a single test.

- The syringe pump is very inefficient in terms of mounting samples. A series of 8 bolts compress the top of the apparatus down to achieve a vacuum tight seal. However,
removing the top and reapplying it is tedious and takes a lot of time. Work is currently underway to help alleviate this problem.

- The way data was collected for this thesis, the operator controlled how much glycerin was being added or removed from the container. The accuracy in removing a specific amount of volume is very low, i.e. it was hard to go from zero expansion to a moderately smaller expansion to displace the bottom of the flask 1 mm. After 1 mm, the pump is easier to control. It seems evident that the reason this was happening was a linear spring that had been added to stop the syringe from unwanted movement. A program to run the pump exists but it is based on a breathing curve and not useful for the amount of data needed for this research. A program could be written within LabVIEW that assigned a specific amount of fluid to be removed and to allow for static images to be collected.

- The pressure sensor responsible for measuring the pressure within the fluid retainer could be upgraded. The sensor would drift +/- 0.05V when trying to read a static value. This translates to a pressure difference of +/-50 Pa. As seen in Chapter 5, a difference of 50 Pa can result in a difference of nearly 0.3mm of deflection. When the total deflection is on the order of 3-4 mm, this degree of drift is significant. To minimize this error, a more accurate sensor is needed to eliminate this voltage fluctuation. The sensor being used was rated for a maximum pressure of 10 kPa. This sensor is sized for a much higher pressure application, where this syringe pump setup goes to around 1500 Pa.
6.3 Closing

The work of this thesis provides a solid foundation of which a lot of future work can be built upon. It has been shown that material characterization can be achieved through the processes outlined. With further pursuit into the suggested corrections from in Section 6.2, a fundamental process for determining tissue properties could be fully implemented in the future.

The research accomplished a process to gather material properties for hyperelastic materials. The data was collected and then analyzed in applied to a curve fit in the form of a Mooney-Rivlin 2-Parameter material model. The model allowed for the generation of coefficients ($C_{01}$ and $C_{10}$) to be applied into other structural models. However, on top of being able to create other structural models in ANSYS, the coefficients from the Mooney-Rivlin 2-Parameter model can be used with COMSOL, which can be used for structural-fluid interaction models. This was one of the initial accomplishments sought after through this research.

It was also shown that the process could work for multiple materials. Analyzing both firm and medium Ultraflex, it was shown that the process could be used for other hyperelastic materials in the future with further refinement and eventually progress to determining properties of tissue properties, ultimately, properties of an alveolar sac. Being able to use true alveoli tissue properties will allow for the most accurate computational models to investigate particle deposition in the future. It will give a better understanding to where particles deposit and how they move within individual alveoli.
References


