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FACULTY OF MECHANICAL ENGINEERING

MASTER THESIS

NONLINEAR MATERIAL PARAMETER IDENTIFICATION OF SOFT MATERIALS BASED ON AN INVERSE FINITE ELEMENT METHOD APPROACH

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Declaration of Authorship

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Aachen, 1st of January 3000

Nadia Pinedo Oruna, B.Sc.

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1 Introduction

1.1 Background and Context

Precise knowledge about the biomechanical characterization of soft tissues has received attention in medical research, e.g., medical image analysis and visualization. For many years, the obtained medical diagnosis have come from assumptions of experts or accumulated experience. This information, although proven to be useful, has its limitations when computed-assisted systems like, medical diagnosis, therapy, and training, rely on more quantifiable data[5]. To gather this data, it is important to gain access to the tissues and perform in-vivo testing experiments. For organs, this procedure is nearly impossible to achieve, due to the involvement of an invasive procedure, and the lack of constant and reproducible external and internal factors.

1.2 Problem Statement

One of the complications associated with the extraction of the organ is that some material properties may change despite examination of the same organ. Their biomechanical properties depend on other factors, such as changes in blood pressure, changes in material properties over time, symptoms from diseases, etc. Furthermore, another encountered issue is the lack of replication, due to the use of different individuals organs, which includes more external factors to add to the equation. Moreover, given a tissue sample, it is difficult to characterize the organ's material properly due to its anisotropy property. The material properties change, resulting in an inaccurate result.

In the situation where the soft material's data can be gather in a constant, fast and reliable process, the data enables the system to predict the behavior of soft tissues and give pre-operative calculations. This shows that material models represent a vital part for medical research, specially for the use of computational models, as their help to increase the accuracy of the simulation and its applications in other systems.

In soft materials analyses, a nonlinear situation is mostly encountered, for which a finite element method becomes a common approach. The application of the finite element method facilitates the analysis of complex structures with complex material behavior, and aids in solving of continuum mechanical problems. Nevertheless, in order to simulate a material with this complexity also requires complex algorithms with high computational costs.

1.3 Objective and Scope of the Study

One of the goals of this study to identify the key parameters of the soft materials, and their influence in the construction of a material model. These key parameters the attempt to approximate such a complex material will be done, and this simplified material model will be validated for its future applications in medical research.

With the application of the experiment testing, and the finite element method it is possible to identify some key material parameters through an inverse finite element method approach. With this method a framework can be established and the results of computational model can be matched to the experimental data, and afterwards be validated with other experiments.

1.4 State of the Art

1.4.1 Experimental Characterization for Soft Materials

In order to characterize the mechanical behavior of a test specimen, the most common method method is to mechanically load the specimen and measure the response of the force against the displacement [1].

- Soft synthetics materials like soft gels are one example for soft synthetic materials. These are commonly applied for tissue engineering applications. Nevertheless, due to their elastic modulus range (kPa) present some challenges for the design of experimental testing[6].

Uniaxial Tension/Compression Testing

This is one of the most common using methods to determine an stress-strain relationship. For uniaxial tension cases, the specimen is well loaded in a machine by gripping the ends and perfoming tension tests. Then, the deformation is usually measured with a strain gauge. [1]

As for compression test, the specimen is loaded by placing it inbetween from two plates and compressing the material. [1]

This method allows the validation of several computational models as it provides with searched parameters done with other experimental procedure.

Aspiration Experiment

Tissue aspiration experiments introduces an aspiration tube which is put against the soft tissue, generating a vacuum. An advantageous feature of this experiment is that it can be perfomed in-vivo and ex-vivo. With the help of a mirror placed next to aspiration hole, the reflection of the side-view of the tissue can be captured with a video camera. This camera captures the images of the iluminated surface of the material and the aspiration pressure is captured through a sensor. Through this process the captured profile of the tissue is obtained and this can be used to characterize the deformation and analyze the viscoelastic properties of the soft tissue[5].

Indentation

Indentation have being gaining popularity in the last decades and it is now one of the most spread experiments for material parameter identification. Indentation presents a bigger advantage in cases where it is not possible to load test specimens in a more conventional way.[1] As some materials, e.g. biomaterials do not always allow the use of uniaxial or biaxial tensile testing, the use of identation testing is essential.

Indentation possesses advantageous characteristics for the mechanical characterization of soft materials. [6] Nanoindentation or microindentation it is useful for the evaluation of nonlinear viscoplastic responses. [1]

The indentation testing set up is described as followed: As shown in Fig. 1.1 A system applies a certain force to an attached indenter rod where and specific indenter tip. After the indenter tip goes to a determined displacement, it is possible to obtain a Load-displacement curve. The deformation can be measured through an capacitance gauge [1] or also optically (via laser measurements).

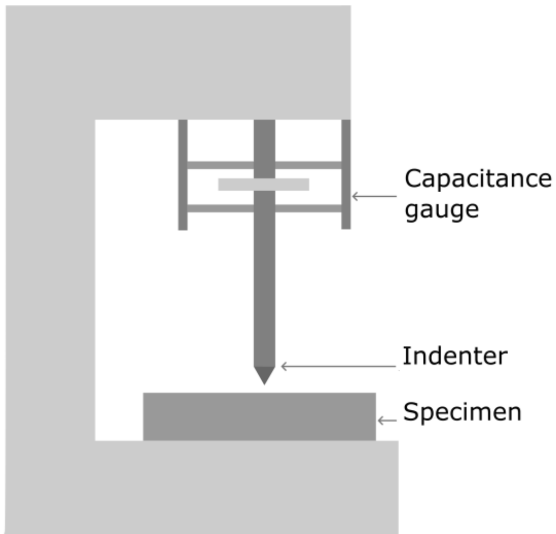


FIGURE 1.1: Nanoindentation experiment setup.

-identation in materials - Identation in soft materials (organs) - Why is identation relevant in organs -what advantages and disadvantges does identation provides - why is relevant for this project

1.4.2 Material Modeling of Soft Materials

Relevant papers tends to use hyperelastic models to represent soft materials as the viscoelasticity is usually neglected. Material model are very relevant for the simulation model (Kauer2002). Soft tissues are approximated as near incompressible due to their highly water content. For the aspiration experiment conducted by Kauer they used the following strain energy function based on the model of Susanne and Bathe (SusanneandBAthe1987)

As derivative from this formula for the uteri metrial modeling the formula used was:

1.4.3 Inverse Finite Element Method for Parameter Identification

An inverse finite element (FE) approach requires usually a certain experimental model, which generates certain information e. g. load-displacement curve, and through a verified computational model match the given data curve to obtain further information of the material's behavior e. g., stress-strain curve.

Specially for nonlinear cases [3], where the complexity of the problems increases, and the interest is focused to generate an action which results in a certain output response, is where an inverse finite element approach can be helpful to discover a certain variable going from an ouput data. Through an iterative process it is possible to describe the material's behavior and validate the output data it through other established testing e. g., uniaxial testing.

Though this approach does not always give a hundred percent match in all obtain points or zones, it allows the researcher to understand the influences of certain parameters for the materials. This is specially useful for complex materials as biomaterials.

Biomaterials, as mentioned previously, depends on multiple external factors, e.g., blood pressure, affected diseases and the their material properties is constantly changing. This issue does not allow the researcher to develop a proper material model which is usable for multiple use-cases.

Therefore, the importance of the inverse element method as relevant key for estimating constantly changing parameters in soft materials.

For biomechanical models, where the models require knowledge from local properties [2], as the biomaterial is not isotropic; it is possible to identify a parameter e.g. Young's Modulus from a 3D model. The model can be matched to multiple experiments and multiple samples in different areas, which allows a better representation of the material for further analysis.

The inverse FE approach can used by optimizing the searched parameter by matching the simulated data to a section of a experimental curve and extending this process through some iterations. Nevertheless, it is important to clarify that this method also requires making assumptions to some values. Furthermore, it is relevant to document these assumptions for the further analysis. With the combination of assumptions, experimental data, and a optimized and matched simulation curve, it is possible to solve the complexity of biomechanical models.

In next sections some of the experimental models and the material models for bio and soft materials are going to be explained to get a further understanding in how is possible to get a realiable computational model for further reasearch

Synthetic Soft Materials

Synthetics materials are commonly used to validate an inverse parameter identification process. Usually these synthetic, soft materials provide similar mechanical behavior to it's biomaterials counterparts. This characterization allows to validate a proposed inverse finite element approach process before its applicatoin with a biomaterial, where the measurements to gather the experimental data are some in-vivo, and more challenging to recreate.

For example, Silgel, a very soft gel-like material [5] was used for the experimental validation of the inverse finite element method proposed, to characterized the tissue of a human uteri. In this work, the tensile behavior of the material was predicted through the parameters obtained in the aspiration method. The matching procedure is optimize through an objective function, which consists of the squared differences between the simulation and exprimental data. With an optimization algorithm an optimal set of the following parameters was found: the material parameters μ_i [N/m^2] and the bulk Modulus κ [N/m^2]. This method showed good prediction quality of the mentioned material parameters.

Biomaterials

Biomaterials as mentioned before, represent a challenge due its difficult access and lesser replicability. Therefore these materials are usually used for the experimetnal validation of a methd applied previously in synthetic materials. Following the first example of the Silgel in the previous section, the inverse finite element parameter estimation is applied now on human uteri [5] through in vivo and ex vivo measurements of the human tissue of different patients. It was mentioned, that in comparison from the silgel the uterus possesses a complex multi layered structure with strongly anistropic and viscoelastic properties. Nevertheless, five material parameters were determined, based on the strain energy function to model a human uterus (Yamada 1970). Through the same inverse method applied with the synthetic material, the obtained parameters facilitated the prediction of stress-elongation curves for tensile experiments. The resulting curves showed the difference of stiffness for in vivo and ex vivo measurements and the material singurality for each uterus.

1.4.4 Standard Verification and Validation for Computational Solid Mechanics (ASME)

VV40

1.5 Overview

2 Experimental Model

The first phase of this project was to design and select an appropriate experimental model. This was essential to gather the necessary data from the tested material. This data will be used to determine the design parameters that can help to characterize the material's mechanical behavior.

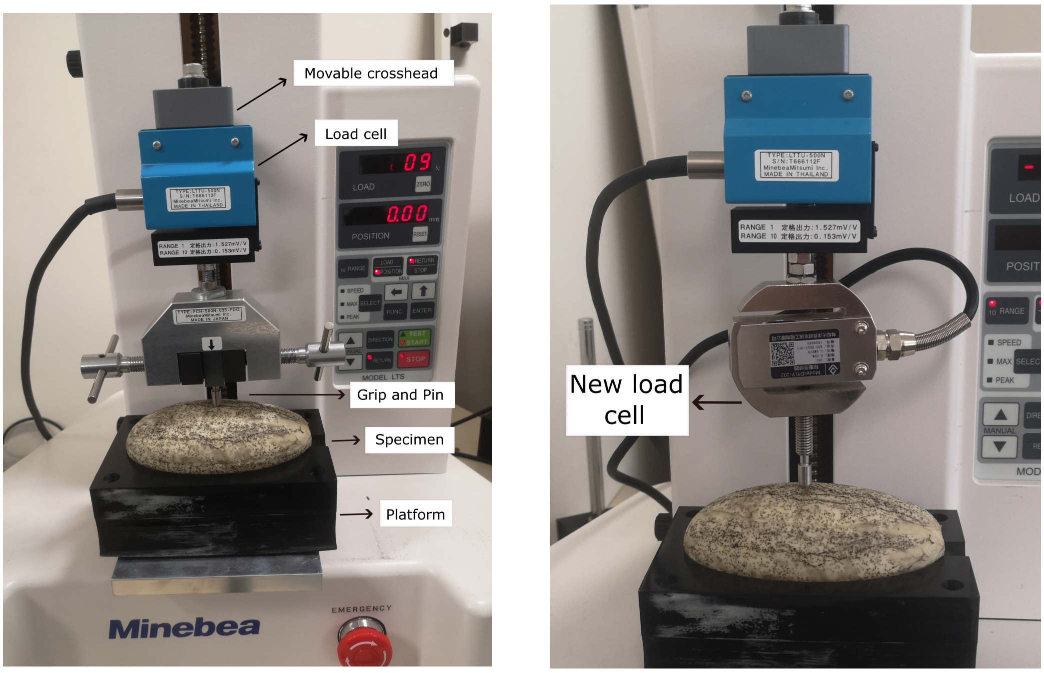
The first experimental model had the purpose of serving as a comparator for the experimental model II (see section 2.2). At the beginning of the project, the desired experimental model to be analyzed was the second experimental model, which was developed and designed by Yokohama National University (YNU). As this second experimental model was still undergoing some improvements and corrections, a similar experiment was designed which could fulfill the same purpose.

The chosen experimental characterization for the inverse finite element method for the identification of material parameters for this project was indentation. The goal of these experiments was to observe the mechanical behavior of a soft material under compression using a rounded indenter. The aim was to determine the material behavior and observe the response under an indentation larger than the indenter radius. Additionally, by performing the indentation tests, the obtained data helped for a more in-depth understanding of the material's mechanical behavior for the chosen use cases and the determination of the main assumptions for the material modeling. The main advantage of indentation is the noninvasive feature, which will mostly become useful when a test sample should not be modified, e.g., an organ.

For both experimental setups, the specimen, which was tested, was made from a human skin gel. The human skin gel material was a two-component ultra-soft urethane resin. Polyurethane is widely used for biomedical applications, e.g., preparation of implants, wound dressings, artificial organs, and medical supplies.

Polyurethane can also be used for simulating organ tissues, as it can be tailored to mimic and match the mechanical properties of the desired biological tissues [8]. Furthermore, polyurethane can be synthesized to have a wide range of stiffness, elasticity, viscoelasticity, and can also be prepared with complex shapes for medical research purposes [4].

In this section, the different experimental models, which were used to evaluate the mechanical behavior of the ultra-soft polyurethane, will be described. In the first two subsections, will focus on the description and procedure of the experimental models, followed by explanation of the indentation test types. Consequently, an evaluation and analysis of the results will be provided and the main assumptions for the design of the material modeling will be defined.



(A) Indentation test configuration with a 500 N load cell

(B) Indentation test configuration with a 10 N load cell

FIGURE 2.1: First experimental model: Tensile and compression machine with an indenter with a rounded head. Test Specimen made from ultra-soft polyurethane resin positioned on a fixed platform with a similar shape for constraint.

2.1 Experimental Model I

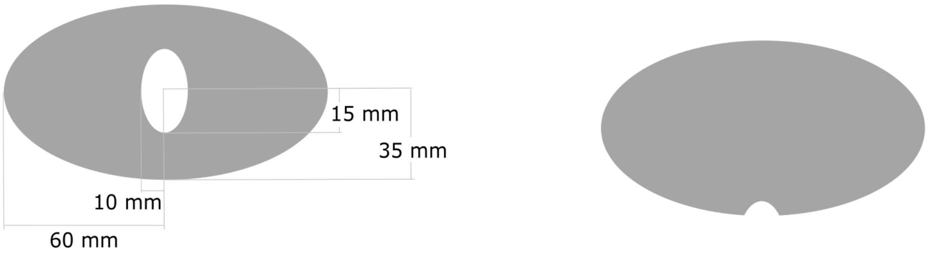
Description of the Experimental Setup

The first indentation test configuration was done by adapting a tensile and compression testing machine, model LTS - 500 NB from MinebeaMitsumi.Inc (Fig. 2.1). This machine possess a maximum load capacity of 500 N, and test speeds of 10 mm/min, 20 mm/min, 30 mm/min, 50 mm/min, 75 mm/min and 100 mm/min. To achieve an indentation testing configuration, a pin was attached to the movable crosshead holding grip, as shown in Fig 2.1a. The indenter had a rounded head made of stainless steel with a radius of $r_p = 3$ mm and a length of $l_p = 11$ mm.

The specimen possesses a ellipsoidal form with with a minor radius $r_1 = 35$ mm and a major radius $r_2 = 60$ mm. This specimen geometry is supposed to simulate a kidney with an extracted tumor; therefore, on the lower part of the specimen a half ellipsoid with a minor radius $r_{l1} = 10$ mm and a major radius $r_{l2} = 15$ mm was removed (Fig. 2.2). The specimen was prepared by a YNU laboratory member, by 3D printing a mold with the wanted dimensions and a ellipsoidal shape, and filling it with liquid resin. Additionally, it was left to cure for around 30 hours. Then, the specimen was positioned on a platform fixed to the base, which suited the ellipsoidal geometry for properly constraint.

Procedure for Conducting the Experiment

For the indentation test after placing the specimen on the platform, the indenter was positioned slightly on the surface of the point of interest. The test was conducted



(A) Specimen dimensions bottom view

(B) Specimen side view

FIGURE 2.2: First experimental model: Specimen dimensions made from ultra-soft polyurethane resin for indentation test.

with a room temperature of approximately 22 °C To perform the test the indenter was then lowered onto the surface of the specimen at a velocity of 10 mm/min. The indentation depth was controlled by limiting the maximum depth, and the test stopped once the inserted depth was reached. The indenter returned to its original position after reaching the maximum depth with a rate of 100 mm/min. Due to the material properties, the specimen returned to its original shape. The result of the indentation test was a load-displacement data, which was recorded with a sampling rate of 63 Hz using a load cell of ±500 N and a encoder to measure the displacement.

The measurement accuracy according to the specification of the machine, has a relative reading error of 1.0 %. The indentation test was repeated five times on the same sample to ensure and observe reliability and repeatability. Furthermore, the raw data collected from the test was processed and analyzed using Excel.

During the initial indentation test using the 500 N load cell, the collected experimental data showed noise that could affect the accuracy and reliability of the results. The noise was likely caused by sensitivity of the lead cell. The ultra-soft polyurethane material showed force readings, which were near the lower limit of the load cell's range, which adding any other external factors, results in noisy measurements. To address this issue, a load cell of 10 N was installed (Fig. 2.1b). This change improved the quality of the measurements and reduced the noise in the data. The change to the load cell had some implication to the experimental setup, such as removing the holding grip, and designing a part which could connect the indenter with the new load cell. In addition to changing the load cell, a simple filtering method was used to improve the experimental data. After applying the filter, the noise in the data was reduced, resulting in more smoother force reaction readings.

Overall, the applications of the combinations helped to improved the quality and acuracy of the data and gave important information about possible measurement errors to take into consideration for of the experimental model designed by YNU. At last, The filtered data was used for subsequent analysis and interpretation for the inverse finite element method approach for the material parameter identification.

2.2 Experimental Model II

The second experimental model was developed and designed by Yuta Mori, a member of the Yamada Laboratory from the Mechanical Engineering department of Yokohama National University. The main aim for this experimental method was to be able to identify the physical properties of organs in a state that closely resembles the in vivo environment. Additionally, this model seekd two achieve two objectives:

firstly, to develop a loading system to acquire the data required for an inverse analysis, and secondly, to establish a measurement process in case of a total nephrectomy [7].

The resulting data from the experimental model served for the basis of the material parameter identification for the inverse finite element method approach. The processed data obtained from this experimental model assisted in the calibration and assessment of the design parameters was employ in the validation for the computational model.

Description of the Experimental Setup

the first experimental model the test specimen and the platform were it lies, has the same dimensions, minor radius $r_1 = 35\,\text{mm}$ and a major radius r_2 of 60 mm. The test specimen is also made from the same material, ultra-soft polyurethane resin.

The indenter on the other hand, is a sphere made of ruby, the sphere radius is also equal to the radius of the pin r_s 3 mm and attached to it, is the force load cell.

A laser is used to measure the displacement which results in a load-displacement curve. With this model it is possible to not only determine the toal force reaction, but also it's components F_x, F_y and F_z. Furthermore, with the laser it is also possible to observe the deformation not only in one point but around the whole area. This allows as to analyze the deformation of the whole structure.

The indentation speed selcted was and with an indentation depth of h_s is 4 mm. With this experiment, 4 key points on the sepcimen's surface were chosen: First, in the middle and three other points, one to right, one down, and one diagonal to middle, forming a square with a distance between points of d_s 20 mm.

Similar to the previous model, Fig. shows a nonlinear behavior with a maximum force reac

2.3 Experimental Tests Description

2.3.1 Middle Point

2.3.2 Load Unloading

2.3.3 Nearby Point

2.4 Analysis and Comparison of Experimental Techniques

2.4.1 Overview of the Data and Results

2.4.2 Main Assumptions for Material Modeling

The first point to be analyzed, which is used to build a material model is point No. 1, in the middle of the surface. The advantages from this case, is the less influence of external factors. For this case it is vaiable to assumed, that shear stresses can be neglected and offers a simple model to focus on the material definition.

For this project, there is a focus on the limitation of each material model, departing from an ideal scenario. From this point on the material will be build accordingly and for each model the influence of the material parameters is going to be assessed.

2.4.3 First Material model

Linear elasticity

Hyperelasticity

The strain energy density function for the Neo-Hookean material model is given with

$$\Psi = C_1(I_1 - 3)\,,$$

where C_1 is a material constant and $I_!$ is the first invariant of the right Cauchy-Green tensor. Neo Hookean and Mooney Rivlin comparison

Furthermore, in order to get the measurement of the load and unloading process of the indentation a displacement sensor was attached to the tensile machine.

The indentation depth h_1 selected for the first model was 3,8 mm on the middle of the top surface of the specimen. This indentation depth surpasses the pin radius r_3 and was chose arbitriarily to analyze the behavior of the material on the defined position. Additionally, it was observed that in soft materials it is easier to capture some parameters with a larger indentation. Some references also observe that with indentation depth lower than indenter radius has a lot of noise and do not describe th results accurately.

From the first experimental model we can observe that the material shows a non-linear behavior and the maximum total force reaction F_1 lies around 0.45 N. Furthermore, when applying different speeds, as show in Fig. it is also possible to observe that the hysteresis increases. This increasement shows that the material possesses a viscoelastic behavior, however as this increasement is not significantly, it is possible to neglect viscoelasticity for the first stages of the project.

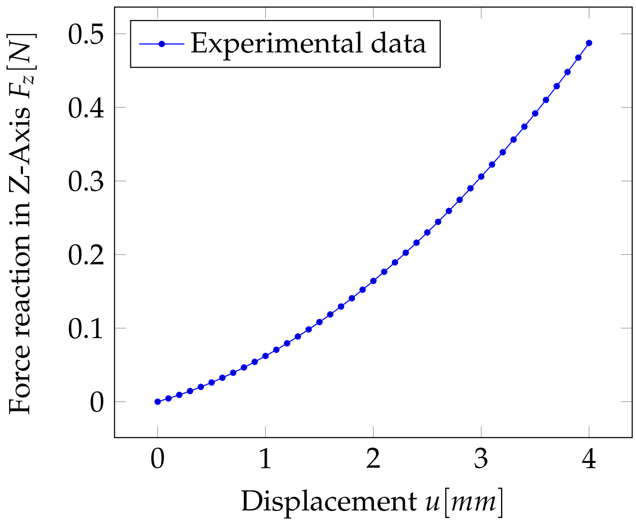


FIGURE 2.3: Experimental Load-displacement curve.

3 Computational model

3.1 Middle point

3.1.1 Description

The quasi static nature of the indentation experiment allows the use of a static structural analysis.

For the creation of the computational model, the SOLID 187 elements were used. The mesh for the whole model is formed from quad tetrahedral elemennts. The platform and the specimen have an global element size of 5 mm. The indenter has an element size of 0.5 mm. In the area of the indentation, there is finer mesh with an element size of 1 mm and a radius of 8 mm.

3.1.2 Analysis and Complications

Their a two main factors which increases the complexity of the validation of the simulation and those are, the contact nonlinearity, and the element distortion due to indentation experiment. These issues make the computational time expensive, as it requires to manual solutions for the meshing in the area of importance, and small time steps. For that, the nonlinear adaptive meshing option in ANSYS Workbench was applied, which does a remeshing process if the a certain parameter is exceeded.Specially, for larger indentation cases, this option shows a more stable model with a good mesh convergence analysis.

A force-displacement curve, shown in Fig... is generated from the first assumption, for this case

For both cases

3.1.3 Verification of the Simulation Model

Mesh Convergence Analysis

Platform vs Fixed Support

3.2 Nearby point

4 Inverse Finite Element Method for Material Parameter Identification

4.1 Procedure of IFEM

4.2 Material Modeling

In an ideal and first scenario, this material can be assumed as linear, isotropic, elastic and nearly imcompressible. For this case, there are two main variables, the Young's Modulus E, and the Poisson's ratio ν.

From the parametric analysis, it is possible to see that the bulk modulus of this material does not possess a big impact in the FE simulation results. This conclusion combined with the results from the Poisson ratio in the first material model coincide with the statements from Bergström, where it is no vital to know these parameters to obtain accurate FE computational models, as these have limited influence on the mechanical response. [1]

4.2.1 Response Surface Optimization

Linear Elastic Model

Hyperelastic Model: Neo-Hookean

4.2.2 Objective Function Optimzation

4.2.3 Analysis and Comparison of Each Approach

5 Results

5.1 Overview and Analysis

5.2 Framework proposal

5.3 Verification and Validation

5.3.1 Deeper indentation

5.3.2 Deformation profile analysis

5.4 Limitations and implications of the results

5.4.1 First Experimental model

The chosen experimental technique for the inverse identification for this project was indentation. The test specimen used for this experiment was a ultra-soft polyurethane resin. As shown in Fig.. the specimen possesses a ellipsoidal form with with a minor radius r_1 = 35 mm and a major radius r_2 = 60 mm. This was positioned on a fixed platform that suited the ellipsoidal geometry of the specimen to constrain its movement. The specimen was tested in a indentation test configuration with a tensile/compression machine. To achieve this congiguration a pin with a rounded head made of structural steel, with a radius of r_3 = 3 mm was attached to the holding grips followed by a force load cell. The result of indentation test was a load-displacement points. The approximated polynomial curve was used as a reference for the material modeling.

The measured force reation F_1 data showed a very small number, so the first 50 N load cell displayed a lot of noise in the measurements. Therefore, the load cell was change to 10N to reduce this interference. The 10 N load cell displayed the force-displacement curve of the indenter and the specimen in a finer way. Furthermore, in order to get the measurement of the load and unloading process of the indentation a displacement sensor was attached to the tensile machine.

The indentation depth h_1 selected for the first model was 3,8 mm on the middle of the top surface of the specimen. This indentation depth surpasses the pin radius r_3 and was chose arbitriarily to analyze the behavior of the material on the defined position. Additionally, it was observed that in soft materials it is easier to capture some parameters with a larger indentation. Some references also observe that with indentation depth lower than indenter radius has a lot of noise and do not describe th results accurately.

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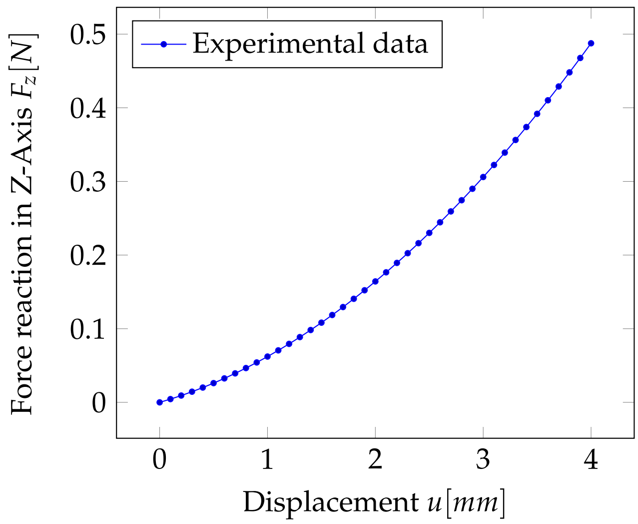

FIGURE 5.1: Experimental Load-displacement curve.

5.4.2 Second Experimental model

The second experimental model was developed by Yokohama National University. Similar to the first experimental model the test specimen and the platform were it lies, has the same dimensions, minor radius $r_1 = 35$ mm and a major radius r_2 of 60 mm. The test specimen is also made from the same material, ultra-soft polyurethane resin.

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From the parametric analysis, it is possible to see that the bulk modulus of this material does not possess a big impact in the FE simulation results. This conclusion combined with the results from the Poisson ratio in the first material model coincide with the statements from Bergström, where it is no vital to know these parameters to obtain accurate FE computational models, as these have limited influence on the mechanical response. [1]

6 Conclusion and Outlook

6.1 Summary and Contributions

6.2 Recommendations for Future Research

6.3 Conclusions and Final Remarks

A Frequently Asked Questions

A.1 How do I change the colors of links?

The color of links can be changed to your liking using:
`\hypersetup{urlcolor=red}`, or
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`\hypersetup{hidelinks}`.
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`\hypersetup{colorlinks=false}`.

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